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Report

THE USE OF LIQUID LITHIUM AS COOLANT IN A TOROIDAL FUSION REACTOR

PART II

Stress Limitations

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ABSTRACT

The pressure gradient induced in liquid lithium as it is pumped across a magnetic field was calculated in Part I of this report. The stress in the walls of the lithium ducts due to this pressure is shown to limit the wall loading in a toroidal reactor, and this limitation is seen to be more severe than the need to restrict the pumping power.

A stress criterion is developed, and then applied to both a low power prototype reactor and a large commercial reactor. It is shown that although the use of the lithium for cooling the nuclear blanket is possible in the former, it leads to an economically unattractive power density in the commerical reactor.

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SYMBOLS

The following are used in addition to those listed in Part I.

f	Stress in the duct wall
A_w	Area of reactor first wall served by a single coolant duct
P_w	Wall loading of reactor first wall, defined as the total power deposited in the nuclear blanket per unit area of first wall
ΔT	Temperature rise of coolant
ℓ	Effective length of duct perpendicular to the magnetic field
P_t	Total thermal power output of reactor
P_p	Pumping power required to circulate coolant
R_m	Major radius of toroidal reactor
r_p	Plasma radius in minor cross-section
y	Ratio of plasma radius to first wall radius
n	Plasma density
(σv)	Nuclear reaction rate
Q_b	Nuclear energy deposited in the blanket per reaction
q	Safety factor in a Tokamak reactor
β_o	Limiting plasma pressure ratio

MKS units are used in all equations.

1. INTRODUCTION

In Part I of this report the power required to pump an electrically conducting fluid, such as lithium, through a strong magnetic field was calculated. A preliminary estimate of the pumping power required to remove the heat from the nuclear blanket of a toroidal fusion reactor suggested that the use of lithium as coolant might not be possible. In this second part of the report the problem of cooling the reactor will be discussed in more detail, with a view to defining the conditions under which lithium could be used as the heat transfer medium.

Because of the easier plasma physics requirements it is very likely that the first generation of fusion reactors will employ the deuterium-tritium fuel cycle. This will require breeding of further tritium fuel in the nuclear blanket by means of the of the reactions ^{7}Li(n,n$'\alpha$)T and ^{6}Li(n,α)T, so that lithium will be a major constituent of the blanket. Much of the energy released by the fusion reactions will be deposited in this blanket by the slowing down and capture of neutrons, and must be removed as heat by a suitable heat transfer medium. The possibility therefore exists of using lithium at a temperature around 500 to 600°C as both the breeding and heat transfer fluid - an attractively simple concept which removes the need for two fluids in the blanket, reduces the structural material required, and minimises the blanket thickness.

In order the simplify the discussion the reactor will be considered to be a steady state device consisting of a single toroidal magnetic field system of the form defined by previous studies of the economics of toroidal reactors. A modular blanket structure inside the magnetic field windings will have a cellular front wall supported from the main structure in the shielding region. The pressure required to circulate the lithium will be calculated, together with the resultant mechanical stresses in the ducting, to show the limitations that these impose upon the reactor parameters. These limitations will be compared with the requirements imposed by the plasma physics, so that a possible operating regime can be defined. Finally, the implication of these limitations for both a power reactor and a low power prototype will be assessed.

2. MODEL REACTOR BLANKET

A possible modular blanket structure is shown diagrammatically in Figure 1. The toroidal magnet is sub-divided into individual coils separated by compressional supports, and heat transfer ducts pass between each pair of coils to the blanket. The liquid lithium coolant passes into the system between coils and is distributed to the cellular blanket structure through circumferential and axial manifolds whose maximum length is 1 to 2 metres in either direction. Cool lithium is supplied through a duct to the front surface of the blanket and then flows back through the whole cross-section of a cell. The length of the ducts through the reflector and blanket is less than 1 metre, so that the total length of a duct

