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HIGH-TEMPERATURE ELECTRICAL INSULATIONS FOR EGS DOWNHOLE EQUIPMENT

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ABSTRACT

The development of highly reliable downhole equipment is an essential element in enabling the widespread utilization of Enhanced Geothermal Systems (EGS). The equipment used in these systems is required to operate at high voltages and temperatures on the order of 200 to 250°C (and eventually to 300˚C). These conditions exceed the practical operating ranges of currently available thermoplastic wire insulations, and thus limit the operating lifetime of motors, cables, and other high-voltage components used in these systems. This paper describes recent work by CTD in which improved performance in inorganic composite insulations was achieved, and relates the results to the anticipated operating requirements for future EGS equipment.

INTRODUCTION

Geothermal power is currently produced in several nations around the world by utilizing relatively shallow wells. In these locations, energy is produced under nearly “ideal” circumstances, which include porous rock and an ample supply of sub-surface water. For geothermal energy to be more widely utilized, and to tap into the large potential offered by generating power from the heat of the earth, deeper wells will be necessary to reach the hot, dry rock located up to 10 km beneath the Earth’s surface. To utilize this thermal resource, water will be introduced into the well to create a geothermal reservoir. This approach is known as an Enhanced Geothermal System (EGS) [1-2].

Because EGS reservoirs are typically at depths of 3 to 10 km, electric submersible pumps (or ESP’s) will be needed to transport geothermal fluids to the surface. ESP’s are currently used in oil-recovery processes and offer the capability to efficiently transfer fluids to the surface from extreme depths. However, the use of ESP’s in Enhanced Geothermal Systems will require advanced materials and components to enable the long-term operation of these devices at temperatures on the order of 200 to 250°C (and eventually up to 300°C).

For geothermal applications, these insulations must be capable of long-term, high-voltage operation at elevated temperatures, as well as withstanding the bending strains associated with the various cabling and motor-winding processes anticipated during manufacture. This paper describes the fabrication and testing of composite-based insulations, and the performance of these new materials is discussed relative to the known requirements for future EGS systems.

Electrical submersible pumps

In ESP systems, an electric motor and a multistage centrifugal pump run on a production string, connected back to a surface control mechanism and transformer via an electric power cable. The energy to turn the pump comes from a high voltage (3 to 5 kV) alternating current source to drive a special motor that can work at temperatures up to 260˚C, pressures up to 35 MPa, from wells up to 4.5 km deep, and with energy requirements up to 1,000-hp (Figure 1). Submersible two-pole, squirrel cage, induction electric motors are manufactured in a variety of horsepower ratings, operating voltages and currents to meet pressure extremes and temperature requirements. The motor size is designed to lift the estimated volume of production fluid to the surface. Wellbore fluids passing over the motor housing act as cooling agents. The motor is powered from the surface using a submersible electric cable.

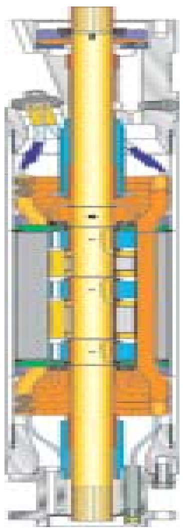

Figure 1. Electric Submersible Pump.

ESP power cables are available in flat or round configurations, specially engineered and manufactured to provide dependability in the harsh, hot, gassy and corrosive conditions found in most downhole environments (Figure 2). The cable is connected to the top of the motor, runs up the side of the pump, is strapped to the outside of every joint of tubing from the motor to the surface of the well, and is extended to the surface to the control junction box. In most cases the cable is flat as it stretches from the motor up beside the pump to the tubing, at which point it is spliced to a round cable.

Most power cables have a metal shield to protect them from damage. Proper selection of cabling can greatly enhance the overall system performance, since substantial power losses can occur in conducting power across a cable that may extend as long as 10 km in geothermal systems.

Temperature extremes and contaminants are primary causes of early motor failure. Completely sealed, a down-hole ESP motor must have exceptional capabilities to dissipate or withstand severe inner core temperatures—requiring high temperature insulation ratings. The method of assembly and quality of the winding, including the pattern, are critical design characteristics. The winding process including the resin used, the application process and the steps taken to prevent voids are critical in constructing a motor that can withstand destructive energies encountered downhole.

Figure 2. Various power cables used with downhole ESP systems.

While ESP's are known to offer excellent downhole performance, the high-temperature reliability of these systems will be an important consideration in determining the overall economic feasibility of EGS. Recently the distribution of failures within ESP systems was presented [3]. As seen in Table 1, the majority of failures occur in the motor (32%), followed by the pump (30%), and cables (21%). As seen below, more than half of all ESP failures occur in either the motor or cable, and as the geothermal application temperatures increase the rate of incidents in these high-voltage components will likely become a larger concern.

