N 2.2/3

APPLICATIONS OF METALLIC COMPOSITES IN THE MAGNET SYSTEM OF A DEMONSTRATION FUSION REACTOR

R. MATERA
Commission of the European Communities, J.R.C.-Ispra Establishment,
I-21020 Ispra (Varese), Italy

R. POTTS, D. H. PROTHERO
International Research and Development Co., Ltd.,
Fossway, Newcastle upon Tyne, NE6 2 YD, United Kingdom

G. PASOTTI, M. V. RICCI, N. SACCHETTI, M. SPADONI
CNEN, Laboratorio Gas Ionizatti,
C.P. n. 65, I-00044 Frascati (Roma), Italy

This paper considers the incorporation of fibre-reinforced composites such as boron/aluminium into the conductor of a demonstration fusion reactor toroidal coils. Such a conductor would be self-supporting against the electromagnetic forces acting on the toroidal coils during operation. The paper considers the stresses to which the conductor would be subjected during coil forming and during operation. It is shown that a reduction in the coil volume and in the coil weight could be achieved, compared with the conventional design, if a composite reinforced conductor were incorporated into the coil.
The possible construction of a composite reinforced conductor and the development work which would be required for its manufacture are also considered.

Although further work is required before a detailed appraisal could be made of the advantages and problems associated with the use of a composite reinforced conductor, it is thought that this solution can largely reduce the radioactive inventory of the toroidal magnet system of future fusion reactors.

1. Introduction

Fusion energy has, among others, the environmental advantage of being a source of potentially "clean" energy. However, this advantage is largely reduced if an extensive use of structural materials which become highly radioactive during operation is made /1/. In this case the radioactive inventory of a fusion reactor is likely to be not far from that of a fission reactor.

One way of alleviating the problem of waste disposal and of allowing the recycle of structures is the use of materials with higher specific strength (ratio of strength to density) to reduce the structural weight, and with lower long-term radiation induced activity, with respect to stainless steel, the candidate material for all structural applications in this field.

Following this approach Matera et al. /2/ have shown the benefits of the design of a fusion reactor considering the use of fibre-reinforced non-metallic composites instead of stainless steel for the cryogenic struts. In this paper we will deal with an improved design of the toroidal field (TF) coils of a demonstration fusion reactor, whose conceptual study is currently under way by the FINTOR group /3/. The new design incorporates a fibre-reinforced aluminium composite to withstand the electro-magnetic forces and to cryogenically stabilize the superconducting wire. This solution is compared with the previous design in which the stabilizer is copper and the reinforcement is a separate layer of stainless steel which has a volume about 80% of that of the conductor. Therefore, in considering a conductor with fibre-reinforcement, it has been initially assumed that the conductor would have a cross-sectional area 80% greater than that of the present conductor. In this way, the two designs could be compared on an equal basis. The dimensions of the cooling channel have been left unaltered from the design as it was felt that altering them would have implications on the refrigeration (i. e. pressure drop, refrigeration power) which were beyond the scope of the present study.

On the basis of the present knowledge of its physical and mechanical properties at cryogenic temperature /4-5/, the boron-aluminium composite has been singled out to this purpose, even if it has found very limited industrial applications because of its high cost. It has an elastic modulus typically twice that of copper, comparable with that of steel (i. e. about 230 GPa), a thermal expansion coefficient approximately one quarter to one third that of copper, an ultimate tensile strength considerably in excess of that of copper. As far as we know, no resistivity measurements have been made at low temperature on boron/aluminium composites. In the present study it has been assumed that the boron/aluminium contains 50% of each component and that the resistivity of aluminium remains unaffected by the fabrication process.

The choice of boron/aluminium does not exclude that other fibre-reinforced composites, commercially available in the future as aluminium-graphite or aluminium-alumina, could display better overall properties.