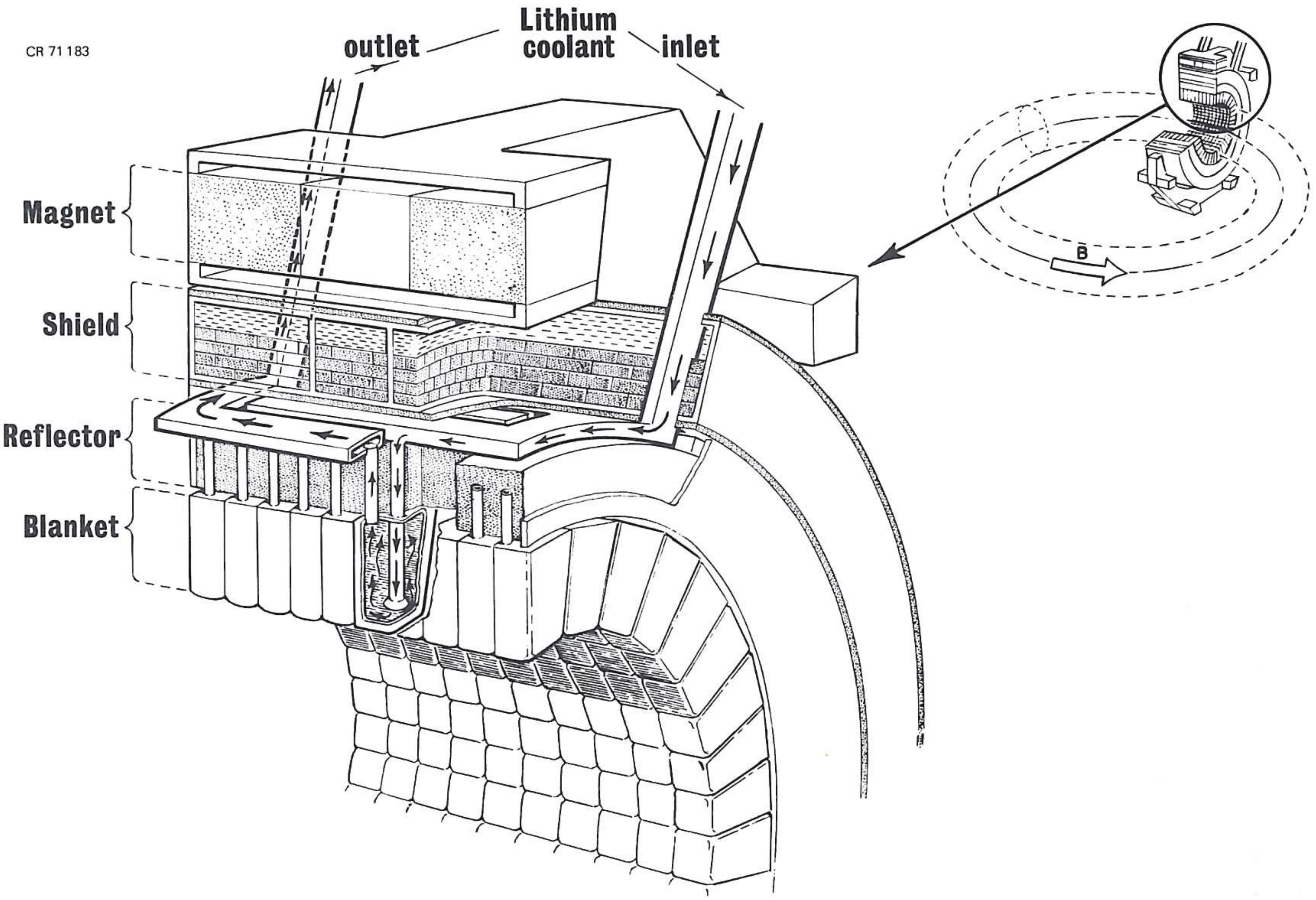


Fig. 1 Section of a modular reactor, showing the flow path for the liquid lithium coolant

perpendicular to the field is about 5 metres.