At this time, the electrical insulations most commonly used in ESP cables and motor windings are either EPDM (Ethylene Propylene Diene Monomer) or PEEK (Poly Ether Ether Ketone). Among currently-available wires and cables, PEEK-insulated products exhibit the best high-temperature properties. However, the volume resistivity of PEEK decreases rapidly at temperature above 150˚C, and this reduced resistivity leads to a corresponding decrease in insulation performance.

Table 1. Component Failures in ESP Systems.

ESP System Component (Primary Failed Item)	Percentage of Total Failures (%)
Assembly (non-specific)	1
Cable	21
Sensor	1
Gas Handler	1
Motor	32
Pump	30
Intake	4
Seal/Protector	10
Other	1

To address the need for higher-temperature wires and cables needed for EGS applications, CTD is currently developing composite insulation systems comprised of fiberglass reinforcements and inorganic polymers. These insulations are applied using scalable manufacturing methods, and are based on a technology that has already been demonstrated in the production high-field magnets [4,5] and high-temperature heaters for the in-situ production of oil shale [6].

EXPERIMENTAL PROCEDURE

In this work, electrical insulation materials were fabricated into both flat-plate laminates and applied to long lengths of insulated copper wire. The flat-plate laminates were used to establish baseline properties of the candidate insulations, whereas the insulated wires were manufactured to demonstrate the application of this technology in its anticipated configuration. The production of the various insulation materials, as well as the electrical and mechanical test procedures used in this work, is described below.

Fabrication and Testing of Laminates

Laminate fabrication

Flat-plate composite laminates were produced using S2-glass fabric and CTD-1200-series resins. In each instance, the polymeric material is an inorganic resin system selected due to its good high-temperature properties and processing characteristics. All of the inorganic polymers are based on thermosetting inorganic polymer chemistries, with modifications made to further improve the strain tolerance and high-temperature electrical performance. The laminates were fabricated using a wet lay up process, and cured under an applied pressure of 3.5 MPa and at a temperature on the order of 150°C. Glass-fiber reinforced parts with nominal thicknesses of 0.5 mm and 3.2 mm, were produced for mechanical and electrical testing, respectively.

Electrical testing

Electrical characterization of the 0.5-mm-thick materials included measurement of both the dielectric breakdown strength and insulation resistance at temperatures ranging from 25 to 250˚C.

Dielectric breakdown testing is a destructive procedure in which an increasing DC voltage is applied across the thickness of the insulator until failure occurs. Next, the Dielectric Breakdown Strength (in kV/mm) and Electrical Strength Constant (in kV/mm$^{1/2}$) were calculated using the measured breakdown voltage and insulation thickness [7].

Electrical resistivity (in Ω–cm) was calculated by measuring the leakage current as a function of applied voltage across the thickness of the specimens. In this procedure, the voltage was increased from 0 to 6 kV and the current was measured at each 1 kV increment. Resistivity was then calculated using the measured current-voltage relationship and the specimen geometry.

Stress-strain testing

Once produced, 15.9-mm x 127-mm flexure test specimens were machined from the 3.2-mm thick laminates. For this testing, the specimens were machined so that the fiber reinforcement has a ±45 orientation within the test article. This orientation approximates the fiber angles that will be used to produce the insulated wires, and is therefore more representative of the ESP cable application.

Next, the stress-strain characteristics of the composite specimens were determined at 25˚C using a four-point bending test [8]. A photograph showing the test hardware used in this work, as well as a specimen under test, is given in Figure 3.

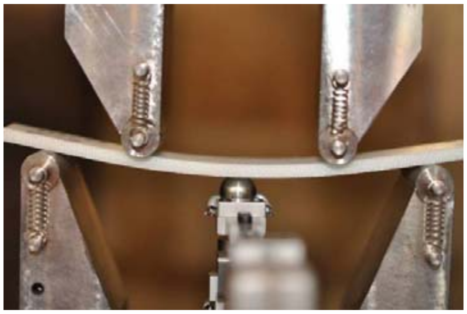

Figure 3. Four-point loading of a composite insulation specimen.

As test data became available, the insulations exhibiting the best combinations of dielectric strength and strain tolerance were selected for continued development and optimization. This included applying the insulations onto lengths of copper wire and testing the insulated wires to ensure that the performance was achieved in this configuration.