The complete study /6/ deals with: A) the aspects of manufacturing of the conductor, of coil forming and of insulation application; B) with the conductor stresses during cool-down, due to the mismatch of the thermal expansion coefficients of the different constituents, and the stresses when the conductor is being energized. In this paper we shall report mainly on this latter point. In the first part of the paper the composite has only be considered to replace the stainless steel reinforcement. Accordingly, the conductor which has been envisaged is one containing separate strands of copper/niobium-titanium and boron/aluminium composites, since both these composites are already available. The results of this analysis can be extended to a composite in which filaments of niobium-titanium and boron are embedded in a matrix of aluminium. However, it must be anticipated that the difficulties of manufacturing such a composite are likely to be severe (at present, boron fibres are prepared by vapour deposition, whereas niobium-titanium filaments are prepared by extrusion). Such a conductor is likely to be available only in short lengths, leading to the problem of many conductor joints in the coil.

2. Manufacturing Aspects

2.1 Manufacture of Conductor

The conductor which has been considered is one that would incorporate:

(i) strands of copper/niobium-titanium superconductor,

(ii) boron/aluminium reinforcement,

(iii) barriers of high resistivity material to limit coupling currents between the strands, and

(iv) any additional copper which must be present for stabilisation purposes. In principle, the manufacture of a single continuous length of conductor, sufficient for one layer of the coil, could be achieved by one of two methods:

(i) following the cabled conductor approach such as was used for the Omega Magnet at CERN /7/ or

(ii) by bonding together the components of the composite conductor during the final stages of manufacture to produce a monolithic conductor.

The cabled conductor is likely to require both development work to optimise the process routes and capital investment for the equipment necessary for the handling of a complex conductor. However, it has the following important advantages:

(i) It can readily be manufactured in long lengths of 1 km so that each layer of the FINTOR coil would require no internal joints.

(ii) The helium coolant would be enclosed in a continuous copper tube so that the conductor could be fabricated reliably free from helium leaks.

In the monolithic conductor the various components would be diffusion-bonded together in the final drawing operation. The fabrication of a monolithic conductor would be a two-part process and strictly it is only monolithic in the first part.

The first stage of the process would be to co-extrude strands of superconductor and copper (or aluminium) through a die and subsequently to transpose them by twisting the whole assembly. The second stage would entail the diffusion bonding of boron-aluminium to the central core, and in this respect is similar to the cable conductor.

With the extrusion machines and billet sizes presently available, single piece lengths of about 1 km cannot be manufactured. Considerable development effort would be necessary to enable continuous lengths of conductor sufficient for one layer of the coil to be manufactured.

2.2 Coil Forming

The D-shaped toroidal field coil will be layer wound with each layer connected in series electrically, but connected in parallel with respect to the circulation of the helium coolant through the hollow conductor.

Some general observations can be made regarding potential difficulties in forming the conductor to a radius of less than 2 m. With such stiff, high strength composite conductors two areas which will require practical examination (as well as theoretical consideration) are:

(i) the degree of "spring-back" of the conductor after coil forming and

(ii) whether a conductor can be formed with the insulation present, or whether it must be applied after forming.

In order to alleviate the problems of coil forming, a conductor of rectangular rather than square section is preferred, as shown in Fig. 1. Also the reinforcing composite strands should be situated close to the neutral axis of the conductor. It is expected that it will be necessary to form the conductor prior to the application of the conductor insulation, otherwise the insulation could be crushed during coil forming. During coil forming, it is likely that plastic deformation of the composite reinforcement will occur in attempting to achieve the required radii. A considerable degree of spring-back will also occur during coil forming.

3. Conductor Stresses During Operation

3.1 Conductor Stresses During Cooldown

Due to the difference in thermal contraction between fibres and matrix the matrix will be under strain as the composite is cooled down from its preparation temperature through room temperature to its operating temperature of 4 K. Investigation [8] on a model fibre-reinforced composite has shown that, close to the fibres, a considerable increase in the dislocation density takes place in the matrix. Because of this, the moduli and strengths of the composites are slightly higher than would be expected. Calculations carried out at IRD, assuming a simplified form of the stress-strain curve for the matrix, have suggested that the region of plastic deformation around the fibres should represent only a small proportion of the total matrix cross-sectional area. The relative strain between the fibres and the matrix during cooldown is $\sim 1\,\%$.

As aluminium electrical resistivity has a large strain sensitivity, low temperature measurements are needed for a more precise appreciation of this effect.

