Dielectric Properties of the ITER TFMC Insulation after Low Temperature Reactor Irradiation

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Abstract. The insulation system for the Toroidal Field Model Coil of ITER is a fiber reinforced plastic (FRP) laminate, which consists of a combined Kapton/R-glass-fiber reinforcement tape, vacuum-impregnated with an epoxy DGEBA system. Pure disk shaped laminates, disk shaped FRP/stainless-steel sandwiches, and conductor insulation prototypes were irradiated at 5 K in a fission reactor up to a fast neutron fluence of 10^{22} m^{-2} (E>0.1 MeV) to investigate the radiation induced degradation of the dielectric strength of the insulation system. After warm-up to room temperature, swelling, weight loss, and the breakdown strength were measured at 77 K. The sandwich swells by 4% at a fluence of $5x10^{21}$ m^{-2} and by 9% at $1x10^{22}$ m^{-2}. The weight loss of the FRP is 2% at $1x10^{22}$ m^{-2}. The dielectric strength remained unchanged over the whole dose range.

1. Introduction

Radiation effects on insulating materials for the windings of superconducting magnets in future fusion reactors, i.e. glass-fiber reinforced plastics, have been identified as an area of concern for the long-term operation of such magnets [1-3]. In earlier work [4-6], we have simulated the operating conditions of the magnet insulation and addressed the influence of different radiation spectra on the *mechanical* damage process of various types of fiber reinforced plastics (FRPs). Since many years, potential insulating materials for ITER (International Thermonuclear Experimental Reactor) have also been investigated by the European and the U.S. Home Teams with respect to their *electrical* performance at cryogenic temperatures with and without reactor irradiation prior to testing [7-11].

This contribution reports on the assessment of the electrical properties (i.e. the dielectric strength and the breakdown voltage) of the conductor insulation system for the Toroidal Field Model Coil (TFMC) of ITER, and on measurements of swelling and weight loss following low temperature reactor irradiation.

2. Sample Manufacturing Procedures

The investigated insulation system of the TFMC is a laminate, which consists of a combined Kapton/R-glass-fiber reinforcement tape, vacuum-impregnated with an epoxy DGEBA (diglycidyl ether of bisphenol A) system. The specimens were manufactured by Ansaldo, Genova, Italy. The manufacturing processes were as follows.

2.1 Pure disk shaped laminate

The laminates from which the disks were cut, were obtained by wrapping the combined Kapton/glass-fabric tape (half-overlapped) around a steel plate. The two longitudinal sides of the steel plate were well rounded, to enable safe wrapping. Before the application of the insulation, Mylar was wrapped around the plate for easy detachment of the laminate after the vacuum pressure impregnation (VPI) process. Two extra steel plates and a set of bolted beams were used to press the insulation during the impregnation process. The whole arrangement was then vacuum impregnated. After the VPI process, two insulation plates were obtained by cutting the insulation along the two longitudinal sides of the steel plate. The disk shaped laminates (diameter 12.5 mm) were obtained by laser cutting the 0.5 mm thick insulation plates.

2.2 Disk shaped laminate-stainless steel sandwich

The manufacturing procedure of the insulation plates was the same as above. For the laminate-steel sandwich, the following fabrication steps were made. A 0.5 mm thick Teflon sheet was used to fix the steel disks on the insulation plate. The Teflon sheets had 35 holes with a diameter of 8 mm to accommodate the steel disks. As for the pure disk shaped laminates, an outer frame was used to press the steel disks against the insulation, and further on, the insulation against the core steel plate. After the VPI process, the disk shaped insulation plated with the steel disks (sandwiches) were cut from the mould by laser cutting (outer dimensions: diameter 12.5 mm; thickness 1 mm).

2.3 Conductor insulation prototype sample

This specimen consists of two concentric stainless steel tubes and an insulation tube located between the steel tubes. In order to avoid excess voltages at the ends of the tubes, the sharp edges of the steel tubes were softened by flanging the inner and outer tube radially inwards and outwards, respectively, with suitably shaped tools. Four pieces of Teflon fillers were then manufactured and fitted inside the inner steel tube to keep this space free from resin during the impregnation process. The Kapton-glass insulation tape was then wrapped onto the inner steel tube, and the Teflon fillers were used to define the two boundaries of the whole tube. The outer steel tube was made by rolling and pressing a sheet of stainless steel onto the surface of the insulation tube. Finally, the whole arrangement was wrapped with a Tedlar (Teflon-type) tape on the outside to enable the extraction of the specimen from the cured resin bath. After the impregnation process, the Teflon filler and the Tedlar tape were removed (outer dimensions: diameter 12 mm; length 32 mm).

