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Report

WALL LOADING LIMITATIONS IN A HELIUM COOLED FUSION REACTOR BLANKET

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ABSTRACT

The maximum wall loading of the simple direct lithium cooled fusion reactor blanket is $\approx 4\ MW/m^2$. It is determined by the limits on working stress in the structure arising from the pressure required to circulate the liquid lithium in the confining magnetic field. One possible alternative is helium gas cooling and this report describes a conceptual blanket design, analysing the system for maximum wall loading. The system performance is compared with the direct lithium cooled concept and the results and advantages of the helium cooled blanket are discussed.

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CONTENTS

INTRODUCTION

1. There is general agreement that the first generation of fusion reactors will be based on the deuterium-tritium fuel cycle. In addition to confinement of the reacting plasma, two other essential features of this type of reactor will be first, the means to produce tritium at a rate at least equal to that at which it is consumed in the reactor and second, the ability to recover the energy of 14 MeV neutrons in some thermodynamically useful form. Both of these requirements can be met by surrounding the plasma by a nuclear blanket containing lithium. Tritium is produced by neutron capture in both ^6Li and ^7Li and the low atomic weight of lithium makes it an ideal neutron moderator. As a result of these two mechanisms about 83% of the total energy of the reactor output appears as heat in the lithium and blanket structure, and it is essential to design the blanket for efficient removal and utilisation of this energy.

2. As liquid lithium is an excellent heat transfer fluid, an obvious solution is to circulate the lithium metal through the blanket and external heat exchangers. However, neglecting the possibility of inertial confinement, magneto-hydrodynamic losses in magnetic confinement systems limit the maximum wall loading to about 3-5 MW/m^2.[1] The successful application of helium heat transfer in fission reactors has led to a number of proposals for helium cooled lithium blankets.[2,3] Helium cooling avoids M.H.D. effects in the blanket and reduces corrosion problems in the external heat exchangers. However, in order to achieve sufficient mass flow for the desired temperature rise through the blanket circuit, both pumping power and gas pressure will be high. Both these parameters are restricted - pumping power by economics and the gas pressure by tritium breeding requirements which limit the amount of cooling tube material in the blanket.

3. In this report, relationships are derived between the principal parameters of a helium cooled blanket. Further by reference to an outline design, the limitations imposed on the choice of values for these parameters are established, and the potential of helium cooling in fusion reactor design discussed.

THE FUSION REACTOR MODEL

4. The fusion reactor model used for this study is described in reference 4. Briefly, it is a steady state Tokamak with a large toroidal magnetic field. It is assumed that diffusion driven currents in the plasma will provide the rotational transform for plasma confinement. For a reactor output of 2500 MW(e) the plasma major and minor diameters would be about 20 m and 3 m - the actual dimensions depending (inter alia) upon the rated wall loading capability of the blanket design incorporated in the reactor. The toroidal confining magnetic field is provided

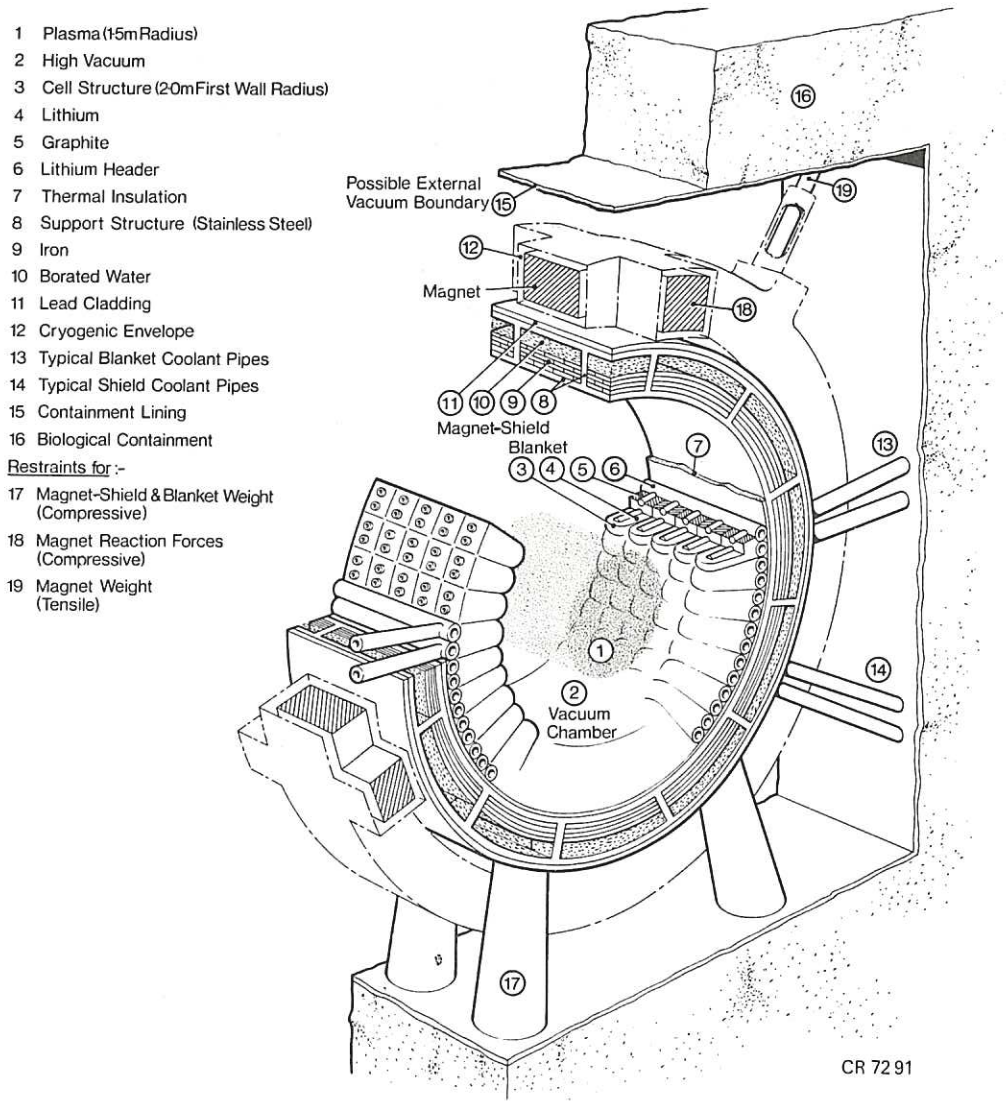

Fig 1 Fusion reactor blanket and magnet - general arrangement.

