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ABSTRACT

The epoxy glass insulation from a JET toroidal field (TF) coil was extensively tested as part of a study to permit operation of JET at a field 20% higher than the design value [1]. The measurements were performed on specimens taken from a coil that had been in use for several years.

The JET TF coils are D-shaped and made of two pancakes of 12 copper turns, with 2mm inter-turn insulation and 6mm inter-pancake insulation, all wrapped by 7mm of ground insulation (the total coil cross-section area being about 0.1m^2). Most of the tests were carried out on specimens taken from the straight leg of the used coil.

Tests on inter-turn insulation included shear strength and shear modulus, fracture tests, micrographic analysis, void and glass-resin content and second order glass transition temperature.

Tests on ground insulation included tensile strength and elastic moduli, shear strength and shear modulus, inter-laminar shear strength and elastic modulus, mode 1 and mode 2 fracture tests.

The results were not as consistent as might be achieved using laboratory specimens, but we consider that they are more representative of the quality achievable in actual manufacture.

1. INTRODUCTION

The JET toroidal field is generated by copper coils with epoxy glass insulation. During manufacture each turn was wrapped in woven glass cloth. To avoid damaging the glass cloth during winding a layer of pre-impregnated cloth was put at the interface between turns. The ground insulation was made by wrapping externally with glass tape. After winding and wrapping, the coil was vacuum impregnated with epoxy resin in a mould. The resin composition was Araldite F (100 parts), hardener CIBA HY 906 (100 parts) and flexibiliser DY040 (15 parts).

Until 1997 the maximum toroidal field was 3.4 Tesla. After a study including several new analyses and tests [1], the maximum field was raised to 4 Tesla. Tests included measurements of mechanical properties of the insulation system of a used coil. This paper describes tests additional to those reported in previous papers [2,3].

2. TEST SPECIMENS

Specimens were cut from a coil, which had been removed from the JET machine after about 10 years of operation, because of an inter-turn fault caused by a water leak. Most of the insulation was in good condition and suitable for testing.

To make the specimens, cross sectional slices were cut from the coil (Fig.1). These slices were further cut and machined to prepare specimens for inspection, analysis and mechanical testing [2]. Sections of ground insulation were removed to make samples for ground insulation tests.

3. TESTS ON INTER-TURN INSULATION

A. STATIC SHEAR STRENGTH

Three types of mechanical test specimens were cut from the slices as shown in Figure 2.

Advantages and disadvantages of the three specimen types are listed in Table I.

Specimen Type	Test Area mm^2	Advantages	Disadvantages
Double Shear	3600	stress is averaged over a large amount of insulation. Can be used for tesing the inter-turn key.	Uses large amount of material analysis needed to determine stress
Single Shear	625	Uses less insulation materilal. Has been used extensively in the coil manufacture industry.	Simple test and test rig. Extensive machining when making from existing coil. Shear stress not uniform. Some inter-laminar tension.
Iosipescu	52	When used with a special test rig, applies pure shear stress at the middle of the notched section.	Extensive and difficult maching when making from existing coil. Area of insulation tested is very small

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Table 1: Shear Test Specimen Types

Test results using these specimens have been reported previously [1, 2]. The three types of specimens gave similar average shear strength. This suggests that:

- the parameter determining breakage is average shear strength,
- the test result is insensitive to specimen design,
- strength is uniformly distributed through the insulation. (If there were areas of weakness the small test region of the Iosipescu specimen would give excessive scatter.)

Far from causing increased scatter the Iosipescu tests showed reduced scatter relative to the other specimen designs. This may be because the Iosipescu specimen produces pure shear in the insulation. In fact, the Iosipescu specimens are measuring the shear strength of the epoxy resin. This is because the specimens fail along one of two planes of weakness (pre-impregnated layer or copper surface) which are pure epoxy with no glass fibre crack stoppers. (Planes between tapes are also weak but more wavy and interleaved.)

Non Iosipescu specimens have failure triggered by inter-laminar tension at the edges. This is a crack triggered phenomenon and depends more on local defects (because the Mode I critical crack size is smaller than Mode II). In some specimens failure may be delayed by inter-laminar pressure. Failure is therefore more random.

B. CYCLIC CREEP

During fatigue testing with Iosipescu specimens (Fig.3) cyclic creep of the specimens was noticed. Fig.4 shows creep with a peak shear stress of 45MPa. This high stress, near the static failure limit, is chosen, because it illustrates the effect clearly. Lower stresses are of more practical interest. Note that, even at high stress, the slope of the stress/strain curve is constant.

