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NOVEL RADIATION-RESISTANT INSULATION SYSTEMS FOR FUSION MAGNETS

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ABSTRACT

Large, capital-intensive, superconducting or resistive magnets are essential components of most current and planned fusion devices. Magnets for these applications must be reliable, have a long mean-time-between-failure (MTBF), and be able to be manufactured using cost-effective materials and fabrication processes. Electrical insulation is often the weak link in magnet design, due to insulation sensitivity to high radiation doses, embrittlement at cryogenic temperatures, and fabrication limitations. Improvements in electrical insulation can contribute to enhanced magnet system performance and achieve considerable cost reduction. For example, an insulator with improved radiation resistance would require less shielding, thus enabling the coil to be located closer to the radiation source, resulting in a lower field requirement for the coil, and thus reducing the conductor and structural needs for the magnet systems. In this manner, improvements in magnet insulator performance and processing can have a cascading effect on overall magnet system cost reductions. Composite Technology Development, Inc. (CTD) has developed two new classes of insulation materials, an organic insulation system based on cyanate ester chemistry, and a ceramic insulation system that can be co-processed with the magnet. Both types of systems are suitable for the high radiation doses anticipated in NSO devices and future fusion reactors. This paper will describe the different material systems under current development, mechanical and electrical properties at cryogenic temperatures, and results of radiation exposure tests for these materials.

I. INSULATION MATERIALS

Current magnets typically utilize some form of fiberglass reinforced epoxy composite insulation. In most instances, these materials provide sufficient electrical insulation, suitable mechanical properties at cryogenic temperatures, flexible processing for cost-effective coil fabrication and assembly, and reasonable cost. However, epoxy resins have been shown to degrade to unacceptable levels of performance when exposed to high levels of radiation, particularly dose levels being considered for next generation fusion devices [1]. Additionally, several NSO devices, such as the National Compact Stellarator Experiment (NCSX) and the Fusion Ignition Research Experiment (FIRE), require that the insulation withstand operating temperatures up to 373 K [2]. Current epoxy/glass insulation systems are designed to operate at cryogenic temperatures and are not suitable for use at these elevated temperatures.

To address the need for composite insulation systems that can perform at both cryogenic and elevated temperatures and also withstand higher radiation doses than the standard epoxy systems, several new classes of insulation systems have been developed. The first new class is composed entirely of an organic matrix system based on cyanate ester chemistry that is reinforced with standard S-2 glass fabric. The second class is composed of a combination inorganic/organic matrix system that utilizes a ceramic matrix that is reinforced with a ceramic fabric, heat treated, and then impregnated with an epoxy resin.

Cyanate Ester Insulation Systems

Cyanate esters are versatile thermosetting resins that exhibit several desirable properties for use in magnet insulation, including improved toughness, low dielectric loss, and excellent adhesion to both metals and glass fibers. Cyanate ester resins also possess a range of physical and chemical properties that make them amenable to a variety of processing methods and provide increased performance in demanding environments. The different available physical states of the cyanate monomers allow them to be incorporated into a multitude of different types of resin systems capable of being processed through vacuum pressure impregnation (VPI), pre-impregnation or B-Stage, and also as high pressure laminates (HPL). Their processing versatility, however, is generally in marked contrast to the other common high temperature thermosetting resins such as bismaleimides (BMIs) and polyimides (PI), which are known for their difficult processing properties.

In terms of end-use temperature, the cyanate esters lie somewhere between the tetrafunctional epoxy resins and the BMIs, having high glass transition temperatures (T_g), from 150 – 300 °C. Di-functional epoxies (DGEBA or DGEBF), typically used in magnet insulation, are not considered high temperature polymers; with T_g's falling between 50-150 °C, limiting them to continuous high-temperature exposure limits of less than 100 °C.

Because of their processing adaptability, cyanate ester systems are easily blended with hot-melt thermoplastics, such as polyimides and other thermosets, like bismaleimides. The hybridizing of the cyanate esters with BMIs and PIs allows the insulation to capitalize on the best characteristics of all of these materials. Up to now, very little radiation exposure data was available on cyanate esters, but the existing data has shown very little reduction in flexural strength or modulus when exposed they are exposed to electron radiation up to 10^7 Gy (10^9 Rad) [3]. Likewise, glass reinforced composites using polyimide and bismaleimide matrix materials have been tested to greater than 100 MGy with little or no degradation in shear strength [4]. Therefore, by combining BMI's and PI's with cyanate esters, resin systems that are easily processed and have the potential for greatly improved radiation and high temperature resistance, may be realized.

