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Report

THE SHIELDING OF SUPERCONDUCTING MAGNETS IN A FUSION REACTOR

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by

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ABSTRACT

The effect of radiation damage on the current density which a superconducting composite can carry is discussed, considering damage in the superconductor itself and in the normal conductor used for stabilization and protection. The maximum fast neutron fluence which can be sustained for a 10% reduction in current density has been estimated to be $\sim 10^{18}$ n cm^{-2} for the superconductor and $\sim 10^{17}$ n cm^{-2} for the normal conductor. Using results from Monte Carlo computations of the neutron flux reduction per unit thickness of shield, the shield thickness required to meet the above criteria has been calculated as a function of reactor wall loading, and these results compared with those calculated on purely thermal criteria.

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1. INTRODUCTION

It is generally agreed that for economic reasons superconductors will be used in fusion reactor magnets. As a result, a 'shield' must be interposed between the primary neutron energy absorber or blanket and the magnet winding to provide sufficient overall neutron flux attenuation. Up to the present time, the nucleonic design criteria used has been the permissible heat load into the magnet refrigeration system. Owing to the low efficiency of refrigeration at 4 K, this limit is defined economically - e.g. by power and refrigerator costs.

There is however, another criterion for the shield design. The neutrons from a reacting hydrogen plasma will cause radiation damage in the materials of the magnet. This may be sufficient to reduce the useful working current density in either or both the superconductor or stabilising conductor. In the following study we compare the thermal load and the radiation damage effects and show their relative importance in defining design criteria for the magnet shield.

2. REACTOR DESIGN

A number of outline reactor designs have been published(1). A typical schematic outline is shown in Fig.1a. Many aspects of the design are largely independent of the type of containment but for simplicity we assume here a plasma of circular cross section which is either a cylinder or a torus, but in both cases confined by a simple solenoidal field. The radius of the first wall inside which the plasma is magnetically contained can be shown to be ~ 2 m(1). Outside the plasma there must be a primary neutron attenuator, typically lithium for a D-T reactor. Outside the breeding blanket there is the shield and the magnet.

Typical radial thicknesses of the components are shown in Fig.1b, which describes the blanket model used in the neutronics calculations. The plasma chamber is a double walled vessel each wall being 0.5 cm thick (regions 2 and 4) with a 3 cm coolant channel between them. The main tritium breeding region is 60 cm of lithium followed by a graphite reflector (30 cm thick) and a further coolant channel (6 cm thick). The shielding begins with region 8, the main purpose of which is to reduce the high energy neutron flux by inelastic scattering in iron. The borated water in region 9 then captures the low energy neutrons, and finally a 5 cm layer of lead shields the front of the magnet region from gamma radiation. The nuclides displayed in the magnet region 11 represent the various constituents of the magnet. For example, 50% by volume of iron represents the non-magnetic stainless steel structure which will be required to resist the large mechanical forces developed in the magnet system. The 35% by volume of copper represents the normal conductor, and the 15% of niobium the superconductor.