3.2 Stresses When the Conductor is Energised

In the conventional design the maximum stress in the stainless steel is 500 N/mm^2 and in the conductor 105 N/mm^2. Since the cross-sectional areas of stainless steel and copper per conductor turn are 610 mm^2 and 770 mm^2, respectively, it follows that the maximum electromagnetic load on a conductor turn is $\sim 4 \times 10^5$ N.

In the alternative conductor design incorporating fibre composite reinforcement the same force must be considered to act on a larger conductor area of 1380 mm^2, giving an overall conductor stress of 290 N/mm^2. The degree to which this stress is shared between the reinforcement and the stabilising matrix depends on the proportions of the materials and the degree, if any, of plastic yielding in the aluminium when the coil is energised.

Because of its low yield stress aluminium will deform plastically during the early stages of operation while the reinforcement remains elastic. The situation is illustrated in Fig. 2. After a few cycles of loading and unloading a steady state will be reached in which the aluminium, hardened by plastic deformation, will have suffered a permanent increase in length. Even with zero applied load, the conductor will be internally stressed since the boron fibres will be in tension and the aluminium in compression. The conductor as a whole will grow by a relative amount, ε_o, compared with its length at the start of cycling. As a consequence the toroidal coil will grow permanently in size as a result of plastic deformation, and increased "training" of the coil is likely as a result of energy release during plastic deformation of the copper.

The stress-strain behaviour of the composite conductor when it is subjected to an electromagnetic load, has been evaluated following the work of Wilson and Walters /9/. Since the proportion of niobium-titanium in the FINTOR conductor is small, it has been ignored in the analyses which follow. The conductor is treated as an aluminium matrix reinforced with boron filaments.

Consider a composite of total area A made up of an area A_f of fibres and A_m of matrix. Let E_m and E_f be the elastic moduli of matrix and fibres, respectively.

After the conductor has been cycled electromagnetically a number of times, the steady state shown in Fig. 2 is reached. To minimise the required hardness of it it is necessary that $\varepsilon_1 = \varepsilon_2 = \varepsilon_s$. The following relations then apply:

a) with no applied load on the conductor:

$$E_m A_m \varepsilon_s = E_f A_f \varepsilon_o \qquad (1)$$

b) with an electromagnetic force, F, on the conductor:

$$F = A_f E_f (\varepsilon_o + 2 \varepsilon_s) + A_m E_m \varepsilon_s \qquad (2)$$

where A is the total area of the conductor (essentially fixed in the present case). Hence from eq. (1) and (2):

$$\varepsilon_s = \frac{F/2E_f}{A - A_m(1-E_m/E_f)} \qquad (3).$$

For a given value of A_m, ε_s can be estimated using eq. (3) and ε_o using eq. (1).

The value for ε will influence to some extent the resistivity of the aluminium and hence the cryostatic stabilisation of the conductor. The resistivity of the conductor has been assumed to obey a law of the form:

$$\rho = \lambda(\rho_o + \alpha B + L\varepsilon) \qquad (4)$$

where B = applied field (= 8 T maximum in the present case) and ρ_o, α, L are constants. The significance of λ is that it represents the increase in resistivity due to nuclear irradiation. Hence the heat transfer coefficient, β, required to ensure stabilisation of the conductor in the event of a quench is given by:

$$\frac{I^2\rho}{A} = \beta P \qquad (5),$$

where I = conductor current = 10^4 Amps and P = perimeter of cooling channel = 4 x 18.4 mm. (In the present design of the FINTOR coils the conductor area at the bottom layer is 760 mm^2 and hence the heat transfer coefficient β is 910 W/m^2K. With two phases helium as coolant, nucleate boiling is assured.)

Hence for a given value of A_m, it is possible to estimate ε_s using equation (3) and β using equation (5).

Fig. 3 shows the values of ε_o, ε_s and β as functions of the conductor composition. It has been assumed that the reinforcing composite deforms in such a way that its maximum compressive strain is numerically equal to its maximum tensile strain.

Fig. 3 furthermore shows that, in order to achieve a value for β close to the present level of 900 W/m^2, the proportion of copper in the conductor need be no greater than 30% assuming that the aluminium contributes to the stabilisation of the conductor. The value of ε_s in this case would be about 7.6×10^{-4} corresponding to a maximum stress of 90 N/mm^2 in the copper. The value for ε_o would be 1.8×10^{-4} which would correspond to a permanent growth of only 4 mm in the major diameter of the toroidal coils.