Production and Testing of Insulated Wires

Insulation application processes

Two methods of applying the insulation were evaluated in this investigation, namely braiding and taping. Both of these processes are commonly used in industry and each has merits for use in the production of wires and cables for ESP systems. In general, braiding allows for the uniform production of thin insulations, whereas taping is used to produce thicker insulations at higher line speeds.

In this work, braided fiberglass was applied to approximately 200 meters of copper wire at a thickness of 0.07 mm. After the braid was produced, an inorganic resin was applied to the wire using a reel-to-reel process. As seen in Figure 4, the insulation application method involves the transport and of the wire (with fiberglass braid) through a reservoir containing an inorganic resin. The insulated wire is then heated in-line to cure the resin and the wire was spooled for future use.

Whereas braiding involves the weaving of fiber reinforcements directly onto the wire, taping involves the application of a woven-glass textile. In this work, a 2.54-cm wide S2-glass tape pre-impregnated with CTD-1202 resin was applied to the wire and cured using a continuous process. The tape was overwrapped to ensure that the wire was completely covered and to achieve the target thickness. Figure 5 illustrates the application of the pre-impregnated tape onto a copper wire, as well as a spool of insulated wire insulated using this process.

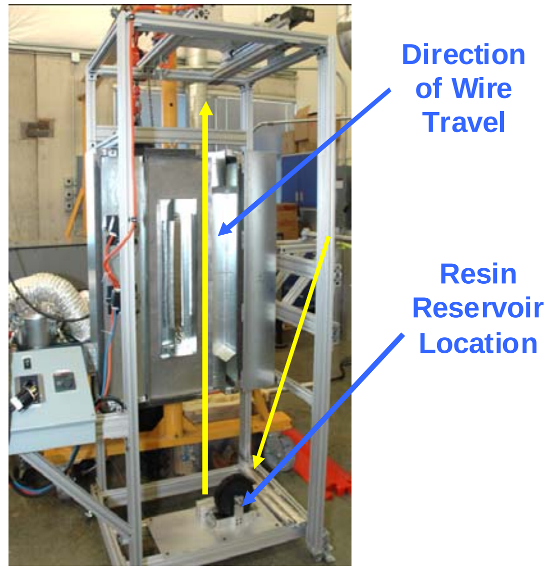

Figure 4. Apparatus for continuous application of insulation onto copper wire.

Figure 5. Application of prepreg tape insulation to copper wire (left) and spool of insulated wire (right).

Electro-mechanical testing of insulated wires

Once produced, the dielectric breakdown strength and resistivity of the wire insulation was measured using the test procedures and equipment previously used to characterize the flat-plate laminates.

In addition to electrical testing, a low-cycle fatigue test was developed in which insulated wires were mechanically cycled at bending strains ranging from 0.5 to 2.0%. The wires were then subjected to either 0.5 or 100 full cycles, where half of a cycle represents one deflection with the specimen returned to the neutral plane. These flexure tests were performed at 25˚C since that is the nominal temperature at which these deformations would occur during both the manufacture and handling of wires and cables. One complete flexure cycle is illustrated below in Figure 6.

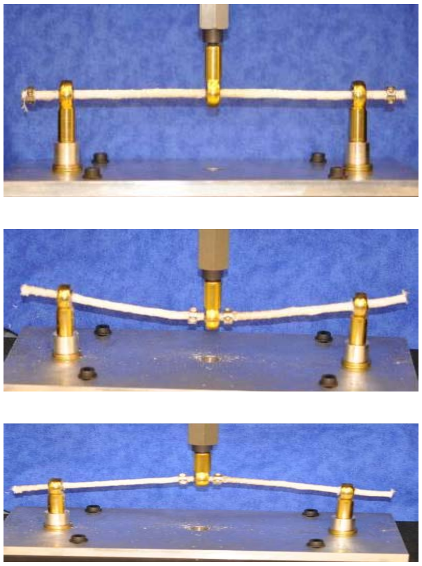

Figure 6. Mechanical cycling of insulated wires.

RESULTS AND DISCUSSION

Properties of Candidate Insulations

Initially, the dielectric strengths of several candidate materials were evaluated at both 25 and 300˚C. Overall more than 20 different materials were tested and five were selected for continued development. In each instance, the insulation identified for continued optimization provided a dielectric strength greater than 20 kV/mm and possessed processing characteristics (e.g., viscosity and pot life) that were suitable for large-scale wire production.

Stress-Strain Behavior of Insulation Materials

After identifying materials that provide suitable electrical properties, the stress-strain behavior of each candidate insulation was tested to ensure that the material would be suitable for use in wire and cable applications. As previously discussed, these specimens were fabricated at a nominal thickness of 3.2 mm using the same manufacturing process as the electrical test articles.