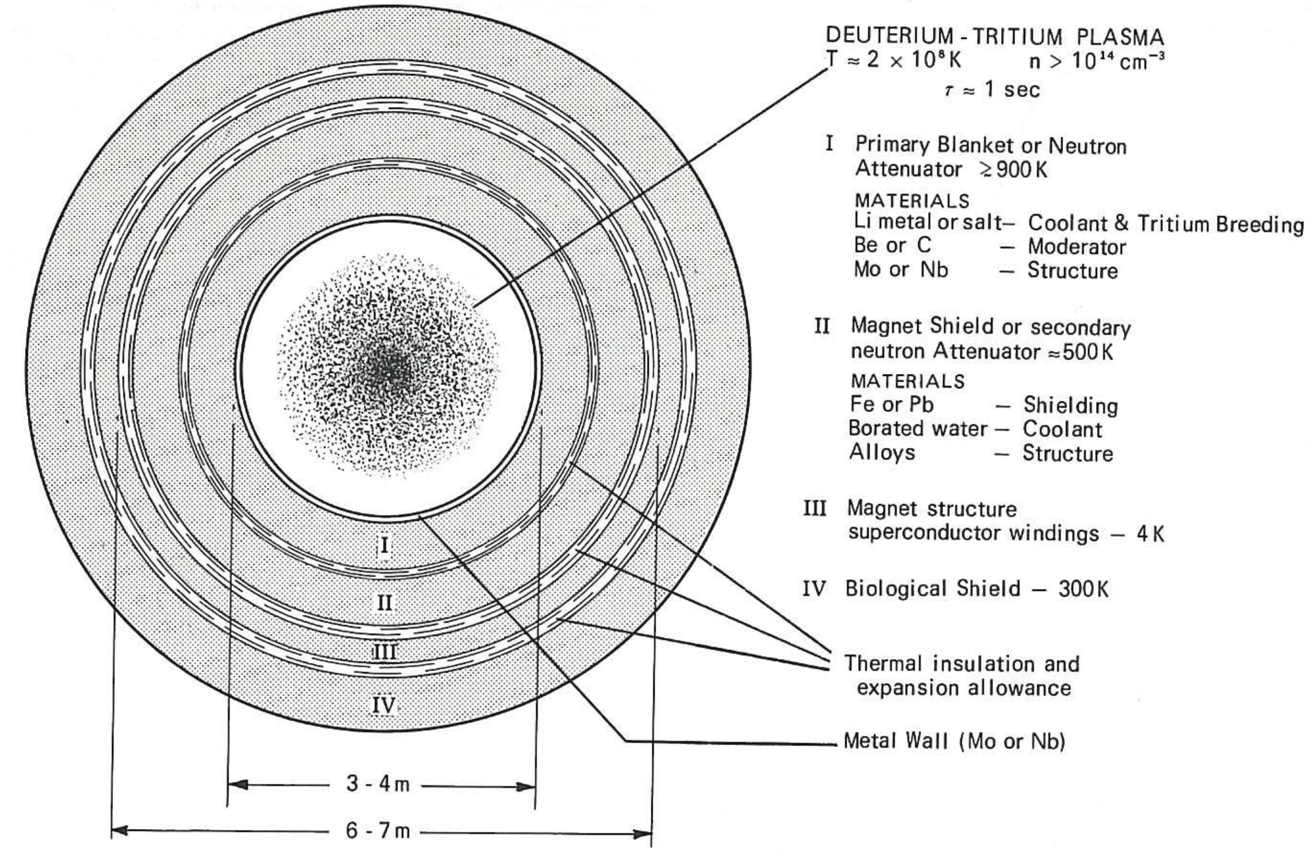

Fig.1a Fusion Reactor – Conceptual Cross Section – showing principle Blanket Regions (I, II), Coil (III) and Biological Shield (IV) surrounding the plasma. 'Service' penetrations to inner regions are not shown.

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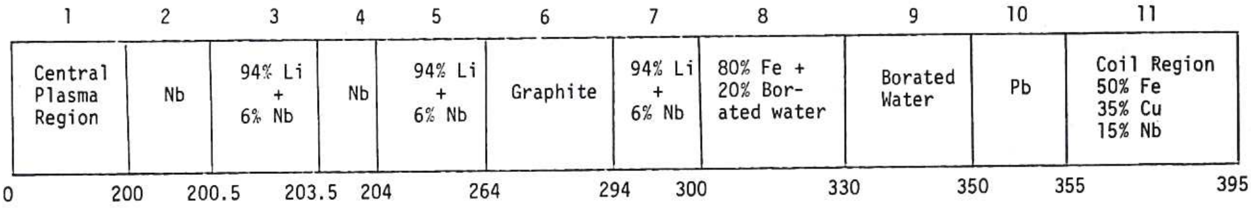

The figures underneath the sketch denote distances in cm from the centre of the cylindrical configuration.

Fig. 1b Blanket shielding model

The shielding system shown in Fig.1b has not been optimised, but the iron/borated water mix is more effective against heat loading than a lead/borated water mix of similar dimensions (Homeyer(2)).

3. ENERGY DEPOSITED IN THE SUPERCONDUCTING COILS

The neutron flux values in the various regions of the blanket and shield are shown in Fig.2. These flux values were calculated using a Monte Carlo code SPECIFIC(3), which incorporates a splitting facility to give a greater statistical accuracy in the outer region of high absorption. The flux values given in Fig.2 were normalised to a first wall loading of 10 MW m^{-2}, defined as the total power output of the reactor divided by the first wall area. Some 6.7 MW m^{-2} of this loading is due to the flux of 14.06 MeV neutrons.

It may be seen from Fig.2 that the neutron flux intensity falls by a value of 10^4 on going through about 60 cm of shielding material. Thus this particular shielding mix gives a decade reduction in flux intensity every 15 cm.

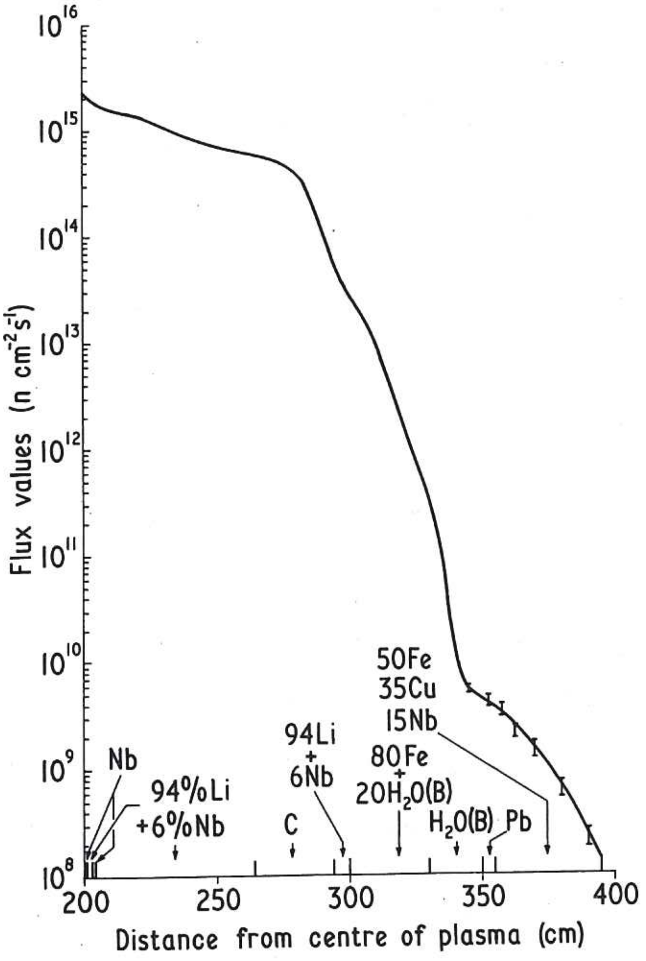

Fig. 2 Neutron flux in the blanket of a fusion reactor calculated using a Monte Carlo neutron code.