Since the pressure gradient due to MHD losses in the lithium is proportional to the velocity it would be desirable to use the largest possible ducts. The availability of space and shielding requirements place a severe restriction on duct size, however, and in practice it is probably only feasible to use a maximum of 10% of the total cross-sectional area to accommodate both the feed and return ducts. Thus the size and length of the lithium ducts are fixed, the latter being almost independent of the physical size or power output of the reactor.

3. LIMITATIONS DUE TO STRESSES IN THE DUCTS

Because of the high pressure of lithium in the ducts they will probably be circular in cross-section, and because excessive quantities of structure will adversely affect breeding in the front sections of the blanket and unnecessarily thick ducts will increase their cost everywhere, the ducts will be relatively thin walled. In this situation the tensile stress in the wall will be simply related to the pressure P, the wall thickness t and duct radius a

$$f = aP/t \ . \tag{1}$$

From Part I of the report the pressure gradient due to MHD losses in a metallic duct with a local perpendicular component of magnetic field B was derived

$$\delta p/\delta z = Q\sigma_f B^2 \phi/A = Q\sigma_w t B^2/aA \tag{2}$$

where Q is the volume flow of coolant. This flow is determined by the permissible temperature rise in the coolant ΔT, the area of nuclear blanket served by each duct A_w, and the power loading of the first wall of the nuclear blanket P_w, defined as the thermal power deposited in the blanket per unit area of wall facing the plasma.

$$Q = P_w A_w / c\rho\Delta T \ . \tag{3}$$

From (1)(2) and (3) we may deduce the maximum stress in the wall of a duct with an effective length ℓ perpendicular to the magnetic field

$$f = \sigma_w \ell B^2 P_w A_w / c\rho\Delta T A \ . \tag{4}$$

Since most of the parameters in equation (4) are fixed or limited in their values, the stress in the duct wall is determined. For example, with $A/A_w \sim 0.05$ and $\ell \sim 5$ metres as indicated in the previous section, and liquid lithium in stainless steel ducts at an average temperature of 450°C and temperature difference of 300°C, the stress is only a function of the power loading of the first wall P_w and the magnetic field B, as shown in Figure 2. The use of lithium as a coolant is seen to be feasible only with low magnetic fields or low wall loadings. It should be noted that the stress is not affected by the wall thickness of the duct or the ratio (t/a) which still remain unspecified.

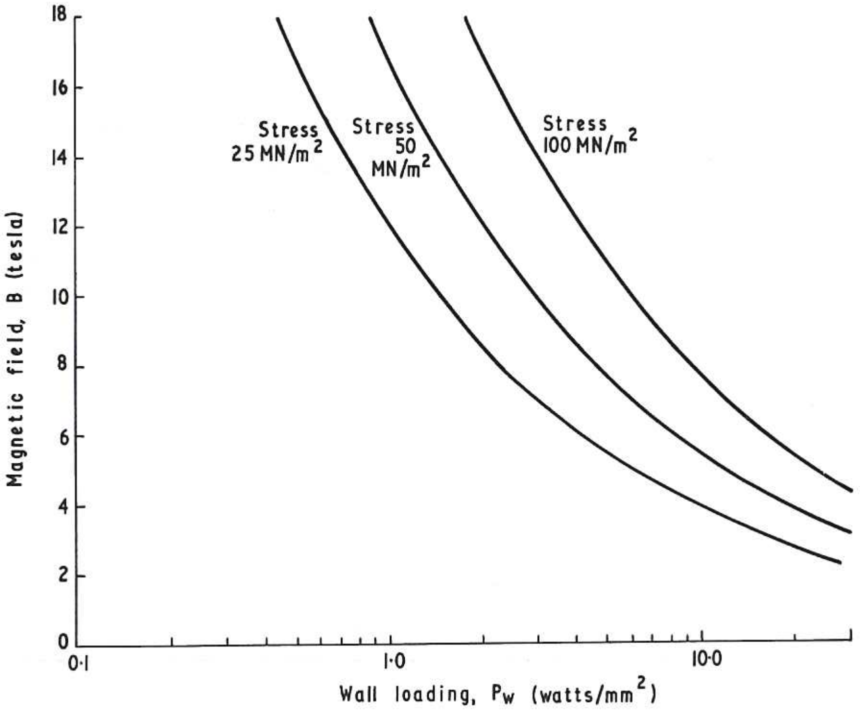


Fig. 2 Limitation imposed on the wall loading and maximum magnetic field by stress in the duct walls