Hence, it is clear that the use of a conductor made up of separate strands of copper/niobium-titanium and boron/aluminium would result in lower stresses than in the present design incorporating stainless steel reinforcement. A possible conductor would consist of 35% copper/niobium-titanium and 65% boron/aluminium. Because of the low density of boron/aluminium, such a conductor would lead to a saving in coil weight of more than 40% over the present design. In addition, it is possible to reduce the conductor area, thereby securing an additional reduction in coil weight. Fig. 4 gives values for ε_o, ε_s and β as functions of the conductor composition for a conductor area of 1000 mm^2. Due to the reduced conductor area, the values for ε_o, ε_s and β are increased and it is no longer possible to obtain a value for β of 900 W/m^2. The best overall configuration would be a conductor with approximately 50% copper and 50% boron/aluminium. In this case the value for β would be 1180 W/m^2, i.e. somewhat greater than in the conventional design but probably still acceptable. The value for ε_s would be 1.2 x 10^{-3}, corresponding to a copper stress of 140 N/mm^2; the value for ε_o would be 6.5 x 10^{-4}, corresponding to a maximum growth of 15 mm in the toroidal coil. Although more severe than the operating conditions derived from Fig. 3, these levels of growth, stress and heat transfer should still be acceptable. The resulting conductor would have a smaller area than that previously considered, leading to the possibility of a more compact coil and of reductions in weight of the equipment around the coil. Also, the problems associated with coil forming would be reduced. The weight per meter of the proposed conductor with 1000 mm^2 sectional area is 15% less than that of the conductor with a cross-sectional area of 1380 mm^2 and less than half the weight of the present conductor in which conventional materials are used.

These favourable conclusions have been reached by assuming that the aluminium of the boron/aluminium composite has a resistivity comparable to that of copper and is available as a conductor stabiliser. Measurements of the low temperature resistivity of boron/aluminium are required to verify this.

4. Summary and Conclusions

This paper has examined the possibility of incorporating an advanced fibre-reinforced composite, such as boron/aluminium, into the conductor for the FINTOR superconducting toroidal coils. The main conclusions are as follows:

- The conductor shall be made in the form of a soldered cable with separate strands of boron/aluminium and copper/niobium-titanium superconductor, cabled around a central core. Such a conductor should be available in long continuous lengths and could be manufactured using presently available machinery.
- The present study has indicated that the use of a conductor intrinsically reinforced with a composite material, offers the following advantages:

a) A reduction in the size of the toroidal coils. Calculations carried out in this study have shown that it would not be necessary to use all the area previously occupied by the present conductor and steel if a composite reinforced conductor were used. Thus, if boron/aluminium reinforcement can be used, a reduction in cross-sectional area of the coil of about 30% could be achieved (e.g. from 1380 mm^2 to about 1000 mm^2 in the bottom layer of the coil).

b) If boron/aluminium reinforcement is used, a significant reduction in coil weight (calculated to be of the order of 40%) over the present design is possible. This is due partly to the lower density of boron/aluminium compared with copper, steel, etc., and partly to the reduced conductor area.

c) Because of the reduced size of the toroidal coils, it should be possible to reduce the size of the components around the coils, leading to a more compact Tokamak system. This should allow general reductions in the weight and cost, even of established components.

A large amount of development work will be required before production of fibre-reinforced superconductors on a large scale is possible. Until then it will probably not be possible to assess in detail the advantages and disadvantages of the use of such conductors. However, at the present time, it is likely that the forming of such a conductor to the required D-shape will be much more difficult than with present conductors, due to the presence of the reinforcement.