Homeyer(2) calculated that, for a model with similar dimensions to ours but with a lead/borated water shield, the heat deposited in the coil would be 2 x 10^{-5} of the heat recoverable from the blanket. For a 5000 MW(th) reactor the Homeyer shield model would thus allow 100 kW of heat to be deposted in the coil. The efficiency of the large liquid helium refrigerators required for the superconductors is expected to reach about 500 watts (electrical)/watt (refrigeration)(4). Allowing for approximately 50% efficiency in the generator station for conversion of thermal to electrical power then the fraction 2 x 10^{-5} of reactor thermal output in the magnet implies a 2% power loss from this cause.

For the Fig.1b model Steiner(5) has estimated that the heat load in the coil would be 6.6 x 10^{-6} of the wall loading, i.e. 33 kW for a 5000 MW(th) reactor. This would mean a power loss of only 0.7%.

Fraas(6) has made a preliminary attempt at system optimisation by using cryogenic data from a large space simulation chamber. The shield thickness was increased until the increase of shield material cost equalled the reduction in cost of the cryogenic system. The nuclear heat deposition rate in the coil was calculated to be 1.15 kW for a 5000 MW(th) system. It was estimated that this would require a lead/borated water thickness approaching 120 cm. This figure of 1 kW may be unduly pessimistic, however, and should be used with caution. The Fraas analysis does not appear to take into account the important contribution of increased superconductor costs, which constraint has led most other authors (e.g. Carruthers et al(1)) to keep the blanket and shield as thin as possible.

Finally we must consider the problem of temperature gradients in the cryogenic region. The heat loading estimated by Steiner corresponds to about 2 x 10^{-4} watts/cm^3 averaged over the coil volume. Assuming an average thermal conductivity in the coil to be 5 x 10^{-3} W cm^{-1} K^{-1} and the maximum temperature rise allowed in the Nb_3Sn to be 1 K, then the distance apart of the coolant channels will be 14 cm. This should not impose any practical difficulty.

Therefore using only thermal criteria and assuming that the maximum power allowed for refrigeration is 1% of total thermal output, a magnet shield thickness of about 55 cm is required.

4. RADIATION DAMAGE

A large superconducting magnet normally comprises four major constituents:

(a) The superconductor itself.
(b) A high conductivity normal conductor such as copper or aluminium for stabilization and protection of the superconductor.
(c) Insulation of the superconducting cable to prevent damage to the conductors due to induced emfs under fault conditions.
(d) Structural materials to contain the large forces produced by the magnet.

We will consider radiation damage in each of these components in turn, and will also consider the increase in resistivity caused by transmutation in ultra pure metals. Firstly however, we must consider the form of the neutron spectrum in the magnet region.

4.1 Neutron Energy Spectrum

Radiation damage can be produced by both fast and slow neutrons; in the first case by knock on lattice atoms and in the second case by recoil lattice atoms resulting from (n,γ) reactions. The relative effect of the two processes depends primarily on the (n,γ) cross section in a particular metal.

Measurements made by Schilling et al$^{(7)}$ of the damage produced by fast neutrons in metals at low temperature will be quoted later. An example of the spectrum used by them is shown in Fig.3 together with the spectrum computed by Monte Carlo techniques at the inside edge of the coil region 11 of Fig.1b. It may be seen from Fig.3 which shows the spectra in integral form, that the fusion reactor spectrum has a slightly greater proportion (55%) of neutrons above 0.1 MeV, than the experimental curve (52%). They both have the same proportion above 0.4 MeV (42%) and above 3.3 MeV (6%), with slight variations between these energies and above. The damage produced by a primary knock-on will increase with neutron energy. For 0.1 MeV neutrons in niobium the damage energy is estimated to be 1.6 keV, for 1 MeV neutrons it is estimated to be 9.7 keV, and for 10 MeV neutrons 49.7 keV$^{(8)}$. Noting these values, and taking into account the variations shown in Fig.3, it would appear that the damaging effect of the experimental fission and theoretical fusion spectra should be closely comparable.

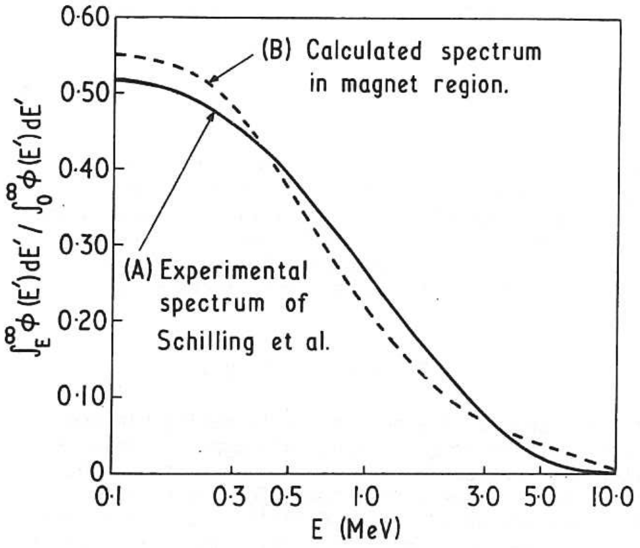

Fig.3 Comparison of the integral flux spectrum calculated for the magnet region of a fusion reactor with the spectrum used for experimental radiation damage measurements.