by 32 superconducting magnets of $\approx$ 8 m internal diameter and of $\approx$ 1 m^2 cross section. Figure 1 indicates conceptually one of the possible 32 identical segments of the toroidal assembly. At the centre is the plasma column surrounded by the cellular blanket, itself thermally insulated from but supported by a load carrying structure which also forms the magnet shield. Between the cells and the support structure there would be manifolds for circulating the coolant and the lithium (for tritium recovery) the manifolds being connected to penetrations through the shield. Finally, surrounding the magnet shield but in this case structurally separated from it, is a cryostat containing the superconducting magnet coil to provide the toroidal magnetic field.

DESCRIPTION OF THE HELIUM COOLED CELL

5. In the direct lithium cooled fusion reactor blanket significant pressure drop arises wherever the coolant flows perpendicular to the magnetic field within the whole volume of the superconducting winding. However, in the indirect helium cooled blanket, most of the pressure drop occurs in the pipes or channels immersed in the lithium of the blanket cells. Also, efficient heat transport from the cell requires high gas pressure, which affects the cooling tube design. Thus, the analysis of the helium cooled fusion reactor is concerned primarily with the conditions in the cell, and the conceptual design of the cell is therefore an important part of the study. It is shown in figure 2.

6. The cells containing the lithium are of rectangular or hexagonal cross section and tapered so that they are close-nested round the plasma and will thus minimise the loss of neutron flux to the magnet shield. They are typically about 0.3 m across by 0.8-1.0 m long to give the blanket thickness determined by tritium breeding calculations. The front ¾ of the cell contains the lithium and cooling pipes and the rear section is the graphite neutron reflector through which pipes carrying the helium pass to external manifolds between the cell base and the magnet shield. Also, small diameter pipes would be arranged as shown for circulation of the lithium.

7. The details of the helium circuit are as follows -

(1) All the cold helium is carried in a 3-5 cm bore pipe to the front of the cell, where the heat input per cm^3 of lithium is highest. The pipe would be kinked to reduce the direct 14 MeV neutron shine through the cell assembly itself.

(2) At the 'front' of the cell the helium divides into a number of cooling tubes of two different types - those cooling the bulk lithium and those cooling the cell wall and the adjacent lithium.

(3) Within practical limits each tube is designed to absorb the same total quantity of heat at the same gas flow, and therefore the gases leaving each tube will be at the same temperature.

(4) Each 'bulk-lithium' cooling tube follows a helical path from front to rear of the cell - with the helix pitch increasing towards the rear in the manner suggested by Forster[5] to maintain constant heat input and materials utilisation per unit length of tube.

(5) Each wall cooling tube follows a scroll pattern across the front and then zig-zags down one side of the cell - tube spacing being varied according to the heat input in a similar way to the helical tubes cooling the bulk lithium.

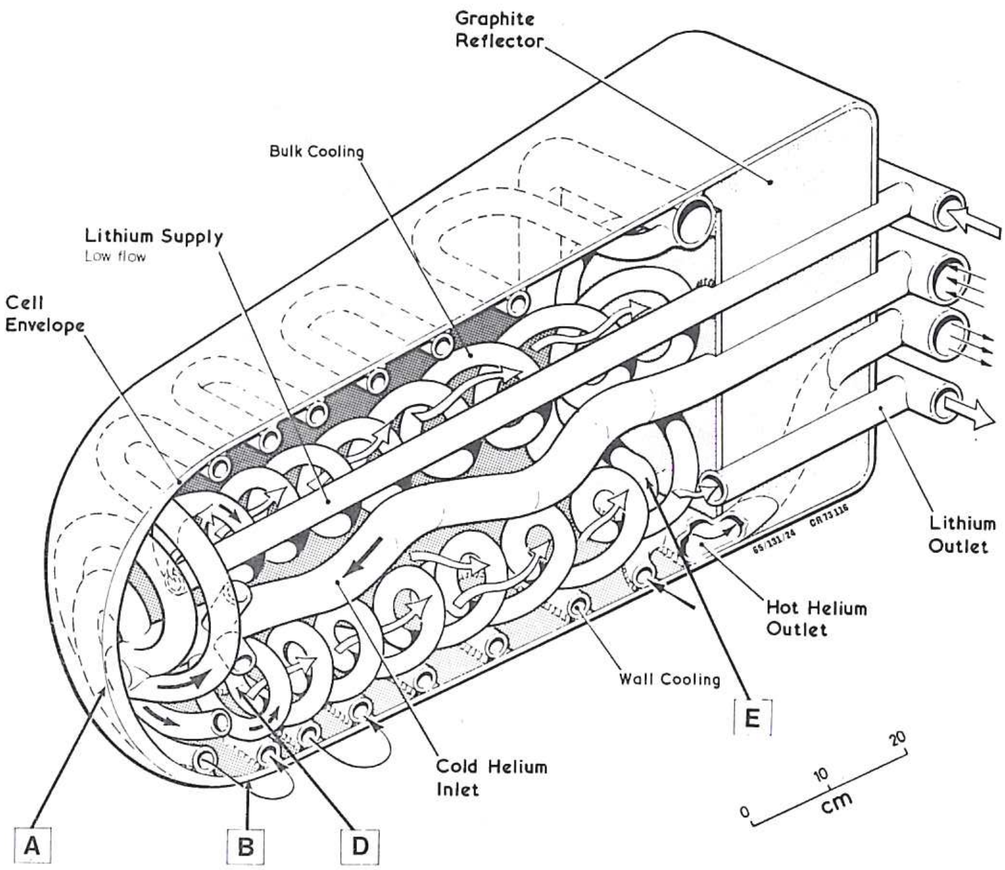

Fig 2 Conceptual design of helium cooled cell for fusion reactor blanket.