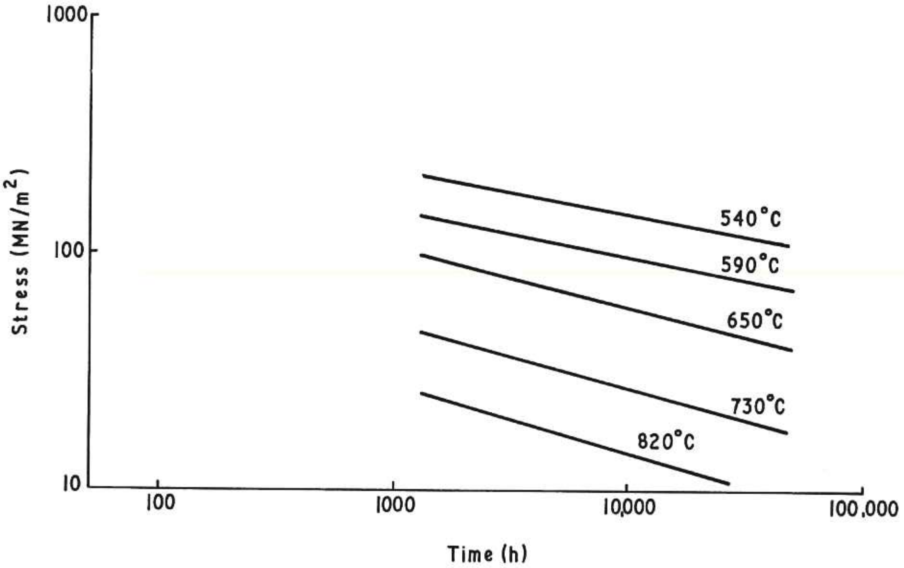
In interpreting Figure 2 it is necessary to have some knowledge of the permissible stresses in the duct materials. The limit at high operating temperatures will be long term creep, and a suitable criterion might be a working level of half the stress required to produce 0.2% creep in 100,000 hours. Typical creep curves for a stainless steel(1) and a nimonic alloy(2) are shown in Figure 3, and extrapolation of such curves suggest the limits shown in Table I.

TABLE I

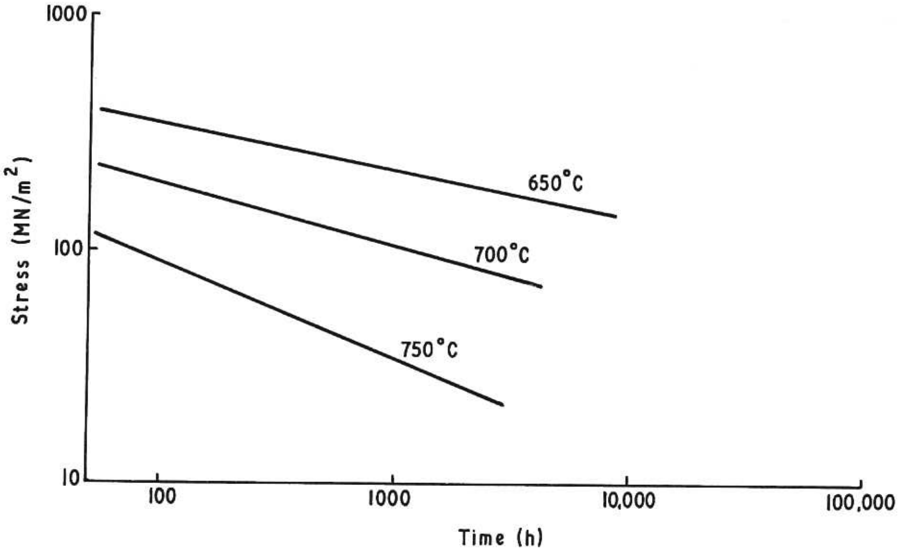
Working stress for various materials, imposed by 0.2% creep limit in 100,000 hours