Ceramic Insulation Systems

Another new type of insulation, based on ceramic technology, has been developed that overcomes many of the processing problems associated with the use of ceramic materials in magnets. This class of insulation system is primarily targeted for magnets utilizing superconducting cable that undergoes a heat treatment cycle, such as Nb_3Sn or Nb_3Al. During manufacturing, these superconductors must be heat treated at 650 °C to 800 °C, hence, traditional organic insulation systems must be applied after this heat treatment. However, the use of a ceramic based insulation, capable of being wrapped around the conductor prior to heat treatment, would enable Wind-and-React processing of coils, which in turn could lower the costs and increase the reliability of these types of superconducting magnet systems.

The newly developed hybrid epoxy/ceramic insulation can be applied by either wrapping a ceramic-based pre-preg onto the conductor or by impregnating a coil that has been wrapped with dry ceramic fabric. The ceramic matrix can be applied in the same way as traditional organic insulation using pre-preg tapes or by a procedure similar to resin transfer molding (RTM). After application of the ceramic matrix and fiber onto the conductor and winding into the desired coil form, it can be placed in the heat treatment furnace and the heating cycle begun. Since there is no organic content within the insulation at this stage to be burned off, heating can be performed in an inert atmosphere. The heat treatment profile used is determined strictly by the superconductor itself and is not affected by the insulation, which can range from 600 °C to 900 °C for anywhere from 30 to over 400 hours. At this point, the magnet is re-placed into its mold and impregnated with an organic resin system, such as the new cyanate ester systems or the traditional di-functional epoxies. This potting by the organic resin system fills any remaining porosity within the ceramic insulation and bonds the coil together to form the final structure.

The resulting insulation produces a system where the majority of the components are ceramic, which are known to be highly radiation resistant [5], but which processes very much like a traditional organic insulation system. Additionally, by combining the ceramic with small amounts of a high performance epoxy resin system, the porous ceramic is filled, producing an insulation system which is electrically superior to traditional ceramics.

II. MECHANICAL AND ELECTRICAL PROPERTIES

The primary mechanical stresses within fusion or superconducting magnets are compressive stresses, normally held to 300 – 500 MPa. In some instances, shear stresses are also developed, and often act simultaneously with compressive stresses, but the shear stresses are usually held to 60 MPa or less. For example, in the FIRE TF coils, the highest mechanical stresses on the insulation are expected to be 520 MPa in compression and around 50-60 MPa in shear [6]. Electrically, magnet insulation must maintain its electrical integrity throughout its life, after exposure to mechanical stresses and high levels of radiation. While few electrical requirements for insulation have been established for NSO devices, the insulation may be subjected to 8 – 10 kV, and would be expected to achieve the same type of dielectric breakdown strengths provided by the traditional epoxy/glass composite insulations, typically around 50-80 kV/mm.

Because of the above-mentioned requirements, the two new classes of materials, the cyanate ester systems and the hybrid organic/ceramic systems, were tested for their compressive, shear, and electrical properties at cryogenic temperatures. Results of these tests are presented in Table 1. The compression tests were performed in the "through-thickness" direction, with the compressive forces applied normal to the fabric plies. Specimens were nominally 6.4 mm square, and were tested in a thickness of approximately 3.2 mm. To evaluate the insulation shear properties, the short beam shear (SBS) test was employed, which has been used extensively to evaluate and screen insulation materials. The same materials used in the compression tests were used for the SBS tests, with a nominal thickness of 3.2 mm.
Electrically, the various insulation systems were evaluated for their dielectric strength at 77 K. Thin specimens, approximately 25 mm square, were placed between electrodes and the voltage increased incrementally until breakdown was achieved. In all cases, the cyanate ester systems and the traditional organic system specimens were reinforced with a nominal 50%, by volume, S-2 glass fabric. The hybrid epoxy/ceramic materials were reinforced with a 50%, by volume, ceramic woven fabric.

Table 1. Cryogenic Property Data for New Insulation Systems

Insulation System	Compressive Strength (GPa)	Compressive Modulus (GPa)	Shear Strength (MPa)	Dielectric Strength* (kV/mm)
Cyanate Ester Systems Cyanate Ester/PI/BMI hybrid family	1.3-1.5	17-20	90-115	60-80
Ceramic Systems Hybrid epoxy/inorganic family	1.2-1.4	32-40	70-114	70-100
Traditional Systems High Performance Epoxy family	1.1-1.4	16-20	90-120	60-80

* Materials tested in thickness ranging from 0.6 – 0.8 mm

As seen from Table 1, both families of new insulation systems compare favorably with the traditional organic systems. The cyanate ester/polyimide/bismaleimide hybrids give virtually identical strengths for compression, shear, and dielectric properties, as do the hybrid epoxy/inorganic family. However, the greatly increased compressive modulus achieved by the ceramic systems over the other systems is quite dramatic. Therefore, the hybrid epoxy/inorganic insulation systems would seem ideal for magnets that require high compressive strength, modulus, and rigidity.