Creep strain per cycle is plotted against stress in Fig.5. The graph shows that very little creep occurs below a threshold of about 36MPa. This result is surprising, because the normal SN curve shows no threshold.

Creep similar to this has been observed before [4]. The referenced paper gives some ideas as to the mechanisms involved.

C. CRACK PROPAGATION

Tests of crack propagation in inter-turn insulation, were made using copper/insulation sandwiches cut from the coil, as shown in Figure 6.

Static tests showed that the mean critical fracture energy (GIIC) was 1220J/m^2. Cyclic tests were then made to determine the crack growth rate. Results are shown in Figure 7.

Figure 7 shows considerable scatter in the crack growth rates but an upper limit can be plotted, which may be useful. Unfortunately, some of the specimens used for the crack growth tests appear to be better than the static specimens, as they did not break at the static limit. Note that cracks grow extremely slowly (>1mm in 106 cycles) when GII is less than a quarter of the static limit.

IV. TESTS ON GROUND INSULATION

Results for inter-turn insulation were dominated by the effects of the copper to insulation interface and of the pre-impregnated layer at the centre of the inter-turn insulation. In order to obtain more representative data for the epoxy glass insulation itself and also because the ground insulation has a mechanical function in our coils, we measured mechanical properties of the ground insulation. Sections of ground insulation were removed from the coil and test specimens, as shown in Fig.8 and Fig. 9, were prepared. The ground insulation of the JET coils was made by wrapping glass tape around the outside of the coil before vacuum impregnation. This means that the ground insulation has different properties parallel and perpendicular to the tape. Orthogonal axes for the test specimens were defined as follows.

i) In the plane of the insulation and parallel to the coil conductors (perpendicular to the tape)
ii) In the plane of the insulation and perpendicular to the coil conductors (parallel to the tape)
iii) Perpendicular to the plane of the insulation

The specimens were tested in suitable test rigs according to industry standards.

Static results are given in Table II and crack growth rates are given in Fig.10 and Fig.11

Type of Test	Parameters	Value	Unit	Coefficient of variation %
Tensile	σ_{11}	103	MPa	20
	σ_{22}	657	MPa	1.5
	E_{11}	20.3	GPa	8
	E_{22}	40.0	GPa	8
	ν_{12}	0.20	10	
	ν_{23}	0.13	11	
	ν_{31}	0.13	21	
Through thickness shear	τ_{11}	61	MPa	3
	τ_{23}	63	MPa	17
Iosipescu	τ_{12}	83	MPa	10
	G_{12}	5.1	GPa	9
Mode I	G_{Ic}	2028	J/m^2	11
Mode II	G_{IIc}	3446	J/m^2	23

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Table II: Static Properties of Ground Insulation

Note: that the insulation is much stronger and stiffer in direction 2 (parallel to tape) than 1 (perpendicular). It was not possible to grow cracks suitable for testing in direction 1. Cracks do grow in direction 1 but not in a straight line down the middle of the specimen, which the test design requires. As a design guide it should be assumed that cracks grow at least as easily in direction 1 as 2.

There is considerable scatter in the crack growth rates shown in Fig. 10 and Fig. 11. The upper limit lines are consistent with the static measurements, as they intersect the static critical fracture energy lines at reasonably high growth rates (of order one millimetres per cycle).

CONCLUSIONS

Tests made on specimens from real coils show more scatter than laboratory specimens. This means that coil designers should be cautious and allow for production variations, when using test data. The fracture mechanics approach may be useful for coils. It enables critical defect sizes to be estimated and estimates of growth rates of existing cracks to be made.

In our tests, cracks did not grow in epoxy glass if the fracture energy was less than a quarter of the critical fracture energy.

There was some inconsistency in our tests of crack growth in inter-turn insulation, as some cyclic tests exceeded the static limit. It would be desirable to extend these tests with more specimens. Cracks in coils may often grow at the copper insulation interface. The critical fracture energy (like the shear strength) is comparable to the fracture energy within the matrix. We would have liked to measure the crack growth rate at the interface but were unable to achieve stable crack growth.

We noticed cyclic creep when shear testing our insulation. We would like to extend these tests to characterise this phenomenon more clearly.

Coil ground insulation made from wound tape has markedly different properties perpendicular and parallel to the tape.

Mode II cracks grew an order of magnitude more slowly in our ground insulation than in our inter-turn insulation. However, our inter-turn insulation has a double pre-impregnated layer at its centre so our ground insulation may be more typical of epoxy glass insulation systems.

