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Characterization and qualification of advanced insulators for fusion magnets

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HIGHLIGHTS

- Various resins were qualified for the ITER TF coil insulation.
- Pre-bonded glass fiber/polyimide tapes were characterized after irradiation.
- A repair scenario of a magnet coil was simulated using a cyanate ester resin.

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ABSTRACT

Intensive research over the past decades demonstrated that the mechanical material performance of epoxy based glass fiber reinforced plastics, which are normally used by industry as insulating materials in magnet technology, degrades dramatically upon irradiation to fast neutron fluences above $1 \times 10^{22}\ m^{-2}$ ($E > 0.1$ MeV), which have to be expected in large fusion devices like ITER. This triggered an insulation development program based on cyanate ester (CE) and blends of CE and epoxies, which are not affected up to twice this fluence level, and therefore appropriate for large fusion magnets like the ITER TF coils. Together with several suppliers resin mixtures with very low viscosity over many hours were developed, which renders them suitable for the impregnation of very large volumes. This paper reports on a qualification program carried out during the past few years to characterize suitable materials, i.e. various boron-free R-glass fiber reinforcements interleaved with polyimide foils embedded in CE/epoxy blends containing 40% of CE, a repair resin, a conductor insulation, and various polyimide/glass fiber bonded tapes. The mechanical properties were assessed at 77 K in tension and in the interlaminar shear mode under static and dynamic load conditions prior to and after reactor irradiation at ~340 K to neutron fluences of up to $2 \times 10^{22}\ m^{-2}$ ($E > 0.1$ MeV), i.e. twice the ITER design fluence. The results confirmed that a sustainable solution has become available for this critical magnet component of ITER.

1. Introduction

Present technical fusion power concepts like ITER [1] rely on the deuterium–tritium reaction in the fusion plasma and the energy deposition of the resulting fast neutrons in the first wall of the tokamak device. The plasma contained by magnetic fields emits both neutron and gamma radiation which interacts with a number of fusion reactor materials, among them also with the superconducting (SC) magnet coils and their *insulation systems*. Before reaching the magnets and their insulation the level of radiation is reduced by the blanket and shield structures as well as by geometrical factors.

Glass-fiber reinforced plastic (GFRP) compound structures are currently employed as insulating materials for the SC magnet system of a fusion device such as ITER [2,3]. The insulation transfers the magnetic (Lorentz) forces from the coil windings to the case. For a high reliability and availability, the mechanical and electrical properties as well as the loads of the insulation materials have to be known for the entire lifetime of the device. The neutron and gamma radiation present at the magnet location leads to a *radiation-induced degradation* of the material properties and has to be taken into account to guarantee adequate performance over the lifetime of the magnet. In addition, cyclic loads in the pulsed reactor operation mode require also the knowledge of the *fatigue properties* down to cryogenic temperatures.

For this reason, a broad spectrum of experimental work was carried out by several research groups during the past 30 years. A few aspects covering the most important results, data and literature bases will be briefly summarized here. Extensive test programs at CERN [4] and in the US [5] led to an incredible amount of data on all kinds of insulating materials. Brown [6] and Weber [7] discussed the radiation effects on SC fusion magnet materials in general, including both the superconductors and their

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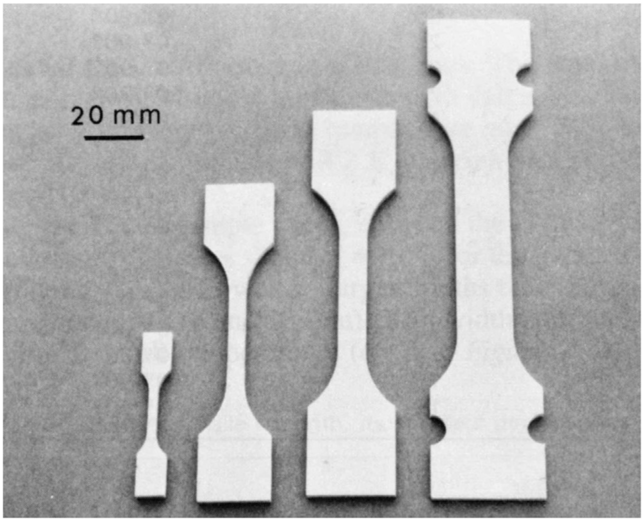

Fig. 1. Photograph of a set of tensile samples for scaling experiments [50].

insulation with respect to their application potential in a fusion device. The paper by Coltman Jr. [8] is focused on the organic insulating material itself and outlines the most important needs for organic insulator research. Fundamental investigations concerning the cryogenic material behavior of the insulation system can be found in the paper by Kasen [9]. Hartwig [10] presented an extended database of work done on irradiated organic insulation systems. The work by Maurer [11] is focused on neutron and gamma irradiation effects on the organic insulation and provides an extended pertinent literature base.

