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Industrialization of Radiation-Resistant Cyanate Ester Magnet Insulation

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***Abstract*— Future magnet systems require electrical insulation that can withstand high levels of incident radiation, while also providing the necessary mechanical robustness and dielectric strength to operate these devices. Moreover, the insulation must also be compatible with industrial fabrication processes to enable their efficient, large-scale manufacture. Cyanate ester-based insulations provide the necessary electro-mechanical performance and radiation resistance for these applications, but more information is needed to demonstrate application-specific issues related to magnet production. To accomplish this, a series of tests were performed to validate the long-term processing behavior of cyanate ester resins, their adhesion to Kapton®, and the fabrication of small-scale coils. The results of this work demonstrated a working time of greater than 85 hours, good adhesion to Kapton®, and the successful fabrication of test coils. Larger-scale industrial trials are ongoing at various sites to further demonstrate the use of cyanate ester insulation for the ITER TF coils, as well as commercial applications.**

***Index Terms*—cryogenic, cyanate ester, insulation, radiation resistant**

I. INTRODUCTION

New machines under development for fusion energy and high energy physics research, as well as medical devices and other industrial systems, require magnet coils that can reliably operate at elevated temperatures (373 to 423 K), cryogenic temperatures (4.2 or 77 K), and/or be exposed to higher levels of radiation than previously necessary (up to 100 MGy). For several years, fiberglass-reinforced epoxy resins have been used to insulate the numerous magnets produced for use in these applications. While epoxies have a long history of success, new machine designs have magnet performance requirements that exceed the practical limits of epoxy-based electrical insulations.

At this time, fusion machines based on either normal or superconducting magnets are being developed and operated to study fusion reactions, and establish a solid basis for energy production. One of the most critical and capital-intensive components of fusion machines are the numerous magnets used to confine, shape, and heat the plasmas associated with these reactions.

By far the largest fusion machine currently under development is the International Thermonuclear Experimental Reactor (ITER) [1]. Recent analyses have indicated that the level of radiation exposure anticipated for the ITER toroidal field (Tf) coils is higher than originally anticipated, with the new end-of-life exposure estimates exceeding 10 MGy. Furthermore, there is a degree of uncertainty associated with these estimated radiation exposure values due to the fact that the neutronics models have never been validated with a true fusion radiation spectrum. Therefore, to maximize the lifetime and utility gained from investing in ITER, it is prudent to select an insulation material that will meet the radiation and electro-mechanical design parameters which will ensure the reliable operation of the ITER device.

In recent years, cyanate ester resins have been shown to possess many of the performance characteristics needed to meet these challenges, while also exhibiting processing characteristics that lend to the improved impregnation of very large magnets [2]-[4]. Additionally, fission-reactor irradiations have shown that after exposure to the anticipated radiation doses for the ITER Tf coils, epoxy resins degrade too much and cyanate ester/epoxy blends will just meet the estimated 10-MGy exposure level (with little or no margin). Alternatively, all-cyanate ester resins have been shown to meet the ITER performance requirements after exposure to more than 100 MGy (more than 10 times the anticipated radiation exposure for the ITER Tf coils) [5]-[6].

While the use of low-viscosity cyanate esters in magnet systems is relatively new, these materials have long been used as adhesives in electronics and integrated circuits. Whereas electronic applications require very small amounts of resin, magnet applications will require the use of larger quantities of material. For smaller coils this could be a few hundred grams, while insulating the ITER Tf coils will require approximately 2 tonnes of resin for each of the 18 Tf coils.

The commercial supply of these larger quantities of cyanate ester can be readily accomplished, but it is necessary to develop appropriate handling and processing procedures to ensure the successful insulation of magnet windings. Cyanate ester resins require some different handling and processing procedures than those that have been used with epoxy resins. In fact, the same procedures and equipment used for epoxies may not result in the successful impregnation of a coil with a cyanate ester material. Some of the key differences between

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the processing of epoxies and low-viscosity cyanate ester resins include:

- Using measurement and mixing equipment that can reliably dispense and mix 100 parts of Part A to 2.13 parts of Part B.
- Preventing the contamination of cyanate ester resins with impurities, particularly moisture.
- Controlling the heating and cooling rates during the cure process, maintaining temperature uniformity during the gel stage (±5°C throughout the entire coil), and eliminating the possibility for hot spots in the coil that could accelerate the cure reaction.