ACKNOWLEDGMENT

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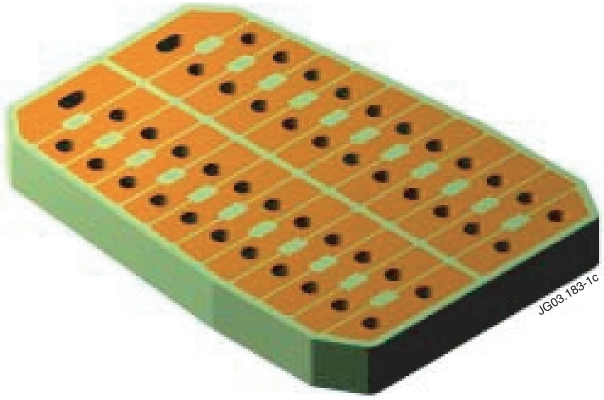


Figure 1: Typical cross-sectional slice of TF coil

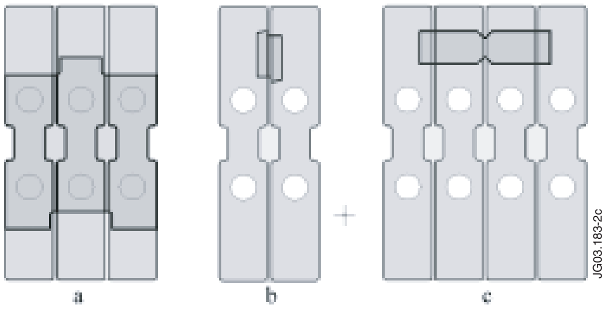


Figure 2: Showing how test specimens are cut from coil conductors; (a) double shear specimen, (b) small single shear specimen, (c) Iosipescu specimen

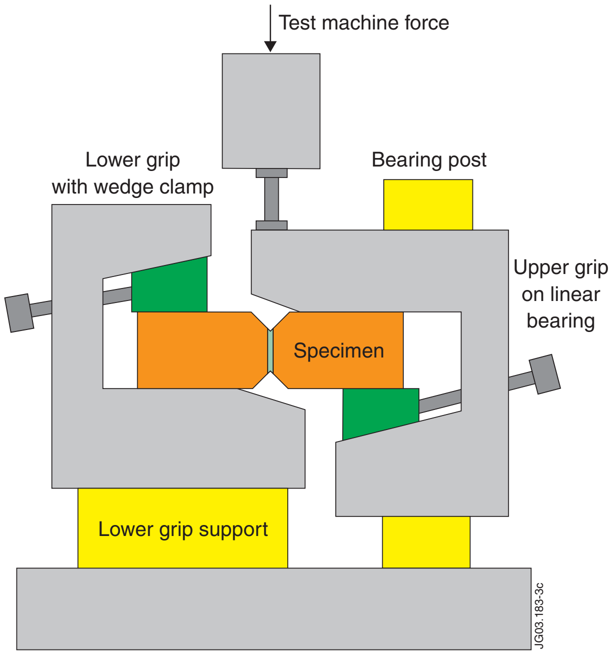


Figure 3: Specimen for inter-turn shear test (Iosipescu). The copper and insulation specimen is cut from a coil cross-section. A special rig applies pure shear to the insulation at the notched centre