8. Figure 3 shows a cross section giving a possible configuration of tubes for a square or rectangular cell: in the latter case the bulk tubes would be in "elliptical" rather than circular coils. In a developed design, the radius of the bulk lithium cooling coil would be chosen to limit the peak temperature rises at points C and C[1] in figure 3.

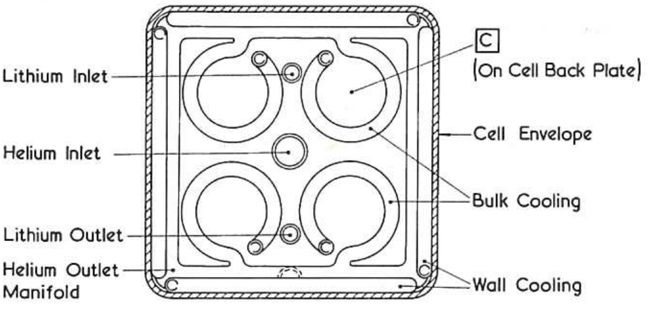

Fig 3 Cross section of helium cooled blanket cell.

TEMPERATURE DIFFERENCE BETWEEN HELIUM AND TUBE WALL

9. Appendix I gives the analysis of heat transfer in a tube cooled by helium with constant heat flux per unit area, and shows that the film temperature drop between the gas and the tube wall is given by

$$\Delta\theta = \frac{4R^2}{C_p{}^3\ M}\left(\frac{\bar{T}}{\Delta T}\right)^2\left(\frac{\alpha}{h}\right)^2 \frac{L^2\ P_w{}^2}{Kf^2} \qquad \ldots\ldots (1)$$

where the parameters are defined in the list of symbols given at the end of this report.

10. Examining the terms of equation 1 shows that

(1) The first term is effectively constant. M is given by (Prandtl number)$^{-0.6}$ and for practical purposes (ie within 1%) is constant for pressures and temperatures between 300-1500°C. R and Cp are constant[6].

(2) The mean temperature, $\bar{T}$, and temperature rise, ΔT, of the helium will be selected according to the maximum temperature allowed in the blanket structure material. ΔT is also chosen with reference to the thermodynamic conditions of the heat engine cycle coupled to the reactor. In gas cooled reactors, $\bar{T}/\Delta T$ varies between 1.5 - 2.5, the higher value being for low thermal efficiency steam cycles eg Magnox reactors. For modern stations with top steam temperature ≈ 540°C and thermal efficiency ≈ 0.43, the gas temperature ratio $\bar{T}/\Delta T = 750/350 = 2.1$.

(3) α, the ratio of the mean volumetric heating rate to the wall loading is determined by the nuclear properties of the blanket materials. Using data from Blow[7] α = 1.35. Arbitrarily but for ease of manufacture and practicability generally, the cell side wall is assumed to be 1 mm thick, resulting in a bulk structure fraction of 0.02(1). For a cell length of 0.75 m, including void allowance and reflector, Blow has calculated a tritium breeding ratio of 1.2 for a bulk structure fraction of 0.06. It is assumed therefore that $\eta = 0.04$.

(4) K is the pumping power necessary to circulate the helium through the cooling tubes, expressed as a fraction of the thermal output of the reactor. In gas cooled fission reactors $0.015 < K_{(total)} < 0.025$ and in this study, $K_{(total)}$ is assumed to be 0.02, of which 0.012 (= K) is allowed for the cooling tubes themselves and the remainder covers pressure losses in the external circuit and the helium/steam heat exchanger. Further development of the concept might indicate an overall system optimum with K = 0.02, which would allow an increase in wall loading or a small reduction of tube stress - all other parameters being constant.

11. Substituting these values in equation 1 gives:-

$$\Delta\theta = 41.71\ \frac{L^2}{f^2}\ P_w{}^2 \qquad \ldots\ldots (2)$$

In Appendix II, the design of the cooling tube coil is outlined showing that the length of a single cooling tube will be about 5 m. Equation 2 has been evaluated for L = 5m and for f = 25, 35 and 50 MN m^{-2} and the results are shown in Figure 4. Also included are the curves for L = 4.5 and 5.5 m. From figure 4, it is a straightforward matter to select limiting values for Δθ for chosen wall loadings, P_w.

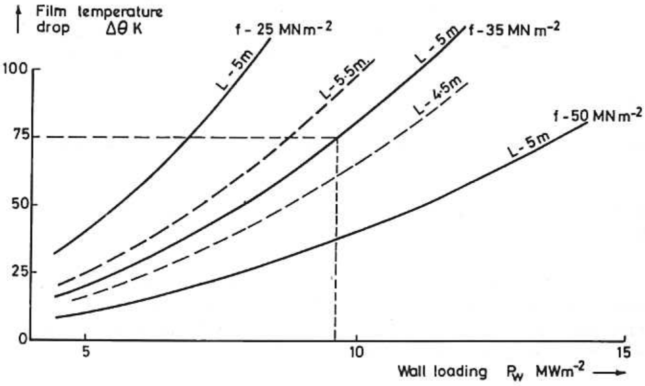

Fig 4 Gas side film temperature drop against wall loading in a helium cooled cell for various values of structure stress and cooling tube lengths.