For both spectra somewhat less than half the neutron flux lies below 0.1 MeV in energy. Consider an (n,γ) reaction at thermal energy in niobium. A value for the recoil energy is deduced by balancing linear momenta of the emitted γ-ray and the recoiling nucleus. The value is calculated to be 0.03 keV, and the damage energy would be about 90% of this. Therefore the damage caused by neutrons below 0.1 MeV will be neglected as the energy transfer to lattice atoms is so small.

On the basis of this comparison we shall consider a fixed neutron dose derived from the experimental fast fission flux to be directly comparable with the same dose experienced in the magnet region of a fusion reactor, in terms of displacement damage effectiveness.

4.2 Damage in Superconductors

(a) Nb_3Sn

Cullen et al$^{(9)}$ have irradiated Nb_3Sn samples in a fast neutron flux at temperatures of 32 K. The principal effect observed was that the critical current J_c was increased, but the increase due to irradiation was smaller the higher the initial value of J_c. Increases in J_c could be obtained for doses up to ∿ 10^{18} n/cm² for samples of low initial J_c and for doses of up to 3 x 10^{17} n/cm² for high initial J_c. With higher neutron doses the value of J_c decreased in each case as shown in Table I. Similar results have been obtained by Betts$^{(10)}$.

In Cullen's experiments the value of the critical temperature was reduced slightly by neutron bombardment e.g. $\Delta T_c = 0.18$ K at 2.7×10^{18} n/cm². The highest field at which measurements were made was 60 kG so the value of the upper critical field H_{c2} was not measured in either the work by Cullen or Betts, and this is one uncertainty in the presently available information. Another uncertainty is that the irradiations were carried out at high temperature where some of the damage may anneal, whereas under operating conditions a magnet will be irradiated at about 4 K. However some irradiations have been carried out at 30 K by Coffey et al$^{(11)}$ using deuterons. Similar effects to the neutron irradiation were observed. For an initially low J_c sample, J_c

TABLE I

EFFECT OF NEUTRON BOMBARDMENT ON CURRENT DENSITY IN Nb_3Sn

Sample Composition (wt % Sn)	T_c midpoint (K)	ΔT_c (K)	(n/cm²) x 10^{-17}	JH (kG.A/cm²) x 10^{-2} H = 10 kG	JH kG.A/cm² x 10^{-6} H = 14 kG
29.5 ± 0.3	18.3	0.04	0	1.36	1.33
			3.4	5.30	6.46
			7.2	9.38	11.4
			10.5	13.0	16.8
			14.0	15.0	18.2
28 ± 0.1	16.1	0.80	0	4.0	4.48
			3.3	6.6	7.84
			6.9	8.0	9.66
			10.1	6.2	7.56
29.2 ± 0.1	16.9	0.80	0	11.5	13.3
			3.4	11.7	14.7
			7.2	0.89	1.3

increased and remained high after annealing at 300 K. It is thus probable that neutron irradiation at room temperature will give a reasonable indication of the effects of irradiation at low temperature. However further experimental work at low temperature is desirable.

(b) Superconducting Alloys NbTi, NbZr

No change in J_c was observed by Keller et al(12) after low temperature (30 K) irradiation of NbZr with 10^{17} deuterons/cm^2. The 'peak effect' i.e. an increase in J_c near the upper critical field H_{c2} was observed. Coffey et al(11) found a 20% decrease in J_c of cold worked NbZr and NbTi irradiated under the same conditions. The change in J_c as a result of bombardment was reduced by a factor of 4 by the annealing effect of warming the samples to room temperature.

Measurements of neutron damage of alloys have been made by Pollock et al(13). Nb-Ti-V alloys of various compositions were irradiated to a single dose of 3.7 x 10^{19} neutrons/cm^2 at 70 °C. This resulted in a large reduction in J_c, a reduction in T_c of up to 0.5 K and a reduction in H_{c2} of between 8 and 14%. In comparison measurements on Nb25Zr, after 10^{18} neutrons/cm^2, by McEvoy et al(14) indicated no change in J_c.

More recently Soell, Wipf and Vogl(15) have irradiated NbTi with doses up to 7.5 x 10^{18} n/cm^2 at 5.0 K. After a dose of 4.5 x 10^{18} n/cm^2 the reduction in critical current is 10-15%. After 7.5 x 10^{18} n/cm^2 the reduction is about a factor 2 at 30 kG. However this improved after annealing at successively higher temperatures until after 4 weeks annealing at 300 K the value of J_c was only 15-20% lower than the unirradiated value. Further measurements at higher fields are necessary to investigate whether there are any effects on the upper critical field and it would obviously be valuable to extend these measurements to other superconductors.