Material		Creep Stress (MN/m^2)	Working Stress (MN/m^2)
Stainless steel (316)	at 550°C	100	50
	at 600°C	80	40
Nimonic alloy (PE16)	at 600°C	150	75
	at 650°C	100	50
Molybdenum alloy (TZM)	at 980°C	120	60

These stresses do not take into account the degrading effect of the severe neutron radiation damage which occurs near the front wall of the reactor blanket, which might further reduce the possible operating stesses. In practice, however, by arranging that the temperature gradient in the cellular wall structure gave the lowest temperature at the front wall it would be possible to avoid having both a high temperature and a high neutron flux at the same place.



(a) Type 316 stainless steel



(b) Nimonic alloy PE16

Fig. 3 Stress-time curves for 0.2% creep

Accepting a working stress of around 50 MN/m^2 together with the previously fixed parameters, reduces equation (4) to

$$P_w B^2 < 3 \times 10^8 .$$

With a magnetic field of 10 tesla this leads to a maximum wall loading of 3 W/mm^2, which is lower than has previously been considered economically feasible. A more detailed discussion of this limitation will be given later.

4. PUMPING POWER LIMITATION

The pumping power required to circulate the lithium coolant P_p is proportional to the power output of the reactor and from equations (1) to (4) the ratio can be shown to be

$$\frac{P_p}{P_t} = \frac{ft}{ac\rho\Delta T} . \quad (5)$$

Since the working stress f has already been fixed, this ratio is only dependent on (t/a), and provided (t/a) is less than 0.1 the pumping power will be less than 2% of the reactor thermal output for a stress of 50 MW/m^2. In practice (t/a) is more severely limited by the need to reduce the structural component of the blanket to optimize tritium breeding, and therefore the pumping limitation is less severe than the stress limitation. This situation is only reversed when very high stresses (~ 100 MN/m^2) can be tolerated or the temperature difference ΔT of the lithium must be reduced - conditions which might exist in a low energy prototype reactor.

5. LIMITATION OF REACTOR PARAMETERS

In a toroidal power reactor the most serious limitation to the use of liquid lithium as a coolant is seen to be the stress in the pumping ducts, so that either low magnetic fields or low wall loadings are required. From considerations of the plasma physics, however, these are not independent variables, so that the limitation may be stated more specifically.

For a toroidal reactor with plasma radius r_p, major radius R_m, and a ratio of plasma radius to first wall radius y, the thermal power is

$$P_t = 4\pi^2 r_p R_m P_w / y \quad (6)$$

assuming that only the energy deposited in the nuclear blanket will be used for the useful generation of electricity. The thermal power can also be expressed in terms of the plasma density n, the reaction rate (σv), and the energy deposited in the nuclear blanket per nuclear reaction Q_b,

$$P_t = \pi^2 r_p^2 R_m n^2 (\sigma v) Q_b / 2 . \quad (7)$$

Assuming the reactor to be a steady state tokamak the limit on the plasma pressure ratio is

$$\beta_o = r_p / R_m q^2 \quad (8)$$

where q is the safety factor and is expected to have a value between 1 and about 3.

For a reactor similar to that discussed by Gibson, Hancox and Bickerton(3) with an aspect ratio R_m/r_p of 6, plasma temperature of 20 keV, and ratio of plasma radius to wall radius y of 0.8, we deduce from equations (6), (7) and (8) that the average magnetic field required to contain the plasma is

$$B = 0.177\ qP_w^{\frac{3}{8}}P_t^{-\frac{1}{8}} \qquad (9)$$

and thus there is a further correlation, similar to Figure 2, relating the magnetic field and wall loading of the reactor. This is shown in Figure 4