The final sample geometries and specifications, which were chosen in view of the existing space limitations in the low temperature irradiation facility, are based on extended scaling experiments and can be found in Ref. [12].

3. Irradiation and Test Procedures

After initial measurements of the sample dimensions and weights, all irradiations were performed in the FRM I reactor (Garching) at ~5 K to neutron fluences of 10^{21}, $5\text{x}10^{21}$ and 10^{22} m^{-2} (E>0.1 MeV). This reactor is operating at a γ-dose rate of $2.8\text{x}10^{6}$ Gy.h^{-1}, a fast neutron flux density of $2.9\text{x}10^{17}$ $\text{m}^{-2}.\text{s}^{-1}$ (E>0.1 MeV), and a total neutron flux density of $9.5\text{x}10^{17}$ $\text{m}^{-2}.\text{s}^{-1}$, respectively. After irradiation, all samples were warmed-up to room temperature and stored for radioactive decay.

For the electrical tests a specially designed device was manufactured to allow testing of both unirradiated and irradiated specimens in liquid nitrogen. The disk shaped laminates could be positioned easily and quickly between the two electrodes. More details and a photograph of the testing device can be found in Ref. [12]. The electrical tests were carried out at room temperature and at 77 K prior to and after low temperature reactor irradiation. For the measurements at 77 K, the device was placed into a polystyrene container filled with liquid nitrogen. The breakdown voltage of the samples was evaluated according to the "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies" (ASTM D149-97a); "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials under Direct-Voltage Stress" (ASTM D3755-97) with Appendix B: "Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials under DC Voltage at Cryogenic Temperatures".

4. Results

4.1 Swelling and weight loss

After low temperature irradiation and thermal cycle to room temperature, the sample dimensions and weights were measured again and then analysed in order to evaluate the radiation induced swelling and weight loss of the specimens. The results are shown in Figure 1, where the data are plotted as a function of the fast neutron fluence. The swelling of the laminate amounts to 1.5 % at a fast neutron fluence of 1×10^{21} m^{-2} and to ~ 2 % at a fast neutron fluence of 5×10^{21} m^{-2}. A considerable increase of swelling (to ~ 5 %) is found at a fluence of 1×10^{22} m^{-2}. The swelling of the sandwich amounts to ~ 1 % at 1×10^{21} m^{-2} and increases continuously to ~ 9 % at a fluence of 1×10^{22} m^{-2}, whereas the swelling of the conductor insulation prototype sample (outer diameter) is almost negligible (~ 0 to 0.5 %). On the other hand, the weight loss of the laminate increases continuously to 2 % at a fluence of 1×10^{22} m^{-2}. Each data point in Figure 1 represents an average, calculated from five to eight measurements (samples showing significant deviations were rejected in the statistical calculations), except those for the conductor insulation prototype sample, where the average was calculated from only two measurements. In general, the measured effects on swelling and weight loss are in good agreement with literature data on similar laminates [9,10].

4.2 Scaling Experiments

Before the electrical tests were carried out on the irradiated samples, scaling experiments were made on approximately 0.5 mm thick pure laminates of the same material at room temperature (under oil environment) and at 77 K, in order to investigate the influence of the diameter of the disk shaped samples as well as of the size of the stainless-steel electrodes on the measured dielectric strength. Three different configurations were investigated [12]. The scaling results for both temperatures are shown in Figure 2 (left-hand side). As can be seen there, no influence of the disk diameter on the dielectric strength was found, which confirms the suitability of 12.5 mm diameter disk shaped laminates for a reliable assessment of the electrical properties (i.e. the breakdown voltage and the dielectric strength). The dielectric strength is about 10 % lower at 77 K.

4.3 Electrical tests

The dielectric strength of the laminate and of the sandwich is plotted in Figure 2 as a function of the neutron fluence. No degradation of the dielectric strength was found for both the laminate and the sandwich over the whole dose range. Slightly higher values were found for the sandwich, but the overall effects are within the calculated standard deviations. The conductor insulation prototype sample (tube) was manufactured with a thickness of the