4.3 Radiation Damage in Normal Conductors

A normal metal is used as an integral part of superconducting composites for the purpose of stabilization and for protection of the coil should it go normal. For both purposes, though particularly for stabilization, low resistivity of the normal conductor is important. Resistivity is normally considered to be due to three components, the ideal lattice resistivity ρ_i, the residual imperfection resistivity ρ_o and the magneto resistance ρ_H. The residual imperfection can be increased by subjecting a speciment to strain. In a radiation environment the radiation induced resistance due to lattice damage ρ_R and the resistance due to impurities produced by transmutation ρ_T must also be considered. We will discuss them separately in relation to the non-radiation induced components, although in effect they are simply increasing ρ_o. Thus

$$\rho = \rho_o + \rho_i(T) + \rho_H + \rho_R + \rho_T \ .$$

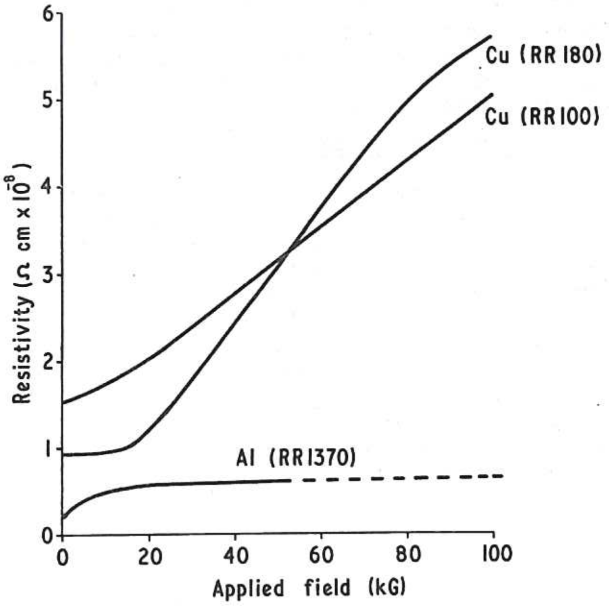

Fig. 4 Magneto resistance in Cu and Al for quoted resistance ratios (R.R.)

At 4.2 K the lattice resistance is negligible and the resistance in the absence of magnetic field is determined primarily by lattice imperfections and impurities. Magneto resistance for copper and aluminium are shown in Fig.4(16,17). In copper the effect increases roughly linearly with field whereas in aluminium it saturates at about 20 kG.

The increase in resistivity of metals due to radiation damage has been investigated in many metals and the results are similar for all types of radiation(18). Results for copper and aluminium irradiated by fast neutrons (0.1-10 MeV) have been obtained from the work of Schilling(19) and are shown in Fig.5. Similar results have been obtained by Blewitt(20). In both cases the resistivity increase ρ_R due to radiation damage increases linearly with dose initially and eventually saturates. The increase is independent of initial resistivity. The rate of increase

TABLE II

CONTRIBUTIONS TO RESISTIVITY OF COPPER AND ALUMINIUM AT 4 K IN A MAGNETIC FIELD OF 100 kG AFTER A NEUTRON DOSE OF 10^{17} n cm^{-2}

	COPPER	ALUMINIUM
Resitivity ρ at 300 K (Ω-cm)	1.73 x 10^{-6}	2.67 x 10^{-6}
Resistance Ratio	120	1370
ρ at 4.2K (Ω-cm)	1.44 x 10^{-8}	1.95 x 10^{-9}
ρ at 4.2K and 100 kG	4.7 x 10^{-8}	6 x 10^{-9}
$\Delta\rho$ for 10^{17} n/cm^2, (Ω-cm)	6.2 x 10^{-9}	2.1 x 10^{-8}
Total ρ,(Ω-cm)	5.3 x 10^{-8}	2.7 x 10^{-8}
Annealing temp	500 K	300 K

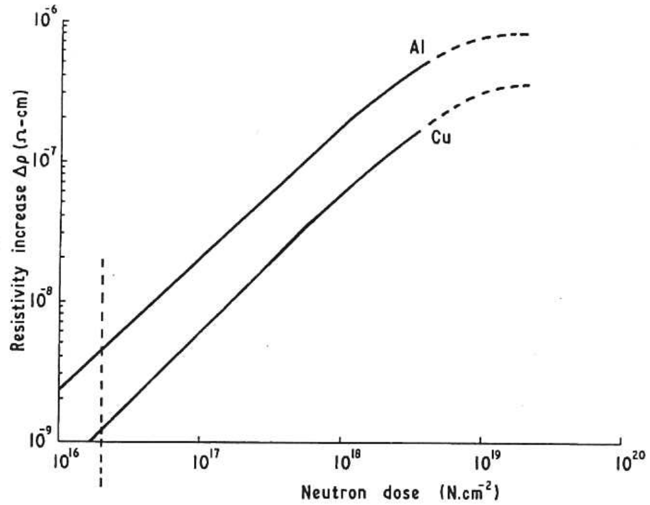

Fig. 5 Effect of fast neutron bombardment (>0.1 MeV) on resistivity of Cu and Al [19]).

of resistivity is higher for aluminium than copper by a factor of about 3.