12. This analysis is independent of tube diameter and gas pressure and for example does not determine the helium void fraction. Appendix III shows how the pressure is determined and can be modified by control of tube roughness. With a cell diameter and length of 0.3 m and 0.6 m respectively and 8 smooth tubes, D ≈ 8.3 mm and p = 137 bar, which may be unsuitable for the external circuit. With $\psi/\psi_o = 1.5$, p can be reduced to 60 bar, D = 1.25 cm and the helium void fraction is 0.12 which is not excessive. Alternatively, from Eqn III.4, D is inversely dependent on $(m)^{0.25}$ and m is proportional to the heat load per cooling tube. For fixed P_w, this is proportional to D_c/n where D_c is the cell diameter. By reducing D_c/n, ie the heat flux per tube, it is possible to increase D and reduce p. However, this solution may require too many cooling tubes and certainly increases the complexity of manufacture. It seems that $D_c/n \approx 0.0375$ is a reasonable practical compromise.

STRUCTURE AND LITHIUM TEMPERATURES

13. Heating rates in the structure and lithium of a direct lithium cooled cylindrical fusion reactor blanket have been calculated by Blow[7] for a wall loading of 9.7 MW/m^2 - see Figure 5. This data is adequate for the present study providing that when necessary the blanket thickness is adjusted for the tube void fraction, the bulk structure fraction of 6% is retained, and it is corrected pro rata for wall loading. Using this data, the structure and lithium temperatures have been calculated for a number of locations in the cell (see fig 2 & 3). The calculations have been worked as follows:-

(1) The gas temperatures are based on a linear temperature rise in the cooling coils.

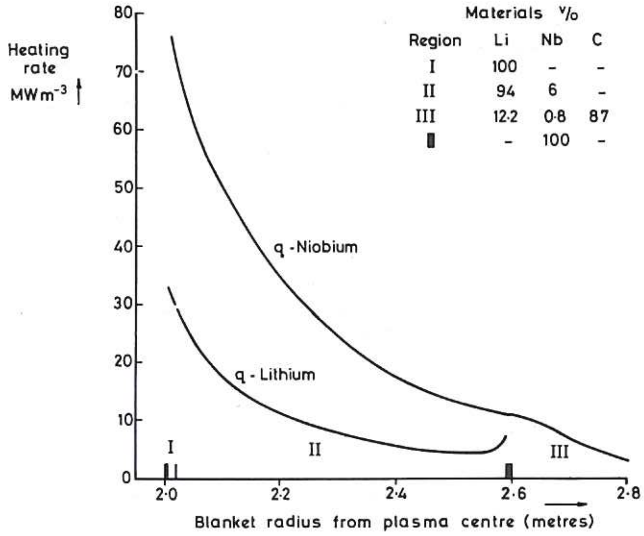

Fig 5 Comparison of heating in the niobium structure and lithium of a fusion reactor blanket.

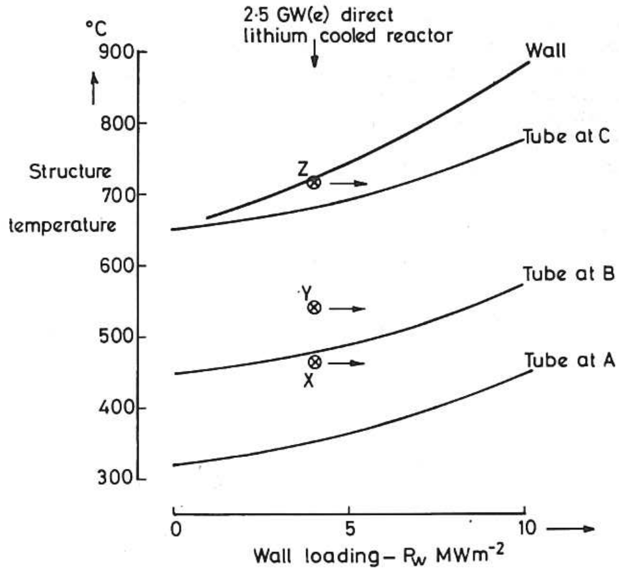

Fig 6 Curves of structure temperatures against wall loading for a helium cooled blanket cell and comparison with temperatures in a 2.5 GW(e) direct lithium cooled reactor structure.

(2) Film temperature drop assumes f = 35 MN/m^2 and L = 5m - see figure 4.

(3) The temperature rises for volumetric and surface heating have been calculated assuming constant thermal conductivity in the niobium. The resulting error is < 5^{o}C and is neglected.

(4) For Point A, the surface temperature rise assumes a radiation flux of 0.05 P_w to allow for possible control of radiation loss by high mass doping of the plasma. For point B, which is shielded by the hemispherical cell nose and by the adjacent cell, the radiation flux is assumed to be only 0.01 P_w.

(5) For calculation of structure temperatures between two cooling coils eg point C, thermal shunting due to the lithium is neglected. The temperature rise is proportional to $q/_k$. Figure 5 shows that $q_{Nb} > 3/2 q_{Li}$ and $k_{Nb} \approx 5/4\ k_{Li}$ so that at all points this will give pessimistic results, ie higher temperatures of the structure.

(6) The temperature of the pressurised cooling tube is the sum of the gas temperature, film temperature rise and tube wall rise at the specific location. As the heat flux per unit area in the tube is assumed constant these rises are constant along the tube length.

(7) The cell body and lithium maximum temperatures include in addition the volumetric and radiation heating between the cooling tube and the test location - ie for point A - the outer surface of the front of the cell nearest the plasma - and for point E - midway between the adjacent cooling tubes.