As seen in Figure 7, all of the CTD-1200-series high-temperature insulation materials exhibit stress-strain behaviors that are less than that of PEEK. The CTD-12010XC and CTD-1215 XPC insulations show low stresses at bending strains on the order of 1 to 2.5%, but all are capable of withstanding the spooling and wire manipulation expected during the manufacture of ESP components.

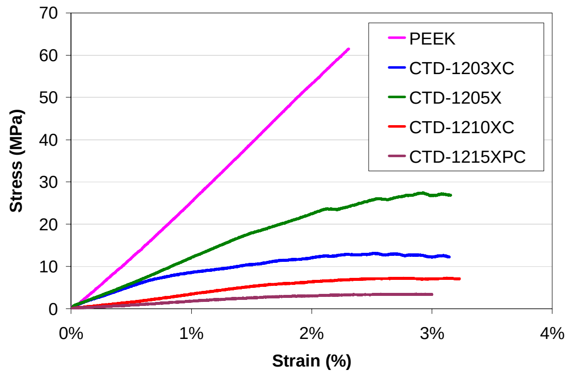

Figure 7. Stress-strain behavior of candidate insulations at 25˚C.

Properties of Insulated Wires

Based on the results of the preliminary investigations, all of the aforementioned composite insulation systems were applied to solid copper wires so that the insulation performance could be evaluated in its intended format. In this work, the insulations were applied onto 8-AWG copper wire in combination with a 0.07-mm-thick S2-glass braid. Once produced, the electrical properties of the insulations were tested at 250˚C.

In addition, the electro-mechanical fatigue properties of a taped CTD-1200 series insulation were also evaluated. In this instance, the composite insulation was applied at a thickness 1.2-mm, and the resulting wires combination was subjected to low-cycle fatigue tests at ambient temperature. The results of these various tests are presented below.

Dielectric properties of braided insulations at 250˚C

As shown in Table 2, all of the insulation systems evaluated in this work exhibit reasonable dielectric properties for use in high-temperature ESP systems. This includes both high dielectric breakdown strengths, as well as high electrical resistivities, at 250˚C. In this work, the three best composite insulations possessed average dielectric breakdown strengths ranging from 67 to 79 kV/mm, and resistivities in excess of 467 GΩ-cm.

Table 2. Dielectric Properties of Candidate Insulations on Copper Wire at 250˚C.

	CTD-1202	CTD-1203XC	CTD-1205X	CTD-1210XC	CTD-1215XPC
Breakdown Voltage (kV)	22.2	**42.4**	**31.2**	37.7	**35.1**
Dielectric Strength (kV/mm)	40.7	**69.7**	**67.0**	61.3	**79.1**
Electrical Strength Constant ($kV/mm^{1/2}$)	30.0	**54.3**	**45.7**	41.2	**52.7**
Resistivity @ 5 kV (GΩ-cm)	286	**512**	**670**	234	**467**

In similar testing, the dielectric breakdown strength of PEEK was found to be approximately 10 kV/mm, and the electrical resistivity on the order of 15 GΩ-cm, at 250˚C. Thus, when compared to PEEK at this same temperature, all of the composite insulations presented in Table 2 exhibit superior electrical performance to the thermoplastic insulation.

In addition, post-test inspection of the PEEK specimens showed that the thermoplastic material deformed considerably during the high-temperature test procedure. This behavior is shown in Figure 8 (left) and the position on the PEEK-insulated wire where the electrode was attached is clearly visible. It is evident from this image that the thermoplastic material deformed when exposed to the high-temperature test condition, and similar deformations could occur in motor windings if operated at these temperatures. The condition of the as-received wire with PEEK insulation is also shown in Figure 8 for reference. Alternatively, the composite insulations retained their dimensional stability during the exposure to the 250˚C test condition. Note all of the CTD composite insulations evaluated in this work possessed a similar post-test appearance to that seen below.

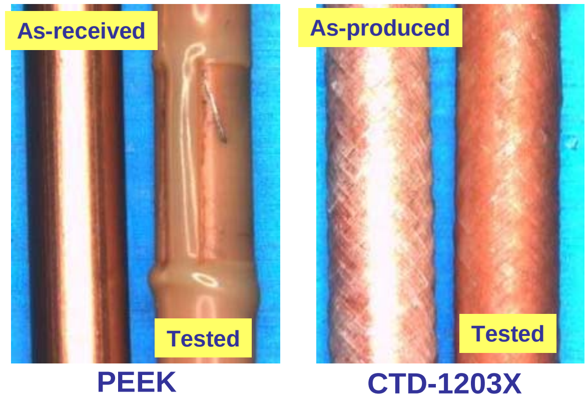

Figure 8. Condition of PEEK (left) and CTD-1200 series (right) insulated wires before and after testing at 250˚C.