All the contributions to resistivity are summarised in Table II for aluminium and copper assuming a coil operating at 100 kG with a dose of 10^{17} neutrons cm^{-2}. The resistivity of samples at 4.2 K in a 100 kG field is shown as a function of neutron dose in Fig.6. It is seen that aluminium has a lower resistivity than copper up to a dose of $\sim 3 \times 10^{17}$ n cm^{-2}.

The criterion for cryogenic stabilization of a composite superconductor is given by(21)

$$J < (Q_c K/\rho)^{2/3} I^{-1/3} \qquad (1)$$

where J is the current density in the composite conductor, ρ the resistivity, I the current, Q_c the maximum heat flux which can be transferred to helium and K a geometrical factor. The criterion for protection(21) is

$$J \leqslant \{f(\theta_m) V_m I/E\}^{\frac{1}{2}} \qquad (2)$$

where

$$f(\theta_m) = \int_{\theta}^{\theta_m} \{\frac{\gamma C}{\rho}\} d\theta ,$$

V_m is the maximum induced emf permitted, E is the stored energy, θ_m the maximum temperature reached, γ is the density and C is the specific heat of the normal metal. Considering equation (1), since Q_c and K are not expected to change significantly from copper to aluminium, aluminium stabilized conductors having a lower resitivity will have superior current density up to a dose of 3×10^{17} n/cm^2. At this dose the current density for a copper stabilized conductor will have been degraded by about 25%.

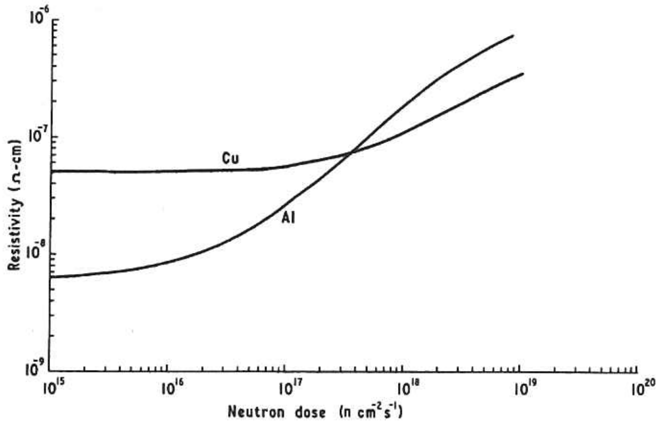

Fig. 6 Resistivity of Cu (RR130) and Al (RR1370) at 4.2K and 100kG as a function of fast neutron flux.

The criterion for protection is less easy to evaluate. A high heat capacity as well as low resistivity is required. Taking equation (2) for a given coil we see that the function $f(\theta)$ determines whether one material is better than another. Values of $f(\theta)$ for different resistivity materials have been calculated by Maddock and James(21), Fig.7. At a dose of 1×10^{17} n/cm^2 the equivalent resistance ratio of Cu and Al are 30 and 100 respectively. From Fig.7 we see that for an allowed temperature rise of 50 K, protection by copper and aluminium would be approximately equal. However for a temperature rise of 100 K the maximum current density for protection with Al would be about 75% that of copper. At a dose of 10^{18} n/cm^2 the resistivity rise in copper will decrease the current density to about half the initial value which would almost certainly be unacceptable on the grounds of the extra capital cost involved.

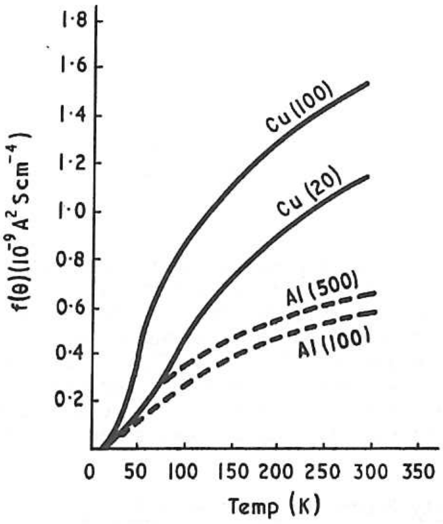

Fig. 7 Comparison of Cu and Al as materials for the protection of superconducting cables for quoted resistance ratios (from Maddock & James [21]).

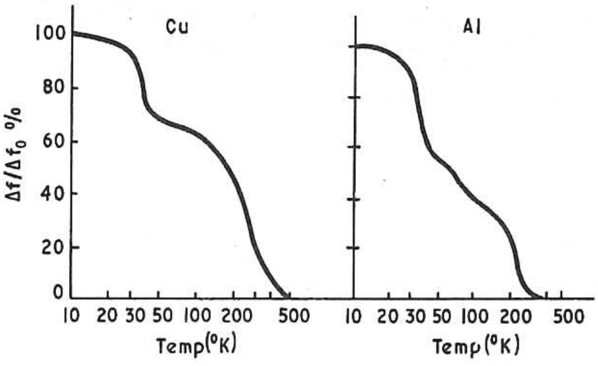

Fig. 8 Thermal annealing of Cu and Al after neutron irradiation

The radiation damage induced at low temperature can be annealed out leading to a reduction in resistivity. The maximum temperature to which the coil can be heated will be determined by the superconductor and by the insulation used. With present materials and techniques used for Nb_3Sn superconductors the maximum coil temperature is $\sim$ 300 K. Annealing curves for copper and aluminium are shown in Fig.8(22).