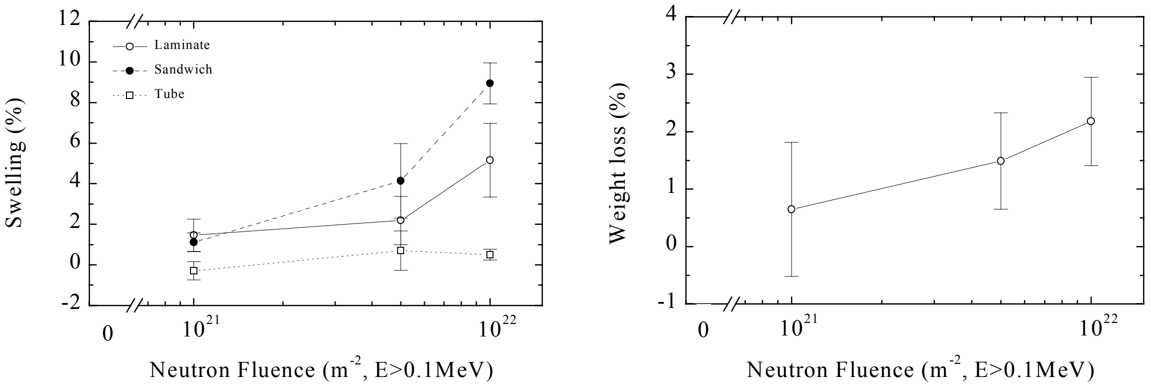

FIG. 1. Swelling of the laminate, the sandwich, and the conductor insulation prototype sample (tube) as well as weight loss of the laminate after reactor irradiation.

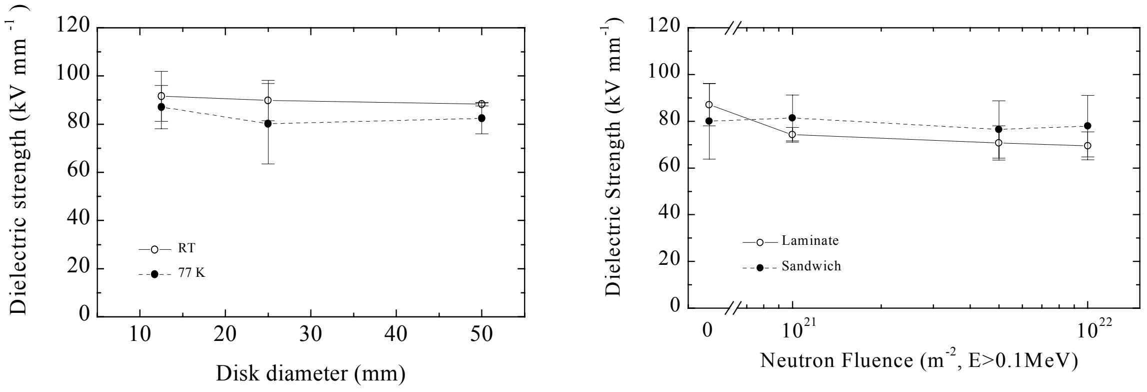

FIG. 2. Scaling results for both test temperatures (left) and dielectric strength for the laminate and for the sandwich as a function of the neutron fluence measured at 77 K (right).

insulation system, which is twice that of the disk shaped samples (i.e. 1 mm). Unfortunately, the voltage needed for electrical breakdown through the laminate exceeded the maximum voltage generated by the high voltage power supply, and thus, breakdown could not be achieved on all of these tubes. Nevertheless, all conductor insulation prototype samples were found to withstand a voltage of at least 60 kV dc without electrical breakdown. The results are discussed in much detail together with fractogaphic investigations made in a SEM in [12].

5. Summary

The dielectric strength of the conductor insulation system used for the Toroidal Field Model Coil of ITER, was assessed in conjunction with data on swelling and weight loss after reactor irradiation at ~ 5 K up to a neutron fluence of 10^{22} m^{-2} (E>0.1 MeV). The results are summarized as follows.

1 At a fluence of 5×10^{21} m^{-2} (E>0.1 MeV), i.e. the ITER dose level, the data on swelling show half overlapping error bars between the pure laminate and the sandwich, the overall effects are within ~ 4 %. For the conductor insulation prototype sample, swelling is almost negligible.

2 The weight loss of the laminate increases continuously to 2 % at a fluence of 10^{22} m^{-2} (E>0.1 MeV).
3 At 77 K, the dielectric strength is ~70 $kV.mm^{-1}$ for the pure laminate and slightly higher for the sandwich. No degradation was found for both specimens over the whole dose range.

In summary it should be noted, that the typical insulation thickness for the Toroidal Field Model Coil (TFMC) of ITER [13] is in a range between 1.9 and 10 mm (e.g. TFMC conductor insulation thickness: ~ 2.5 mm, pancake insulation: thickness ~ 1.9 mm, and ground insulation: thickness 1.9 mm + 8 mm = ~ 10 mm). Considering the data on the electrical tests presented in this contribution, we conclude that the *electrical performance of these materials exceeds* by far the design limits of the ITER EDA criteria.

Acknowledgements

The authors are greatly endebted to Dr. R. Maix and Mr. H. Fillunger (EUHT) for their efforts with the sample procurement. The technical assistance of Mr. E. Tischler is also acknowledged. This work has been carried out within the Association EURATOM-OEAW.

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