References

[1] KULCINSKI, G. L., "Critical Issues Facing the Long Term Deployment of Fission and Fusion Breeder Reactors", UWFDM-234, March (1978)

[2] MATERA, R., BIOGIO, M., CAPRINO, G., CRIVELLI-VISCONTI, I., FARFALETTI-CASALI, F., and NICOLAIS, C., "Advanced Material Design of a Demonstration Fusion Reactor Central Support", Proceedings First Topical Meeting on Fusion Reactor Materials, Bal Harbour, Florida, Jan. 29-31, 1979, Paper L-4

[3] FINTOR GROUP, "FINTOR D - A Demonstration Fusion Power Reactor of the Tokamak Type", to be published as EUR-report

[4] SCRAMM, R. E. and KASEN, M. B., "Static Tensile Properties of Boron-Aluminium and Boron-Epoxy Composites at Cryogenic Temperature", in Advances in Cryogenic Engineering, vol. 22, Ed. by K. D. Timmerhaus, R. P. Reed and A. F. Clark, Plenum Press, New York (1975)

[5] READ, D. T. and LEDBETTER, H. M., "Elastic Properties of a Boron-Aluminium Composite at Low Temperatures", J. Appl. Phys., 48, 10, p. 2827-2831 (1977)

[6] KNOX, R., McLENNAN, C., POTTS, R. and PROTHERO, D. H., "The Use of Fibre-Reinforced Composites in the FINTOR Toroidal Coils", I. R. D. 78/56, Dec. (1978)

[7] MORPURGO, H., "Design of Superconducting Magnet for the Omega Project", Particle Accelerators, vol. 1, p. 225 (1970)

[8] LEE, R. E. and HARRIS, S. J., "The Effects of Fibre Diameter and Interfibre Spacing on the Tensile Properties of Copper-Tungsten Composites", J. Phys. D., 7, p. 2312 (1974)

[9] WILSON, M. N. and WALTERS, C. R., "Development of Superconductors for Fusion Technology", Rutherford Laboratory Report RL-76-038 (1976).