14. The results are summarised in Table 1 and figure 6. Table 1 shows the results for all locations and components of the total temperature for a wall loading of 7.5 MW/m^2. Figure 6 shows the variation of the more important temperatures with wall loading for a constant tube stress, f = 35 MN/m^2. The temperatures given are the maxima for the material at the given location - eg the tube temperature is that of the outer tube surface. Tube

Table 1

Structure and Lithium Temperatures in Helium Cooled Cell

Wall Loading	Location	Gas Temperature ^{o}C	Temperature Differentials ^{o}C				Maximum Temperatures		
			Primary (1)	Structure		Lithium	Structure		Lithium
				Volumetric Heating	Radiation Heating	Transfer and Volumetric Heating	Tube	Cell wall	
7.5 MW/m^2	A	320	Film Δθ	44 (3)	56 (4)	-	399	499	-
	B	445	46	30 (5)	10 (6)	-	524	564	-
			plus tube wall						
	C	650	33 (2)	77 (7)	-	-	729	806	-
	D	370	-	-	-	205	449	-	654
	E	650	Total 79^{o}C	-	-	62	729	-	791

Notes

(1) Common to all locations.

(2) For 1.25 cm dia, 0.2 cm wall tubes.

(3) Midway between tubes and for 7 mm wall.

(4) Bremsstrahlung 0.05 Pw.

(5) Midway between tubes and for 5 mm wall.

(6) Bremsstrahlung 0.01 P_w.

(7) Neglects conduction in bulk lithium.

(8) All calculations assume physical properties of niobium, f = 35 MN m^{-2}, and η = 0.06.

temperatures as well as can wall temperatures have been included because the former are the most highly stressed parts of the structure. No special optimisation has been carried out eg to define tube wall thickness or diameter owing to the lack of relevant irradiated materials data.

DISCUSSION

15. Equation 1 can be rewritten as follows:-

$$P_W = \left(\frac{C_p^{3/2}\, M}{2 \qquad R}\right) x \left(\frac{\Delta T \quad \sqrt{K}}{T \quad \alpha \quad L}\right) x\ (\sqrt{\Delta\theta}\ \eta\ f)$$

The first term in brackets is constant. In deriving the data for figure 4, best estimated values were selected for the parameters in the second brackets. If all reasonable variations of these parameters were in the same direction, the total change in P_W could approach a factor 2 up or down. However, this is an unlikely condition and the probable accuracy of the second term is $\pm$ 20%. Possible errors in the other parameters are not so easily assessed.

16. Considering the tube structure fraction η - at constant P_W/η - increase of η by 50% to 0.06 - η_{total} = 0.08 - will mean reduction of the tritium breeding from 1.2 to $\approx$ 1.1 - perhaps too much in a 0.8 metre thick blanket.

The breeding could be restored with a thicker 1.0 metre blanket, but at increased cost of blanket and magnet. Reducing η to 0.02 will not give a commensurate economic advantage because 0.02 structure fraction is required for the cell wall. (See para 10(3). It would seem that the possible range for η is between say 0.03 - 0.06, and this can only be determined after more detailed design studies.

17. The most important single parameter to quantify accurately is the permissible working stress f - for it depends on the material of the cooling tubes and is also a function of both the remaining parameters. It depends on the material temperature and therefore on $\Delta\theta$ and on the integrated neutron dose and therefore on P_W. A body of knowledge is being amassed on materials performance under irradiation [(8)] but it is correctly concerned with current problems eg stainless steels in fast breeder reactors. The work reported includes application of data and theories of irradiation damage to improving fast reactor core designs. Some work was also reported on the refractory metals Mo + V, but is in an early stage. There are good prospects therefore for much improved understanding of materials properties in a nuclear environment.

18. Actually, it is not clear what should be the stress limiting factor in the design of a cellular blanket as outlined here. Obviously the design should be optimised to the maximum economic use of material - eg as indicated by the total irradiation per kilogramme of structure. This compares with fission reactor fuel design to maximum irradiation per kg of fuel. It would seem that creep and/or swelling will be the likely limitation though since the structure contains only fluids, internal deformation can be accommodated. External swelling or deformation so that adjacent cells touch seems the probable limitation because under the clean high temperature conditions the cells would weld together where they touch. This would be probably undesirable eg leading to shrinkage stresses on shutdowns. The stress chosen for the calculations - 35 MN/m^2 - is low but this must be accepted owing to the uncertainties of the design and data.

19. In the study of direct lithium cooling (1), it was shown that at a wall loading of $\approx$ 4 MW/m^2 and materials stress of 40 MN/m^2 - structure temperatures would be between 460 - 720°C. The points on figure 6 marked X, Y and Z are respectively the cell front, front side wall and rear structure temperatures of the lithium cooled cell. These locations are directly comparable to the tube temperatures of the helium cooled cell at points A, B and C. Comparing the point Z temperature with that for tubes at C, indicates that the helium cooled cell has a higher wall loading rating by over 50%. At this increased wall loading the front helium tube temperatures are still below the equivalent lithium cell temperatures. This is in part due to the lower cold coolant inlet temperature of 300°C as compared with 350°C for the lithium cooled cell. These lower front wall temperature coupled with the slightly lower stress of the helium cooled cell (35 MN/m^2) may be sufficient margin for increased radiation damage due to the higher wall loading indicated for helium cooling. For reference, it should be noted that the front wall neutron flux for 10 MW/m^2 wall loading 25 year life is $\approx 10^{24}$ total, and the rear wall flux is about $^1/_{10}$ of this.

20. Apart from its potentially higher wall loading as compared with the simple direct lithium cooled cell, helium cooling has some other features to compensate for the more complex construction to incorporate the heat transfer tubes and the $\approx$ 10% increase in cell length to accommodate the tube void fraction.

(1) The cell wall or outer containment of the lithium (or other blanket fluid) is not normally highly stressed. This reduces the possibility of leakage of lithium into the plasma volume.