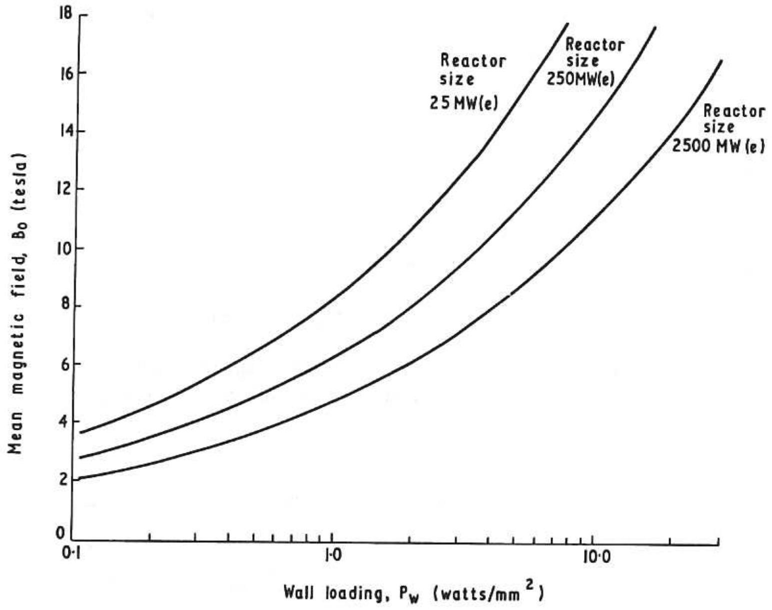


Fig. 4 Average magnetic field required in Tokamak reactors for plasma equilibrium

for three reactors with different levels of electrical power output assuming a thermal conversion efficiency of 43%.

6. POSSIBLE OPERATING REGIMES FOR REACTORS

The limitations deduced in the previous sections may now be compared in order to establish the possibility of using liquid lithium as a reactor coolant. Unfortunately an adjustment must be made since the magnetic field deduced from plasma physics calculations is an average value whereas the stress limitation is most severe at the point in the toroidal system where the local field is highest. This correction factor, relating the maximum field in the reactor blanket to the average field in the plasma, has been computed and is shown in Figure 5. There should also be a corresponding but smaller correction factor for the wall loading, but this will depend on the plasma density and temperature distribution which are unknown and is therefore omitted.

Using the appropriate correction, the two criteria have been plotted in Figures 6 and 7 for both a 2500 MW(e) power reactor and a 125 MW(e) prototype, the magnetic field being expressed in terms of the maximum magnetic field in the system.