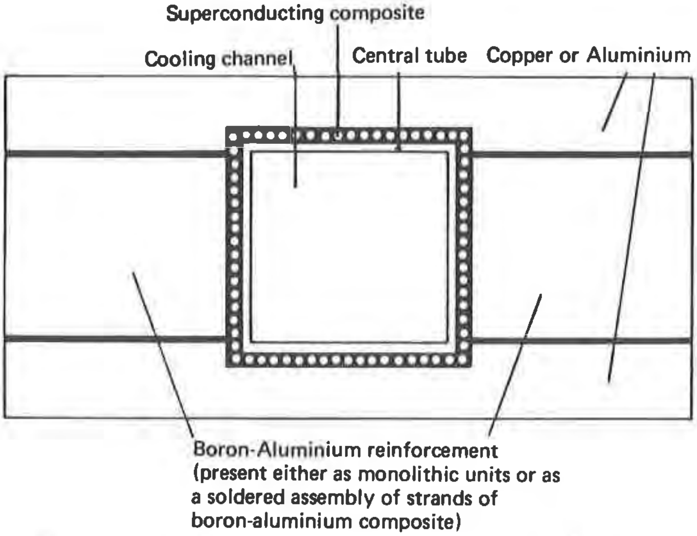

Fig. 1 - Cross section of the FINTOR-D conductor in the advanced solution

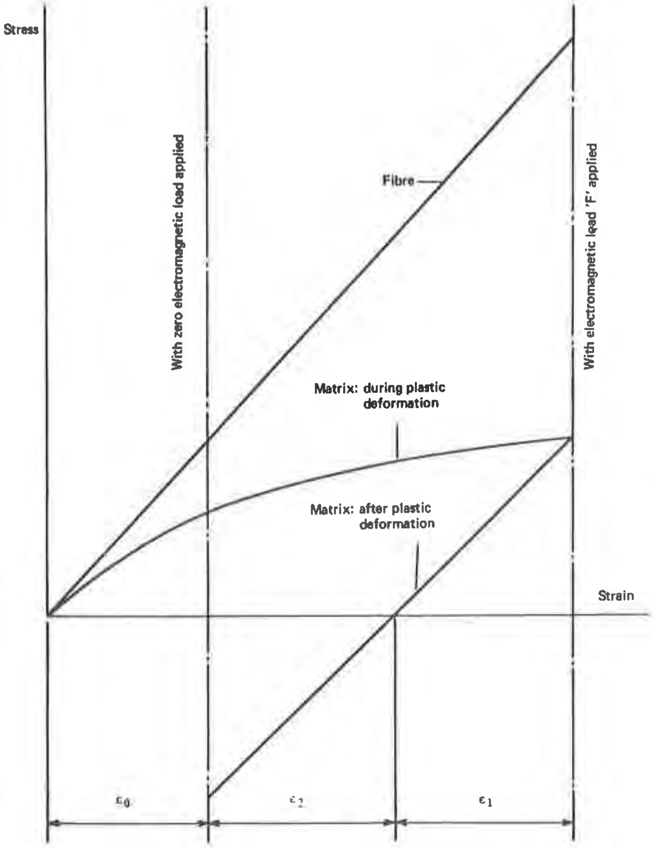

Fig. 2 - Tensile behaviour of plastically deformed conductor

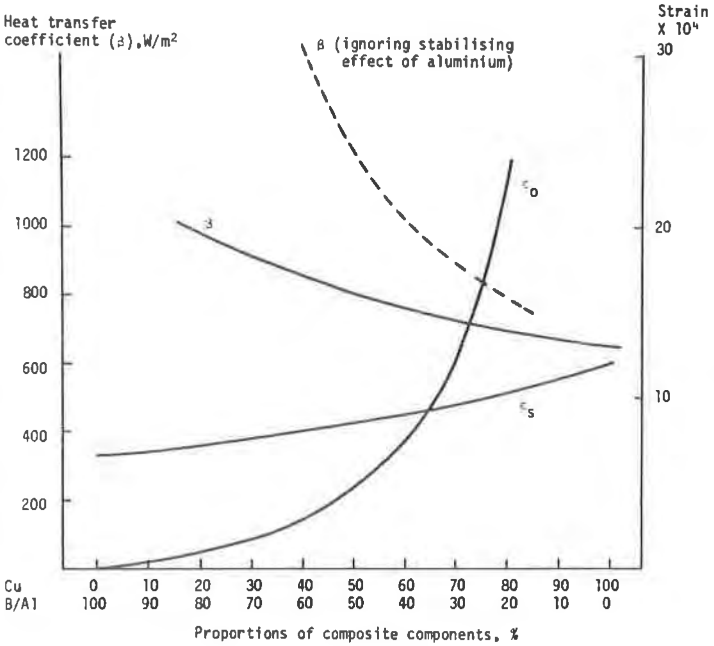

Fig. 3 - Heat transfer coefficient and strain as a function of the proportions of composite components.
Conductor area=1380 mm^2

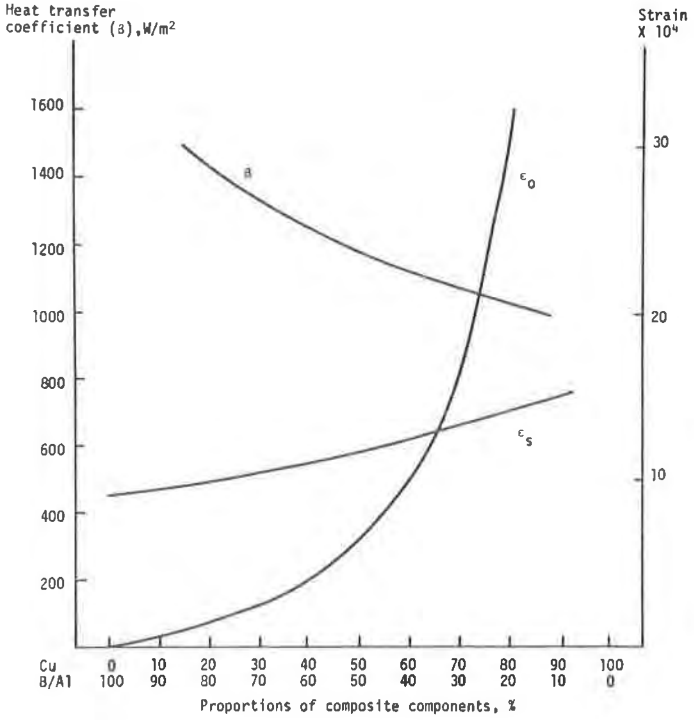

Fig. 4 - Heat transfer coefficient and strain as a function of the proportions of composite components.
Conductor area=1000 mm^2