TABLE III

REACTIONS AND IMPURITY CONCENTRATION FOR COPPER AND ALUMINIUM IN THE MAGNET COIL (REGION 11 Fig.1b)

Number	Reaction	Impurity		Concentration in p.p.m. per year
1	$^{27}Al(n\gamma)^{28}Al$	2.3 m	^{28}Si	6.7×10^{-4}
2	$^{27}Al(n\alpha)^{24}Na$	15.4 hr	^{24}Mg	8.1×10^{-5}
3	$^{63}Cu(n,2n)^{62}Cu$	9.8 m	^{62}Ni	9.8×10^{-5}
4	$^{65}Cu(n,2n)^{64}Cu$	12.8 hr	^{64}Zn ^{64}Ni	
5.	$^{63}Cu(n\gamma)^{64}Cu$	12.8 hr	^{64}Zn ^{64}Ni	8.9×10^{-3}
6	$^{65}Cu(n\gamma)^{66}Cu$	5.1 m	^{66}Zn	
7	$^{63}Cu(np)^{63}Ni$	(92 y)	^{63}Ni	3.1×10^{-4}
8	$^{65}Cu(np)^{65}Ni$	2.6 hr	^{65}Cu	
9	$^{63}Cu(n\alpha)^{60}Co$	(5.3 y)	^{60}Co	3.3×10^{-5}
10	$^{65}Cu(n\alpha)^{62}Co$	13.9 m	^{62}Ni	

Complete recovery of the radiation induced resistivity can be obtained at 300 K in aluminium but it requires 500 K in copper. This means that, in principle, the superconducting coils could be annealed out at intervals so that higher total neutron fluxes could be allowed. However, the time required for heating and re-cooling a magnet coil is likely to be months(23) so that annealing will only be considered at intervals of years.

4.4 Impurity Production by Transmutation

As mentioned in the previous section impurities in metals lead to increased resistivity particularly at low temperatures. Reaction rates leading to impurity production by transmutation were therefore calculated in the magnet region of the reactor model shown in Fig.1 using a wall loading of 10 MW/cm^2. The reactions considered are shown in Table III. After thirty years irradiation the impurity concentration will be less than 0.03 ppm for aluminium and 0.3 ppm for copper. The important impurities resulting from transmutation are silicon and magnesium in aluminium, and zinc and nickel in copper. The calculated concentrations of the metals are less than those normally present in the high resistance ratio ultra pure metals normally used forstabilizating superconducting magnets. Therefore transmulation can be neglected as a problem in this context.

4.5 Radiation Damage in Insulators

The insulators used in present superconducting coils are

(a) Thin layers ($\sim$0.005 cm) of PVA,PTFE or similar materials for the insulation of the wire;

(b) A mixture of 80% glass 20% epoxy resin for potting of coils which provides general structural support;

(c) Some form of porcelain or ceramic for the electrical insulation of terminals.

Under normal conditions the electric fields in the magnet are small but when the coil goes normal high emfs are induced in it. For proper protection of large coils as discussed in section 4.3, it may be necessary to withstand voltages of 20 kV across the coil terminals.

We must therefore ask whether it is possible to maintain the breakdown strength of the insulating materials in the presence of a neutron flux $\sim 10^9$ n cm^{-2} sec^{-1} for a period of 20 years i.e. a total dose $\sim 10^{18}$ n cm^{-2}. It is possible that the terminal insulators could be replaced, but replacing the internal insulation would require dismantling the whole superconducting coil which is undesirable on economic grounds. Unfortunately there is little data on the resistivity or breakdown strength of insulators as a function of dose. Some information has been compiled by Kircher and Bowman(24) which indicates that under fast neutron irradiation the resistivity of Al_2O_3 can be reduced by two orders of magnitude, but that in many cases this reduction is not serious enough to prevent the use of refractory oxides as insulating materials. The effects up to doses of 3.5×10^{18} n/cm^2, do not appear to be permanent i.e. in post irradiation tests the resistivity recovers. No change in resistivity during irradiation was reported when MgO was subjected to a dose of 3.5×10^{18} n/cm ^{2}(24).

At least two other effects could arise in the insulation as a result of irradiation; the loss of mechanical strength and swelling due to gas formation. Martin(25) has estimated the cross section for hydrogen and helium production by 14 MeV neutrons in SiO_2 and Al_2O_3 and on this basis the atomic fraction of gas after a dose of 10^{18} neutrons/cm^2 would be $\sim 5 \times 10^{-7}$. Thus this effect should be negligible. The gas fraction in glasses should be similar with the exception of borosilicate glass.

In general, mechanical properties of refractory oxides are not significantly altered by neutron doses of up to 10^{20} n/cm^2. The density change is less than 1%. However most measurements have been carried out at room temperature or above. Results at liquid helium temperatures may be different because there is no possibility of annealing.

The effects of neutron bombardment on fluorinated hydrocarbons and hydrocarbon polymers have been reviewed by Brechna(26) with a view to estimating the effect on their use in superconducting magnets. It is clear that the mechanical properties are affected at doses of 10^{15} to 10^{16} n/cm^2, though the properties are better in general in a low temperature environment than at room temperature. Glass fibre epoxy laminates however retain good mechanical strength up to at least 2.5 x 10^{16} n/cm^2. No measurements have been made at higher doses, and no measurements of dielectric strength have been found.