Whereas previous work with cyanate ester insulations has tested the material's electro-mechanical performance and radiation resistance, the objective of this work was to demonstrate the industrialization of these materials for large-scale magnet production. This included evaluation of pot life over extended periods of time, compatibility with Kapton® films, and fabrication of subscale coil assemblies.

II. EXPERIMENTAL PROCEDURE

A. *Viscosity Measurements*

The viscosity of cyanate ester resin (CTD-403) was measured at 50˚C for 85 hours to demonstrate the pot life of this resin for use in the impregnation of very large coils. These measurements were performed using a Brookfield DV-II viscometer with an automated data acquisition system. The impregnation temperature for these materials is typically 30 to 50˚C, so testing its performance at 50˚C provides a good estimate of the resin's long-term stability at its highest processing temperature.

In addition, the viscosity of both CTD-101K (epoxy) and CTD-422 (cyanate ester/epoxy blend) were also measured to compare the relative performance of the cyanate ester to other commercially-available insulation products.

B. *Adhesion to Kapton®*

S2-glass-reinforced flat-plate laminates with nominal dimensions of 10-cm x 20-cm x 0.32-cm were fabricated with continuous Kapton® films located within the S2-glass plies. All of the composites produced in this work had a nominal fiber volume content of 50%, and laminates were fabricated with either a Kapton® film at the mid-plane or two Kapton® films located at positions of 1/3 and 2/3 through the thickness of the composite. A S2-glass/CTD-403 laminate with no Kapton® was also produced to provide a measure of baseline material performance.

In each instance, S2-glass fabric and Kapton® films were first placed in a closed mold according to the laminate designs. Next, the mold and resin were de-gassed for at least two hours at 50˚C and at a pressure below 200 mTorr. The de-gassed resin was then transferred into the closed mold using a vacuum-pressure impregnation process. The cure cycle for all test laminates included gelling of the resin at 110˚C for 8 hours followed by a final cure at 150˚C for 4 hours. Heating rates of 0.5˚C/minute were used throughout this work.

After curing, short-beam-shear [7] specimens with dimensions of 2.79-cm x 0.64-cm x 0.32-cm were machined from each laminate. The specimens were mechanically tested to evaluate the adhesion of cyanate ester to Kapton® at temperatures of interest for various fusion machines. Five specimens of each design were tested at 77, 293, and 373 K. A schematic illustration of a short-beam-shear specimen with two Kapton® films is shown in Fig. 1.

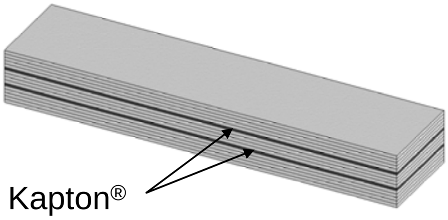

Fig. 1. Design of short-beam-shear test specimen with two Kapton® layers.

C. *Fabrication of Test Coils*

Sub-scale coils were fabricated at the University of Tennessee Magnet Development Laboratory (UT-MDL) by winding copper conductors with S2-glass-tape into configurations that simulate magnet windings. This work included the impregnation of approximately 60-cm-long racetrack coils as well as a larger coil with a circular cross section and diameter of approximately 45-cm. Fig. 2 shows the vacuum-pressure impregnation of a racetrack coil and Fig. 3 shows a circular coil prior to molding and impregnation with CTD-403.

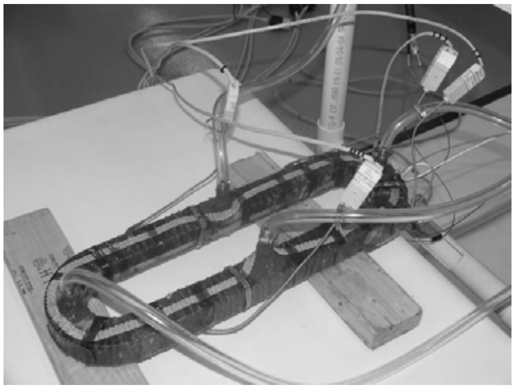

Fig 2. Vacuum pressure impregnation of racetrack coil with CTD-403.