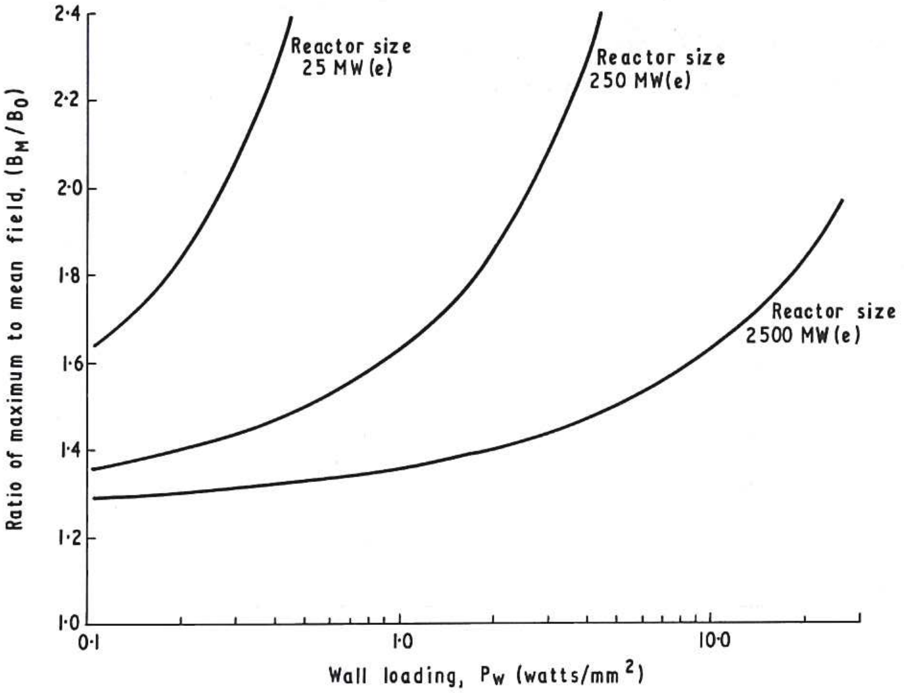


Fig. 5 Ratio of maximum to mean magnetic field in a Tokamak reactor as a function of the wall loading

In the case of the power reactor, Figure 6 shows that the optimum magnetic field is about 10 tesla (corresponding to an average axial magnetic field of 7 tesla), and that the wall loading is then 2.9 W/mm^2. This wall loading is much less than the 13 W/mm^2, envisaged by Carruthers, Davenport and Mitchell(4) in their outline reactor design. It is also lower than the 3.5 W/mm^2 proposed by Lubell et al(5), although if their reduced safety factor ($q = 1.4$) had been used in equation (9) their maximum magnetic field and wall loading would just be acceptable to these criteria. Thus the use of liquid lithium forces the acceptance of a system which is physically larger than generally appears desirable from other considerations. The overall power density would be less than 250 kW/m^3, averaged over the volume of the containment vessel, nuclear blanket and magnet winding, and the economic disadvantage of this rather low figure could be serious. On the other hand the low wall loading would result in a low neutron flux so that the total neutron dose received by the first wall, even after 20 years life, would not be much more than the dose received by the cladding of a fast reactor fuel element, so that it might not be unrealistic to conceive of a blanket structure that would not need replacing during the life of the reactor. On balance however, although it is not possible to rule out the use of liquid lithium as a coolant in a power reactor, it does appear that the limitation which it imposes on the wall loading would make the reactor unnecessarily large and expensive.

For a low power prototype reactor the situation is different. As a result of the plasma physics limitations which lead to equation (9) the wall loading in a reactor with a small power output is necessarily low.

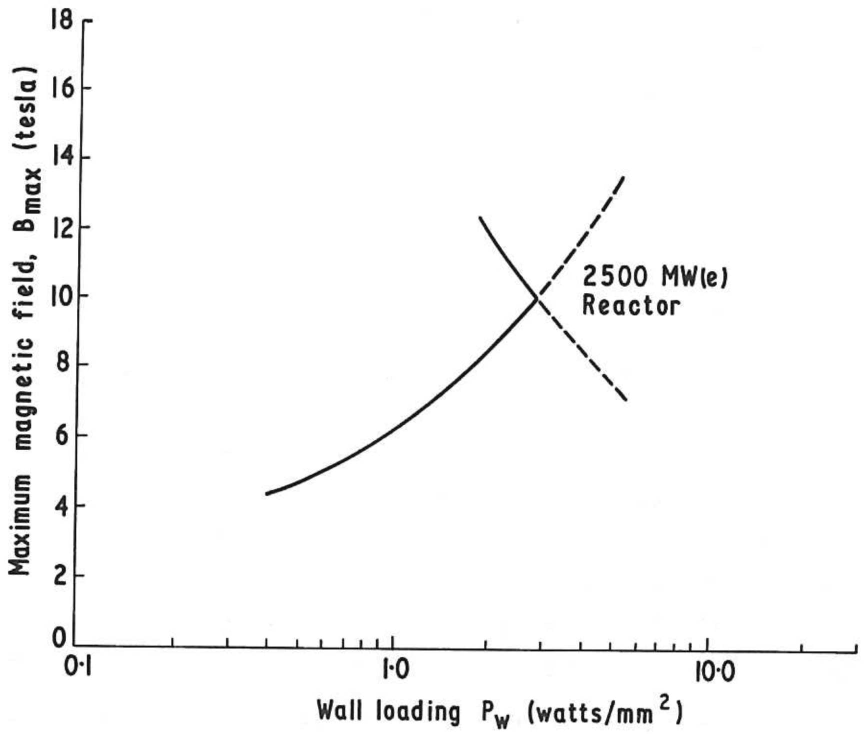


Fig. 6 Combined limitations imposed on the wall loading and maximum magnetic field in a 2500 MW(e) commercial reactor