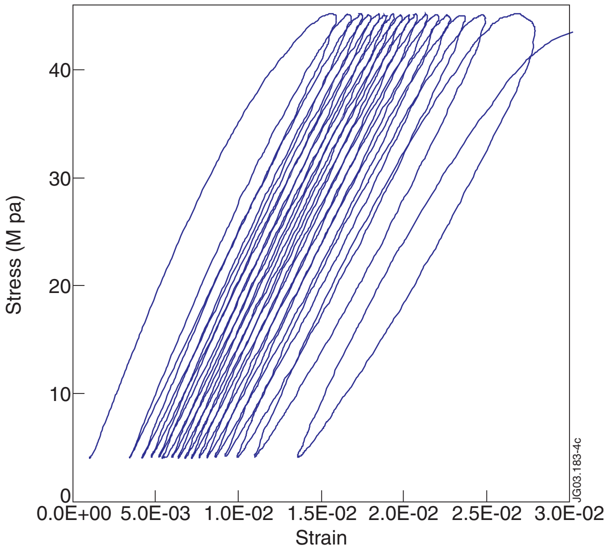


Figure 4: Cyclic creep with shear stress cycling between 4 and 45MPa

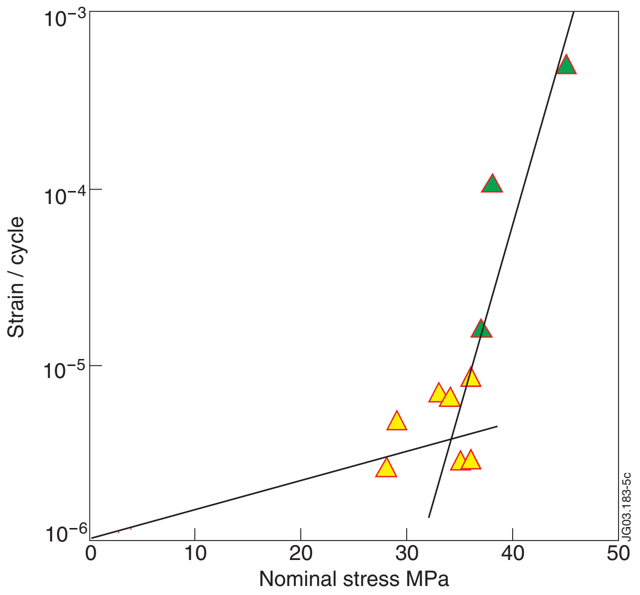


Figure 5: Creep strain per cycle versus shear stress

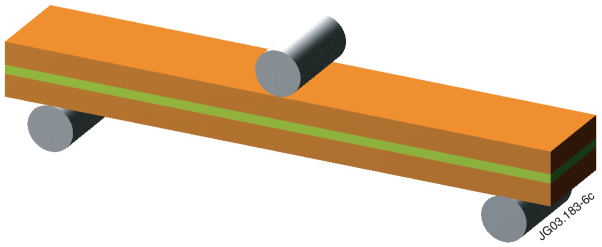
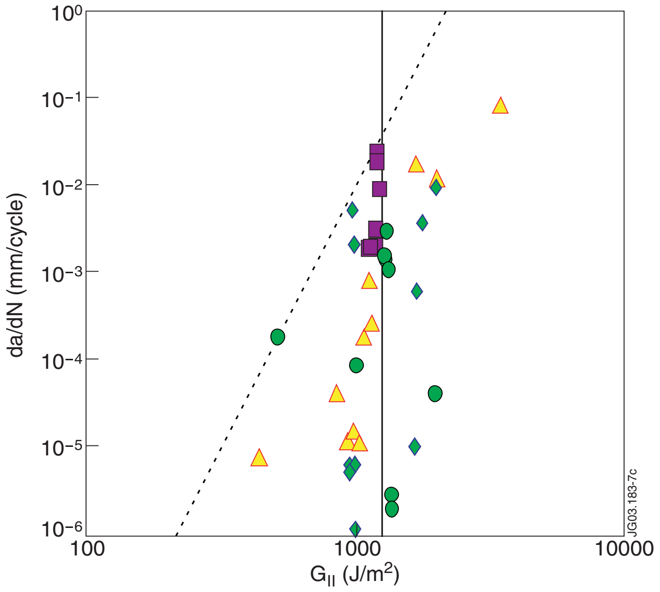


Figure 6: Specimen for crack propagation tests in inter-turn insulation. The copper/insulation/copper sandwich was cut from a coil cross-section. The rollers are for applying a 3 point bending load. A crack is started at the centre of the insulation at one end.



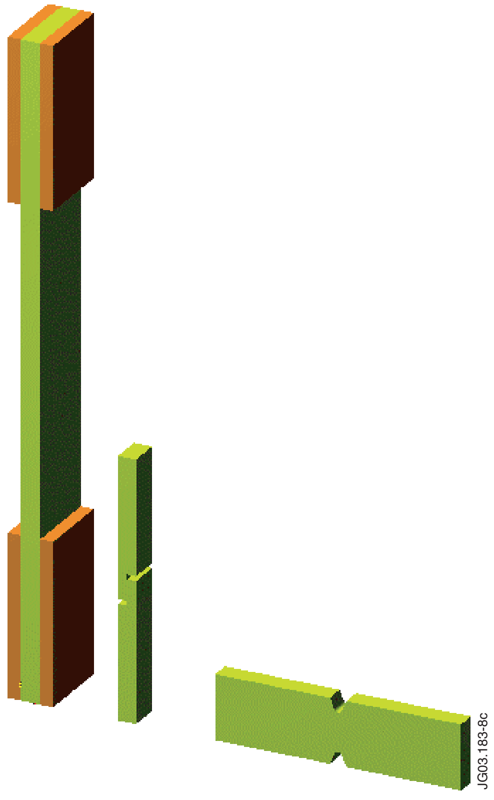


Figure 7: Crack propagation rate as a function of G_{II} for copper/insulation sandwich specimens. The vertical solid line represents the static critical fracture energy. The dotted line is a suggested upper limit for growth rate as a function of G_{II}