In 1990, a research group formed at the Atomic Institute of the Austrian Universities (ATI), Vienna, initiated a research program aimed at identifying magnet insulation systems suitable for the operating conditions of such SC magnets [12]. Initial work focused on *scaling experiments* employing standardized and non-standardized test methods and with the application of fracture mechanical test methods. A typical example is shown in Fig. 1, where a set of tensile samples includes both the DIN or ASTM standards as well as a larger but especially a "small" geometry, which can be used for irradiation experiments. After studies on scaling and material anisotropy effects under static load in tension [13] the program was extended to dynamic load [14] and further to interlaminar shear load conditions [15]. In addition, attempts were made to characterize the material by newly developed fracture mechanical test procedures in mode I [16] and mode II [17] applying the *fracture energy concept* (including FEM) and scaling investigations on appropriate specimen geometries.

Further work was then dedicated to *radiation effects* on the magnet insulation. The most important results on the *mechanical material properties* obtained under *various radiation environments, load conditions*, and *test temperatures* are summarized in [18–21]. In these experiments an initial selection of material compositions containing different types of matrices and reinforcements was irradiated both at ambient and at cryogenic temperatures by various spectra (neutrons and/or gammas, electrons, cf. Fig. 2) prior to testing at 77 K with and without an *annealing cycle* to room temperature (RT) using the tensile test as well as the mode I and II load procedure, respectively. Later on further material compositions were added to the program and the complete data set up to 1995 was published in [22], where the most important features regarding radiation effects (i.e. the *total absorbed dose* as a scaling quantity) were summarized including fractographic investigations and a literature base of pertinent research.

The research of the ATI group was then extended to studies of the *interlaminar shear* behavior [23,24,15] including FEM investigations [25,26] on selected specimen geometries, because this quantity is known to be the most sensitive mechanical material parameter under irradiation in a laminate structure. Hybrid organic/inorganic [27,28] as well as other novel insulation systems [29] were investigated as well.

Based on this fundamental work and the database obtained, further research focused on ITER relevant insulation systems. The mechanical properties of an insulation system for the Central Solenoid (CS) Model Coil (MC) were investigated [30,31] as well as the insulation system used for the Toroidal Field (TF) MC [32–34] and the stress distribution under interlaminar shear loading using FEM [35].

Studies on the effects of *gas evolution* [36], *swelling* and *weight loss* [31,27] caused by irradiation were also done on several organic and inorganic insulation materials proposed by industry. The radiation hardness of the TFMC insulation was investigated concerning the *dielectric properties*, i.e. the breakdown strength (including scaling experiments), as well as concerning *swelling* and *weight loss* of the material [37].

Several investigations of the ITER TF Model Coil insulation [32,33,37,38] made it clear that the epoxy resins usually used by magnet industry cannot withstand the neutron fluence expected at the ITER TF coils. Therefore, ITER and EFDA initiated an R&D program to develop and test radiation resistant insulation systems, which would fulfill all requirements concerning electrical and mechanical strength, radiation resistance as well as application characteristics, such as low viscosity over many hours (pot life). Chemical industries played an essential role in the development of such advanced systems [39–41].

Already in the CERN report 98-01 [4] cyanate esters (CE) and mixtures of CE and epoxy resins were reported to show excellent radiation resistance, but their application parameters would not have allowed an impregnation of the ITER coil. A breakthrough was achieved when a low viscosity CE system became available (LMB6653/LMB6622 from Huntsman, Switzerland), which not only showed excellent radiation hardness, but also allowed mixing with epoxy resins in a wide range.

The first investigated pure CE and CE/epoxy blends fulfilled the ITER criteria even at a considerably higher absorbed dose level, i.e. extend the "lifetime" of such magnets at least by a factor of 2 or 3 compared to conventional insulation systems [39]. In further test campaigns, the improvement of commercially available (and cost saving) resins by blending epoxies with the more expensive CE system was demonstrated in an unambiguous way [40,42–44] and the optimum was found for 40 wt% CE in the CE/epoxy blend, which was also confirmed by an analysis of their chemistry, where the optimal miscibility of the resins was expected for around 40 wt% CE and 60 wt% epoxy. As a result, the 40 wt% blend was chosen as the insulation material for the ITER TF coils. However, the pot-life of up to 10 h was not sufficient to ensure an impregnation of a large structure like the TF coils. Further R&D work was focused on the catalyst in order to extend the pot-life sufficiently. In the so-called "mock-up" experiment, larger tests in an industrial environment confirmed the feasibility of employing the 40/60 blend for the vacuum impregnation of large units [45,46]. Subsequently also other suppliers offered resin systems of similar composition and Huntsman modified their system to allow pot lives of more than 100 h. All these considerations were laid down in a study on the "Specification of the Resin System for Impregnation" [44] made at ATI in the years 2007/2008, which served as the basis for the ITER specification of the resin system to be used (Table 1).

As a consequence, an additional qualification program [47,48] on the insulation system selected for the ITER TF coils was carried out during the last few years, where various industrial resin