(2) The principal stresses in the helium cooling tubes are the simple hoop stresses. At a wall thickness/diameter ratio of $\approx$ 5, a minor correction will be required and also thermal stresses must be taken into account. However, at the suggested wall loading these are about 10% of the simple hoop stress, which seems adequately low.

(3) In the event of a small pinhole defect in the helium pressurised tubing, helium will leak into the lithium where there is a possibility of detection of failure prior to any catastrophic rupture of the cell wall and contamination of the plasma itself. Detection might be by monitoring variations of the tritium/helium ratio in the lithium.

(4) The helium cooled cell will eliminate the secondary heat transfer circuit used in the lithium system to reduce primary circuit pressures. This will compensate in part for the complexity of the cells themselves.

(5) Since the functions of the tubes and the cell wall are different, there is a possibility of material specialisation. The cell body material might be chosen specially for its resistance to erosion by the plasma, whilst the cooling tubes would be protected. They alternatively would be more highly stressed and must be compatible with contaminants in the helium, eg oxygen. Unless coated or composite materials are used, both must be compatible with the lithium. If creep and swelling of the stressed tubes can occur without aggravating distortion of the relatively unstressed cell wall the cell to cell clearances can be minimised.

CONCLUSION

21. An outline design for helium (or other gas) cooling of a fusion reactor blanket has been described and analysed for performance. Conservative materials data has been used in an attempt to allow for the unknown effects of long time irradiation in

a fusion neutron flux. The helium cooled blanket has advantages over the direct lithium cooled system. It has a higher potential wall loading by 50% and a number of other advantages to compensate for the increased complexity of the cell. However, it must not be forgotten that the principal reason for adopting helium cooling is to overcome limitations of MHD losses in the direct lithium cooled system. Since it is not affected by magnetic fields, the principal advantage of helium cooling may well be that the design can be independent of the magnetic configuration required for plasma confinement.

NOTATION

TUBE PARAMETERS

L = length of tube (m)

D = diameter of tube (m)

t = wall thickness (m)

f = working stress of tube material (N/m^2)

n = number of cooling tubes per blanket cell

P_t = thermal power removed per tube (W)

k_w = thermal conductivity of tube material (= 65.0 W/mK @ 873K for niobium)

CELL PARAMETERS

V_c = volume of cell (m^3)

$\alpha = \dfrac{\text{mean value of volumetric rate of energy deposition in cell}}{\text{wall loading}}$ (m^{-1})

P_w = wall loading on cell (watts/m^2)

η = volume of structural material in cell tubes $\div V_c$

P_c = thermal power output of cell (W)

k_L = thermal conductivity of lithium (= 52.0 W/mK @ 873K)

GAS FLOW PARAMETERS

Q = volume flow (m^3/sec)

m = mass flow (kg/sec)

p = pressure (N/m^2)

Δp = pressure drop (N/m^2)

ρ = density (kg/m^3)

T = temperature (K)

ΔT = temperature rise of gas flowing through blanket tube (K)

R = gas constant (= 2080 joules/kg K for helium)

ψ = friction coefficient

C_p = specific heat (= 5195 joules/kg K for helium)

G = mass flow density (kg/m^2.s) ($= \rho V = \dfrac{4m}{\pi D^2}$)

μ = absolute viscosity of gas (= 3.78×10^{-5} kg/m s for helium @ 750K)

k_g = thermal conductivity of gas (= 0.298 W/mK for helium @ 750K)

HEAT TRANSFER

h = heat transfer coefficient (watts/m^2K)

W_s = heat flux on tube wall (watts/m^2)

K = tube pumping power fraction (= tube pumping power/total output)

$\Delta\theta$ = film temperature drop K

Re = Reynolds number = $\rho VD/\mu$

Pr = Prandtl number = $C_p\mu/k_g$

M = $(Pr)^{-0.6}$ = Constant in Reynolds analogy

q = heating rate watts/m^3

NOTE

A barred symbol, eg $\overline{T}$, indicates 'mean value'.

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APPENDIX I

HEAT TRANSFER AND PUMPING POWER

AI.1 Let us consider a blanket cell cooled by n helium cooling tubes each of the same length, L, and diameter, D. The frictional pressure drop in each tube is given by the expression

$$\Delta p = {}^1/_2 \; \bar{\rho} \; \bar{v}^2 \; \psi \; \frac{L}{D}$$

where $\bar{\rho}$ is the mean gas density.

We shall assume a constant heat flux of W_s on the tube wall. Therefore by the Reynolds analogy - (general case)

$$h = \left(\frac{W_s}{\Delta\theta}\right) = M \; \bar{\rho} \; V \; C_p \; \frac{\psi}{8}$$

where $M = Pr^{-0.6}$. M is often taken as unity, but for helium at $\bar{T} = 475^oC$, Pr = 0.66, and M = 1.28.

Taking a heat balance along the tube:

$$\frac{\pi D^2}{4} \bar{V} \; \bar{\rho} \; C_p \; \Delta T = W_s \; \pi \; D \; L$$

The pumping power fraction, $K = \dfrac{\Delta p \; Q}{Q \; \bar{\rho} \; C_p \; \Delta T}$

Eliminating ψ, V and Δp from these four equations

$$\Delta\theta = 16 \left(\frac{L}{D} \times \frac{W_s}{\bar{\rho}}\right)^2 \frac{1}{C_p^3 \; \Delta T^2 \; K \; M} \qquad \ldots\ldots (I.1)$$

AI.2 The heat flux, W_s, may be derived from the total heat deposited in the blanket cell divided by the total tube wall area, thus:

$$W_s = \frac{\alpha \; P_W \; V_c}{n \; L \; \pi \; D}$$

The gas pressure is related to the tube diameter, wall thickness and wall stress and to the density, temperature and gas constant.