III. POST IRRADIATION PROPERTIES

The total insulation radiation doses for new NSO devices are continuously evolving to ever increasing levels. As noted by Shultz [6], the benchmark design insulation dose for the International Thermonuclear Experimental Reactor (ITER) was 5 x 10^7 Gy, the Burning Plasma

Experiment (BPX) was 1 x 10^8 Gy, while FIRE is up to 2 x 10^8 Gy. Continued increases in radiation doses are to be expected in future magnet designs. Therefore, the development of new, highly radiation resistant insulation systems such as the cyanate ester and hybrid epoxy/inorganic families become very critical to the success of these new programs.

Therefore, the new insulation systems were irradiated at the TRIGA Mark-II reactor in Vienna, Austria, made available to CTD through the Atomic Institute of the Austrian Universities (ATI). The reactor provides a fast neutron flux density (E > 0.1 MeV) of 7.6 x 10^{16} $n/m^2/s$, a total neutron flux density of 2.1 x 10^{17} $n/m^2/s$, and a gamma dose rate of 1 x 10^6 Gy/h at approximately 340 K. Specimens from each family of new systems were irradiated to three different levels to gauge their response to increasing levels of radiation. The three levels corresponded to fast neutron fluences of 10^{21}, 10^{22}, and 5 x 10^{22} n/m^2. These levels equate to total absorbed dose levels of approximately 5, 50, and 250 MGy.

Compression testing, performed by CTD at liquid nitrogen temperature, revealed virtually no change in compressive strength by any of the materials at all radiation levels. The compressive modulus for the cyanate ester family of insulation systems did show an increase with increasing radiation by approximately 20% at the upper level.

More revealing were the results of the SBS tests at 77 K after irradiation carried out by ATI, as shown in Figure 1. As seen in the figure, while all of the families start out at approximately the

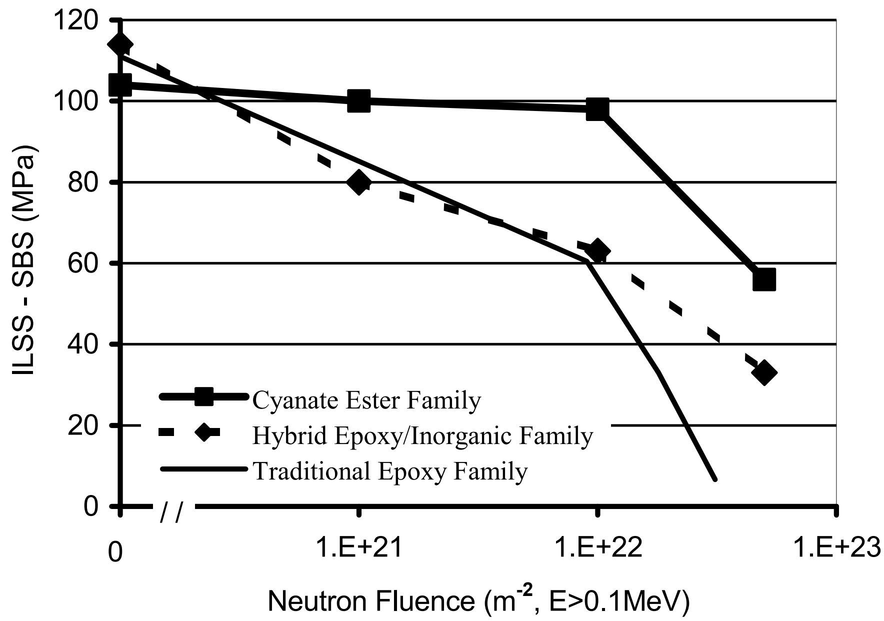

Figure 1. Radiation effects on the interlaminar shear strength of insulation systems at 77 K.

same interlaminar shear strength (ILSS), as the radiation dose increases, both the hybrid epoxy/inorganic family and the traditional epoxy family's strength decreases rapidly. This decrease by both families with increasing radiation dose is most likely due to the effects of the radiation on the epoxy, which is present in both systems. The hybrid epoxy/inorganic family does maintain a higher degree of shear strength than the epoxy family at the highest level of radiation. However, the cyanate ester family maintains its shear strength through the first two levels of radiation exposure, falling only after the highest dose.

IV. SUMMARY

Two new families of radiation resistant insulation materials have been introduced and tested at cryogenic temperatures. Both the cyanate ester family and the hybrid epoxy/inorganic family have shown to be suitable for a wide variety of fusion magnet fabrication processes and possess as good as or better mechanical and electrical properties prior to irradiation than traditional epoxy insulation systems. Both families have undergone radiation exposure testing up to approximately 250 MGy and show promise for improved performance under demanding radiation exposure levels.

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