4.6 Radiation Damage in Structural Components

In the design of large superconducting magnets with high fields the mechanical forces produced will be extremely large and in designing such magnets it is expected that strength of materials will be a limiting factor. We should therefore consider what effect the neutron flux has on structural materials at low temperatures. In general, yield and tensile strengths of steels are improved by neutron doses of up to 10^{20} n/cm^2. Results are available for copper irradiated at 4.2 K which shows that in post irradiation test yield stress increases with neutron doses from 10^{17} to 10^{20} n/cm^2 (27).

It has however, been shown that creep stength actually during irradiation is much lower than in post irradiation tests(28). It would therefore be valuable to have data on creep strength of structural materials under the conditions obtaining in a fusion reactor magnet i.e. with a flux of 10^8-10^9n cm^{-2}s^{-1} at a temperature of 4 K.

5. CONCLUSIONS

Radiation damage in both the superconductor and in the normal conductor has the effect of reducing the current density in the magnet which has a direct effect on the economics of a reactor. Because the superconducting magnet is a major component of the cost of a fusion reactor it is important to keep the current density as high as possible. It seems possible on the basis of the rather limited data available that doses up to 10^{18} neutrons/cm^2 could be accepted by the superconductor without a reduction of more than 10% in the critical current. On the other hand a dose of 10^{17} neutrons/cm^2 in copper would change the resistivity by 20% and hence the current density by ∿ 10%. Aluminium at the same dose would be better for stabilization but could be slightly worse for protection as well as having lower mechanical strength.

Aluminium can be fully annealed at room temperature so that by allowing say ten annealing cycles in the lifetime of the reactor the allowable dose could be raised to ∿ 10^{18} neutrons/cm^2, i.e. of the same order as the superconductor. Copper anneals about 80% of radiation induced resistivity at room temperature so that a useful extension of life could be gained in this way for copper also. Thus without annealing the normal conductor should withstand a maximum dose of ∿10^{17} n/cm^2; if 10 anneals are allowable within the life of the reactor the maximum dose is 10^{18} n/cm^2. Over a 20 year reactor life these doses correspond to fluxes of 1.6 x 10^8 and 1.6 x 10^9 n.cm^{-2}s^{-1} respectively. They have to be compared with the flux of 4 x 10^9 n cm^{-2}s^{-1} estimated previously on the basis of the thermal power which could be tolerated in the magnet. The thermal criterion however does not depend on wall loading, in contrast to the neutron flux which for a given power decreases proportionately as the wall loading is reduced. Thus the thermal load will be the more severe criterion at low wall loading and the radiation damage at high wall loading. This is illustrated in Fig.9, where the shield thickness is plotted as a function of wall loading for two different maximum neutron doses to the magnet, based on the radiation damage criteria outlined. The curves have been calculated using the blanket model outlined earlier and the estimate based on the Monte Carlo calculations, that 15 cm thickness of shield is required to reduce the neutron flux by a factor 10. No account has been taken of the change in the neutron spectrum with blanket thickness. An approximate thermal criterion has been plotted for comparison.

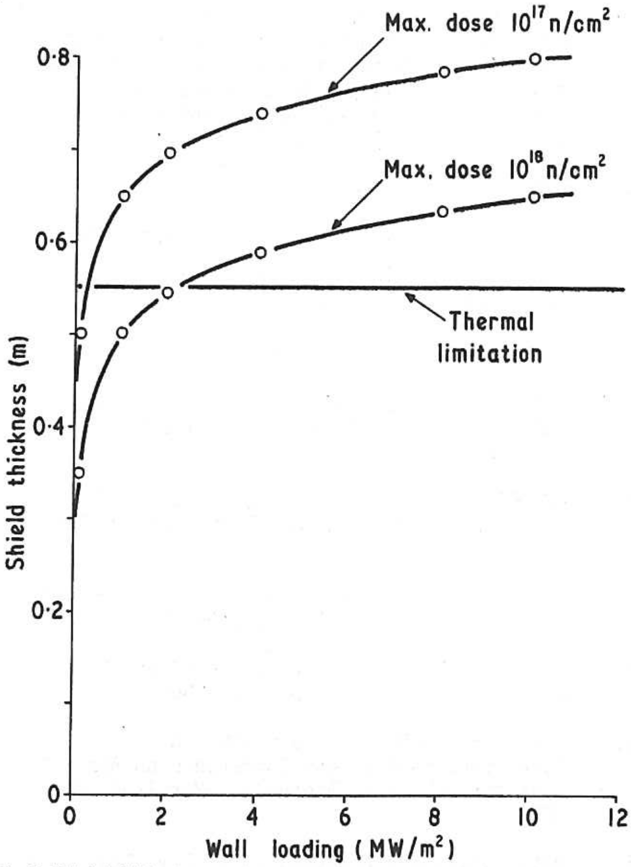

Fig. 9 Shield thickness required as a function of first wall power loading, based on thermal limitations and on two maximum neutron dose criteria in the magnet.

Possible radiation damage in insulators or structural materials is difficult to estimate at the moment because of scarcity of data. However there is a greater range of radiation resistant insulators than there is superconductors or normal conductors. More effort on the measurement of the appropriate properties in a fast neutron flux is nevertheless required.

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