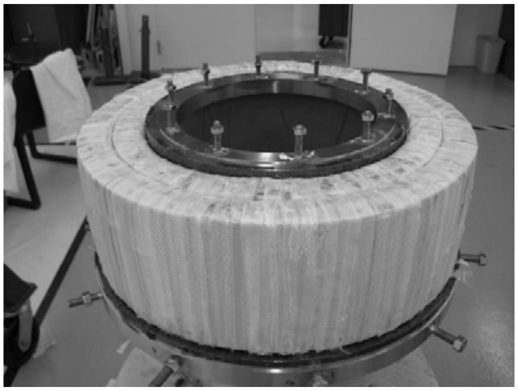

Fig. 3. Copper coil with S2-glass overwrap prior to impregnation.

A removable mold was used to produce the small racetrack coils seen in Fig. 2 to enable inspection of the parts after impregnation. Alternatively, the larger coil (Fig. 3) was enclosed in a stainless steel vacuum shroud prior to impregnation to simulate the process planned for use in fabricating stellarator coils for the QPS [8] program.

III. RESULTS AND DISCUSSION

A. *Viscosity*

As seen in Figure 4, CTD-403 (cyanate ester) has a low viscosity which remained constant throughout the duration of the 85-hour test at 50˚C. This finding is important for the fabrication of large magnets because the resin flow characteristics will remain constant through the impregnation process. The long pot life is especially important for the ITER TF coils as those could take several days to insulate. In addition, this long pot life will also give magnet fabricators more flexibility in magnet design and insulation application process development when producing numerous other magnets currently under development for a variety of applications.

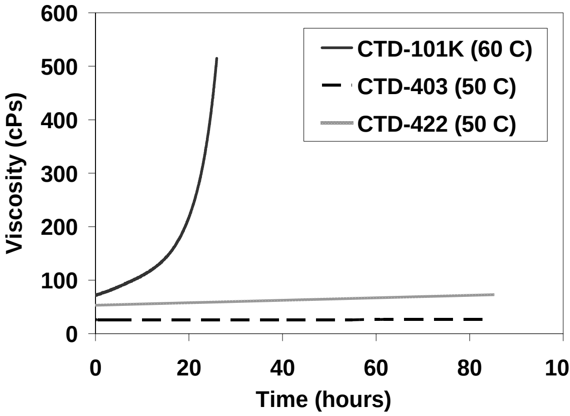

Fig. 4. Viscosity-versus-time behavior of VPI resins.

The viscosity of CTD-403 and CTD-422 (cyanate ester/epoxy blend) both remained relatively constant and below 100 cPs over the 85-hour period. The long working time of these materials is beneficial for the impregnation of large coils, and the overall working time is quite long compared to many other commercially-available products. For example, CTD-101K (epoxy) has a pot life of approximately 24 hours and is regularly used to insulate magnets for fusion, high-energy physics, and various commercial systems.

B. *Adhesion to Kapton®*

Another important consideration in the industrialization of cyanate ester resins is verifying its compatibility with Kapton®. As previously discussed, Kapton® has been used extensively in combination with S2-glass and epoxy resins to insulate a variety of coils.

In this work, short-beam-shear tests were used as a means of assessing the compatibility of Kapton® and cyanate ester resins. Both of the laminates containing Kapton® produced in this investigation were impregnated and cured with no anomalies.

Testing of the short-beam-shear specimens at 77 and 293 K revealed that the shear strength of the composites decreased as the number of Kapton® layers within the assembly was increased. As seen in Fig. 5, the average short-beam-shear strength of the S2-glass/CTD-403 insulation is 104 MPa at 77K. The addition of one Kapton® layer did not significantly alter this strength, but the presence of the second layer decreased the shear strength of the insulation to 92 MPa, or approximately 12%.

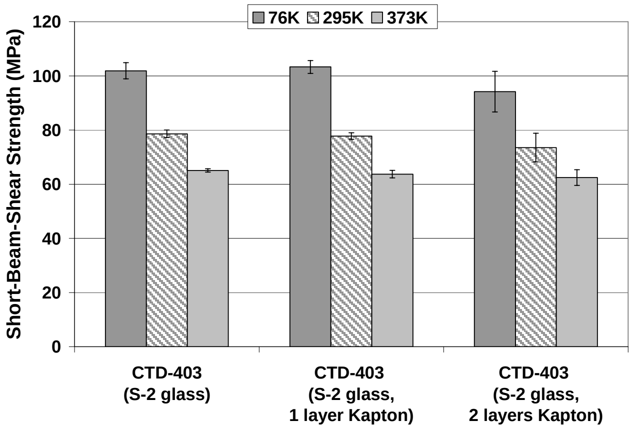

Fig 5. Short-beam-shear strength of cyanate ester/S2-glass insulation with Kapton® films located within the composite laminate.