Figure 8: Specimens for tensile, through thickness shear and in-plane shear tests

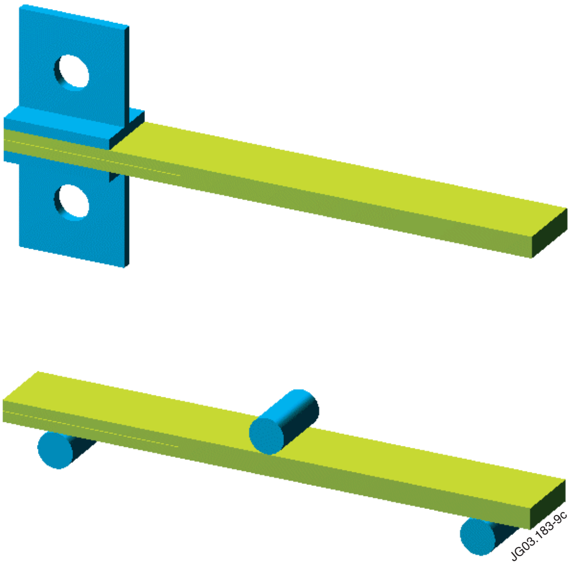


Figure 9: Specimens for Mode I tests with glued on pieces for applying load and Mode II test with rollers for applying 3 point bending load. A crack is started on the centre plane at the left hand end of the specimen

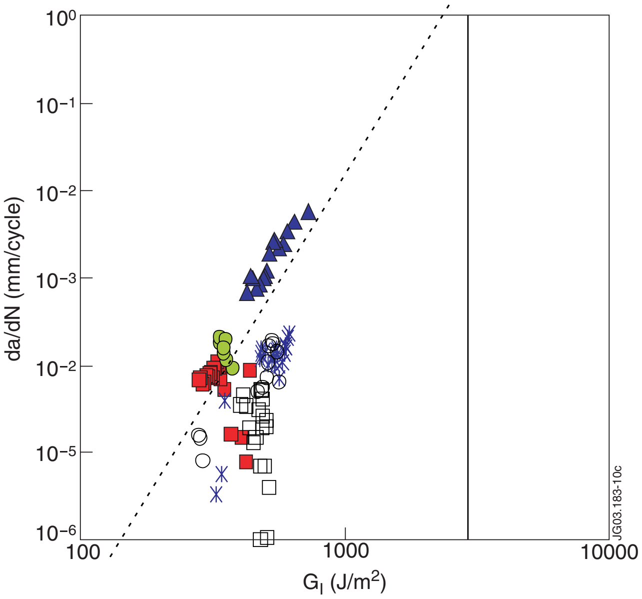


Figure 10: Crack growth rate vs. crack strain energy (G_I) for Mode I cracks in ground insulation. The vertical solid line represents the static critical fracture energy. The dotted line is a suggested upper limit for growth rate as a function of G_I

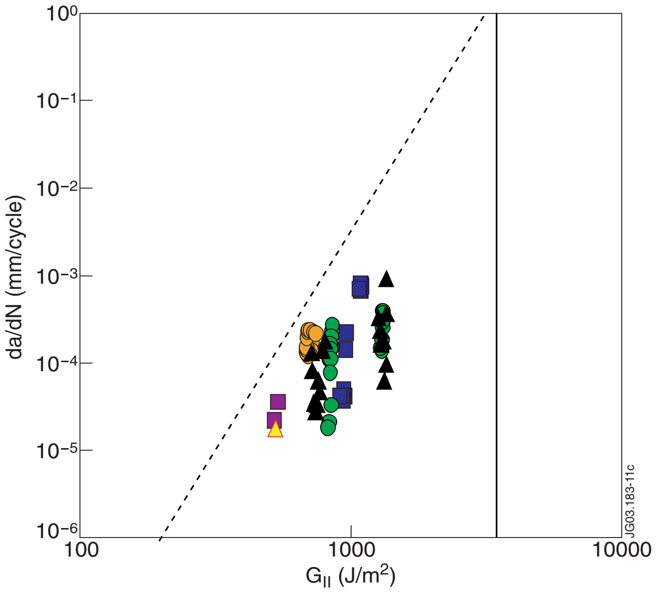


Figure 11: Crack growth rate vs. crack strain energy (GII) for Mode II cracks in ground insulation. Lines as described for Fig.10, except G_{II} instead of G_I