Thus $$\bar{p} = \frac{2 \; f \; t}{D} = \bar{\rho} \; R \; \bar{T}$$

But $$t = \frac{\eta \; V_c}{n \; L \; \pi \; D}$$

Combining this second group of equations, eliminating V_c, t, and p,

$$\frac{W_s}{\bar{\rho} \; D} = \frac{\alpha \; P_W \; R \; \bar{T}}{2 \; f \; \eta} \qquad \ldots\ldots (I.2)$$

Substituting I.2 in I.1,

$$\Delta\theta = \frac{4R^2}{M \; C_p^3} \left(\frac{\bar{T}}{\Delta T}\right)^2 \left(\frac{\alpha}{\eta}\right)^2 \cdot \frac{L^2}{K \; f^2} \cdot P_W^2 \; , \qquad \ldots\ldots (I.3)$$

AI.3 Some justification is required for the use of the mean density in the first expression to derive the pressure drop in the tube - since, clearly, the gas density, ρ, is not constant along the tube. First we consider the variation of ρ with pressure in the system. Since the pumping power fraction K is to be kept low ($\approx$ 2% total) $\frac{\Delta p}{p}$ is itself small - ie $\leq$ 0.05. Therefore if the mean pressure $\bar{p}$ is used in calculations the error due to density variations will be small - of order 2 - 3%. Secondly the gas temperature rise is considerable - from T_1 = 573 to T_2 = 923 K in our example - and therefore the density of the gas must vary. Since $\rho = p/RT$ it is easily seen that at constant pressure the overall density variation is about 1.7 - 1.

AI.4 Now, substituting for ρ in the pressure drop equation

$$\frac{dp}{d\ell} = {}^1/_2 \left(\frac{4m}{\pi D^2}\right)^2 \frac{\psi}{D} \frac{RT}{p}$$

where m, the mass flow $= \frac{\pi}{4} D^2 \; \rho \; V$ which must, by continuity, be constant along a single tube. Clearly also with p approximately constant

$$\frac{dp}{d\ell} = k' \; T$$

$$= k' \left(T_1 + \ell \; \frac{dT}{d\ell}\right)$$

where ℓ is the distance along the tube of total length L at which pressure drop is required. However, since the system is designed so that the heat flux W_s is constant - then

$$\frac{dT}{d\ell} = \text{constant} = \frac{\Delta T}{L}$$

and $$\Delta p_{(L)} = k' \int_0^L \left(T_1 + \frac{\Delta T}{L} \cdot \ell\right) d\ell$$

$$= k' \left(T_1 \; L + \Delta T \; \frac{L}{2}\right)$$

$$= k' \; L \; \bar{T} = k' L \; p/_{R\rho}$$

Since the variation of p has been shown to be small - ρ given by the above, may be used in the pressure drop equation. In other words, the mean gas density $\bar{\rho}$ is defined as the density at the mean temperature.

APPENDIX II

LENGTH OF THE HELICAL COOLING COILS

AII.1 We consider a cylindrical element, diameter d_e, - comprising a single helium filled cooling coil, diameter d_c, supply pipes and the lithium and structure to be cooled by this element as shown in figure AII.1. It is one of a number of such coils incorporated into a blanket cell - or even of an infinite blanket system. The cooling coil comprises four principal sections; the straight input pipe (A,B), a 'pancake' coil incorporated in the front wall (B,C), the primary cooling coil (C,D) in a helix of smoothly varying helix angle (as suggested by Forster), and finally a second pancake (D,E) incorporated in the rear wall. The ratio of coil to element diameters d_c/d_e is chosen to minimise the variation in temperature differences between hot spots in the lithium and the tube wall. The supply

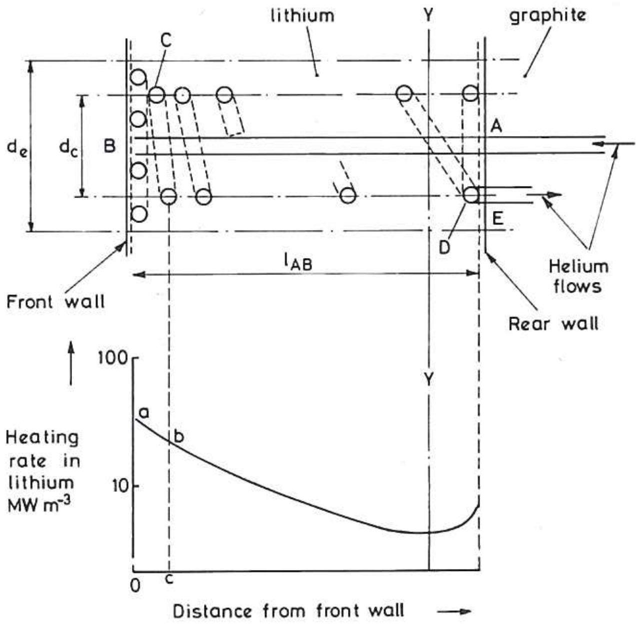

Fig AII.1 Simplified model of helium cooling coil in a fusion reactor blanket and comparison with heating rate in the lithium.

pipe (A,B) is made straight in order to minimise the absolute temperature of the first wall where the highest heating rate and irradiation damage occurs.

AII.2 The total length of the cooling tube within the primary blanket is given by

$$L = AB + BC + CD + DE$$

and where n(..) is the number of turns of tube in the section -

$$L = \ell_{AB} + \pi\ d_c\ (n_{BC} + n_{CD} + n_{DE})$$

With the exception of the straight supply pipe the other terms are all given by the ratio

$$\frac{\text{Heat flux into element concerned}}{\text{Heat flux removed per turn}} \text{ or } \frac{\phi(..)}{\phi_T}$$

Therefore

$$L = \ell_{AB} + \frac{\pi\ d_c}{\phi_T}\ (\phi_{AB} + \phi_{CD} + \phi_{DE})$$

With the exception of ℓ_{AB}, which is determined by the depth of blanket required for adequate tritium breeding - the heat flux terms can be expressed per unit area of the whole element and the only term over which the coolant system designer has any choice is the heat flux per turn, ϕ_T.