The shear strength of the insulation specimens with two Kapton® layers integrated into the laminate was also decreased by 10% at 293 K. The reduction in strength at 373 K is less pronounced, likely because the composite strength is closer to the strength of Kapton® at this condition.

Post-test inspection of the short-beam-shear specimens showed that the Kapton® film was uniformly positioned within each test specimen. Additionally, the failures in the laminates containing Kapton® were not due to poor adhesion, but rather the lower strength of the Kapton® itself. Fig. 6 shows a typical example of mechanical failure within a Kapton® film. As seen below, the crack propagated through the Kapton® film while the failed film remained strongly adhered to the CTD-403/S2-glass insulation. The image below is representative of the failures observed in all specimens and at all test temperatures evaluated in this work.

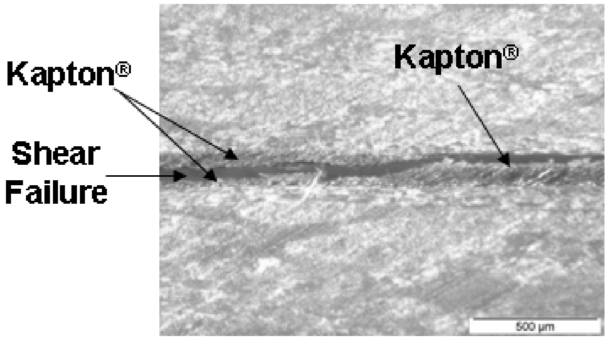

Fig. 6. Typical example of a failure within a Kapton® film embedded within a S2-glass/cyanate ester insulation test specimens.

While increasing the number of Kapton® layers within the composite insulation appears to decrease its overall shear strength, the presence of these layers is integral to the insulation designs currently planned for several fusion machines. Therefore, CTD and the United Kingdom Atomic Energy Authority are further testing the shear strength of cyanate ester insulations with Kapton® layers using torsion and flatwise tensile test specimens. These efforts will provide additional information on the shear strengths of cyanate ester/Kapton® interfaces in a different test configuration. That work is ongoing and expected to be published later this year.

C. Fabrication of Test Coils

The fabrication of test coils is an important step in the industrialization of cyanate ester insulations because these new materials require some processing steps that are different than those used with traditional epoxies. For example, the mix ratio of CTD-403 requires that 100 parts of Part A be blended with 2.13 parts of Part B. In addition, cyanate ester resins are more susceptible to degradation due to contamination, particularly moisture, than epoxies. Finally, the environmental and thermal control required for cyanate esters are more stringent than generally used by industry for epoxies.

Using the results of the above work as a basis, copper test coils were successfully fabricated at UT-MDL. As previously discussed, these test articles were fabricated by vacuum-pressure impregnating copper conductors with S2-glass tape as planned for the QPS machine. The resulting coils possessed a uniform insulation and demonstrated that cyanate esters can be reliably used to impregnate future magnets.

Since these coils were completed, other groups have also demonstrated the use of CTD-403 insulations in industrialization trials. For example, 60-cm lengths of conductor and double-pancake specimens were insulated by Hemmi et al. to evaluate the use of CTD-403 in ITER TF coils [9]. The results of that investigation showed that cyanate esters can be applied to insulate the large magnets planned for ITER. Moreover, those ITER industrialization tests further validated the long pot life of the resin, as well as its use with Kapton® in magnet windings.

Other cyanate ester-insulated coils are currently being developed for use in government and commercial applications. In each of these instances the radiation resistance and high-temperature performance of the resin is considered critical for the long-term success of the devices.

IV. CONCLUSION

The work described herein demonstrates several aspects of cyanate ester performance necessary to qualify these materials for use in large magnet systems. Whereas previous efforts demonstrated the good mechanical strength and radiation resistance of cyanate esters, this work verified the very long pot life of the resin, validated its good adhesion to Kapton® (although the use of Kapton® reduced the overall strength of the insulation), and showed that coils can be successfully impregnated and cured.

Larger-scale industrialization tests are currently ongoing worldwide to further demonstrate the application of cyanate ester insulations in fusion programs such as ITER and MAST, as well as high-energy physics and commercial magnet systems. In several instances, CTD is working with the customer to develop procedures and techniques to apply these resins in industrial environments.

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