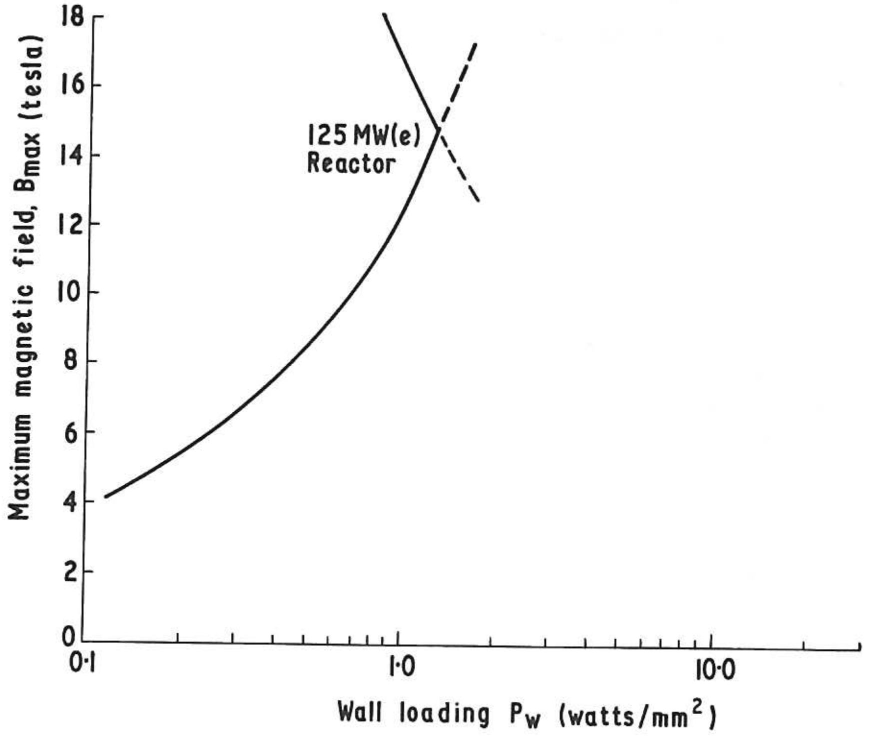


Fig. 7 Combined limitations imposed on the wall loading and maximum magnetic field in a 125 MW(e) prototype reactor

Furthermore the economic argument for a high power density is not relevant. The optimum magnetic field given by Figure 7 is 15 tesla (corresponding to an average axial magnetic field of 7.5 tesla) giving a wall loading of 1.3 W/mm^2. Since it is unlikely that a peak magnetic field much in excess of 15 tesla is practically possible, it appears that liquid lithium cooling is feasible for a prototype reactor.

7. CONCLUSIONS

Whilst it has been possible to draw some general conclusions from this consideration of the pressure required to pump liquid through a magnetic field, it will be appreciated that they may be subject to modification in the light of further detailed study. On one hand as our understanding of plasma physics develops the criterion for plasma equilibrium used in equation (8) or the value of the safety factor used in equation (9) may change. On the other hand, as more materials data becomes available it may be necessary to modify the stress levels used in equation (4), and the development of new materials could radically change the situation. Finally, the criterion is based on pressure calculations which assume fully developed laminar flow of the liquid lithium, whereas in a detailed design there are bound to be bends and field gradients which will affect the total pressure.

Nevertheless, the trends are clear and it seems reasonable to draw general conclusions from this study. Liquid lithium cooling of a low power prototype toroidal reactor is probably feasible, but in a commercial power reactor the limitation on the overall power density is such as to make lithium cooling economically unattractive. The reason for this is not the pumping power required, which can be made acceptably low, but the stress in the cooling ducts.

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