AII.3 However ϕ_T is itself constrained. It is a minimum when one single turn, close coiled absorbs the heat from the lithium at the front of the cell. Alternatively ϕ_T can be maximised if the coil is designed with the helix angle 90° in the plane YY, where the heat flux in the lithium is a minimum. It will be readily appreciated that this second case is probably not acceptable because of excessive hot spots occurring in the lithium at YY. Thus, the maximum number of turns in the coil for the minimum ϕ_T is given by

$$n_{CD} = \frac{\text{Total Integral under curve Fig AII(b)}}{\text{Integral area abcO}}$$

where Oc = 2d - twice the tube diameter.

Considering a blanket cell module of 0.03 m square, suitable values for d_c = 10 cm and tube diameter d = 1-1.5 cm. Using Blow's data (6) gives values as follows:

d (cm)	1	1.25	1.5
ϕ_T Watts/turn ..	91.2	90	88.8
n_{CD}	12.6	10	8.3

AII.4 Assuming the bremsstrahlung radiation power onto the first wall is between 5-10% of the total, n_{BC} = 2 turns will allow 1 turn for bremsstrahlung and one turn for the first wall material cooling. Similarly we estimate n_{DE} = 1 turn to allow both for the rear wall heating and the local increase in (n^6Li) reactions due to thermal neutrons from the graphite reflector. Thus, for an overall length of cell 0.75 metres

$$L = 0.75 + \pi.0.1\ (2 + 10 + 1)$$

$$= 4.85 \text{ metres (for d = 1.25 cm)}$$

Following the same principles, it can be shown that for d = 1.5 cm, the minimum value of L = 3.5 metres. A more detailed analysis would be necessary to determine $\Delta\theta$ in the lithium and establish a satisfactory design. However, it would seem that the more satisfactory design will be given using the longer tube, ie for L = 4.85 metres. For simplicity in the analysis in the main report we use L = 5 metres to include allowance for ducting in the graphite etc.

AII.5 The total number of cooling tubes required in a cell is given by the ratio of the frontal areas of the single tube element to the 'first wall' area of the whole cell. For the simple model discussed here, ie d_e = 12 cm and the cell 0.3 m square, the number of cooling tubes is 8, divided in suitable proportions between bulk lithium cooling tubes and wall tubes, which will cool both the wall and the adjacent lithium.

APPENDIX III

DERIVATION OF THE HELIUM COOLING TUBE DIAMETER

AIII.1 The expression for $\Delta\theta$ derived in Appendix I does not involve the tube diameter, D. However, a derivation of D consistent with Appendices I and II is required to determine the system working pressure, ie from the material stress and volume fraction.

AIII.2 The film temperature drop between the tube and the helium, and the total helium temperature rise respectively are given by

$$\Delta\theta = \frac{W_s}{h} \quad \text{and} \quad \Delta T = \frac{W_s\ L\ \pi D}{m\ C_p}$$

$$\text{Thus} \quad \frac{\Delta\theta}{\Delta T} = \frac{m\ C_p}{L\ \pi D\ h} \qquad \text{..... (III1)}$$

Substituting in equation (III1) for h from the Reynolds analogy

$$h = M\ \rho\ V\ C_p\ \frac{\psi}{8} \text{ and for } m = \rho\ V\ \frac{\pi D^2}{4}$$

$$\text{and re-arranging} \quad D = \frac{M\ L\ \psi}{2}\ \frac{\Delta\theta}{\Delta T} \qquad \text{..... (III2)}$$

For a smooth tube $\psi = 0.184\ (Re)^{-0.2}$

and Re $= \frac{GD}{\mu} = \frac{4m}{\pi D \mu}$

Substituting for ψ and rearranging

$$D = \left(\frac{0.092\ ML\ \Delta\theta}{\Delta T}\right)^{1.25}\left(\frac{\pi\mu}{4m}\right)^{0.25} \quad \text{..... (III3)}$$

Inserting values for the constants

$$D = 5.238 \times 10^{-3}\left(\frac{L\ \Delta\theta}{\Delta T}\right)^{1.25} m^{-0.25} \quad \text{..... (III4)}$$

AIII.3 It will be noted that μ at 750K has been used instead of the mean viscosity over the temperature range ΔT: the difference is < 0.5% which is satisfactory for this study. Over the whole temperature range between 750 < T < 1200K $(\mu_{\bar{T}})^{0.25}$ varies by less than 8% - and equation III4 may be used for scaling studies within this accuracy.

AIII.4 The value of D calculated from equation III4 is consistent with Appendix I. It is used to obtain the operating pressure of the helium from the equation -

$$p = \frac{2\ f\ \eta\ V_c}{n\ L\ \pi\ D^2} \quad \text{..... (III5)}$$

If the resulting value of p is considered too high for other system engineering requirements, it may be reduced by increasing D to D′ where D′ = βD. From equation III5, at constant mass flow, p = p/β^2. The increased diameter βD reduces the pumping power K but increases the film temperature drop, $\Delta\theta$ and the helium void fraction, since L is constant.

AIII.5 Hitherto, the tube bore has been assumed to be smooth and the friction factor, $\psi = 0.184\ Re^{0.2}$ eg in equation III4. If the tube bore is roughened or spiral wire turbulators are added, ψ may be increased to raise the gas side heat transfer coefficient, h, and reduce $\Delta\theta$ eg to the original value. Overall, this has to be at the expense of a small increase of pumping power K, over the original value at the higher system pressure because of non-linearity between h and ψ.

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