Electro-mechanical performance

Finally, low-cycle mechanical fatigue tests, followed by dielectric breakdown tests, were performed to evaluate the effects of repeated strain applications to the taped CTD-1200 series composite insulation. As seen previously in Figure 6, these tests were conducted by placing short segments of insulated wire into a three-point loading configuration and deflecting the wire to achieve the desired strain.

Before enduring any mechanical strain, the Electrical Strength Constant of the 1.2-mm thick taped insulation was 25 $kV/mm^{1/2}$, which provides a good operating margin for the 3-5 kV operating voltage anticipated for most ESP applications. After mechanical fatigue cycling, the Electric Strength Constant of the insulation was tested at 25˚C. As seen in Figure 9, the performance of the insulation was essentially unchanged after repeated cycling at all three strain conditions. It should be noted that when cycling the insulated wire to 2% strain, the copper wires failed after approximately 60 cycles. However, subsequent dielectric testing indicated that the insulation at adjacent positions along the wire was not negatively affected by the repeating mechanical cycling. That data set is denoted with an asterisk (*) in the chart below.

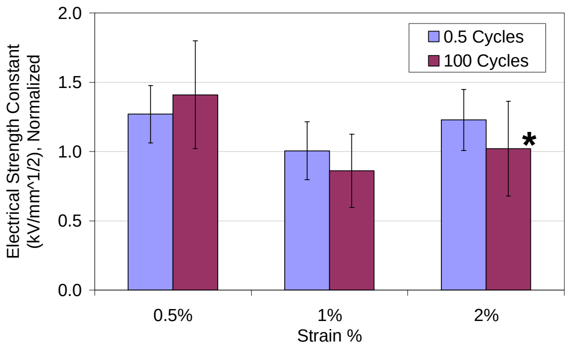

Figure 9. Normalized electrical strength constants of insulation after cyclic loading.

In this example, the insulation was applied using a prepreg taping process. Future work will include similar testing of additional resin systems combined with braided reinforcements.

FUTURE PLANS

The next steps in the development and demonstration of high-temperature insulations will include the fabrication and testing of sub-scale motor windings and engineered cables. In each instance, the insulated wires will be integrated into test articles that simulate the strains and configurations currently used in downhole equipment.

The first of these trials involves the fabrication of small motor windings, referred to as statorettes. As seen in Figure 10, these windings possess the same geometry as the motors used in Electric Submersible Pumps and thus enable the insulated wires to be tested in a meaningful configuration. In this instance, the statorettes will be wound using braided insulation to minimize the thickness of the dielectric material, and thus maximize the volume of conductor within the winding.

After winding, CTD will test these statorettes to a protocol provided by Wood Group ESP. Upon successfully passing these test protocols with statorettes, CTD plans to work with Wood Group ESP to build larger prototype motors and cables for qualification testing and consideration for incorporation into motor products.

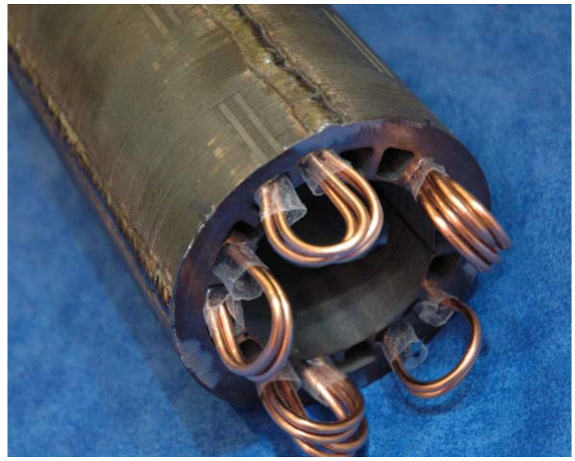

Figure 10. Example of statorette wound with PEEK-insulated wire.

In addition to fabricating motor windings, plans also exist to fabricate lengths of three-phase cable. The insulation in downhole cables can be thicker than that used in motors, so both braided and taped insulations will be considered in producing the prototype cables. It is anticipated that these cables will be on the order of 30-meters in length.

CONCLUSIONS

Over the course of this work, inorganic composite insulations were fabricated and tested relative to the known requirements for use in ESP equipment. Applications in both motor windings and motor lead extensions were considered. In each instance, the insulations were found to provide improved performance to thermoplastic insulations at temperatures up to 250˚C. These findings are important for future EGS applications because of the high temperatures present in these wells, and the need to ensure the reliability of the downhole equipment used in the generation of power from these resources.

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