

A New Ductile, Tougher Resin for Impregnation of Superconducting Magnets

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Abstract

A major remaining challenge for Nb₃Sn high field magnets is their training due to random temperature variations in the coils. The main objective of our research is to reduce or eliminate it by finding novel impregnation materials with respect to the epoxies currently used. An organic olefin-based thermosetting dicyclopentadiene (DCP) resin, C₁₀H₁₂, commercially available in Japan as TELENE[®] by RIMTEC, was used to impregnate a short Nb₃Sn undulator coil developed by ANL and FNAL. This magnet reached short sample limit after only two quenches, compared with 50+ when CTD-101K[®] was used. Ductility, i.e. the ability to accept large strains, and toughness were identified as key properties to achieve these results. In addition, we have been investigating whether mixing TELENE with high heat capacity ceramic powders, increases the specific heat (C_p) of impregnated Nb₃Sn superconducting magnets. The viscosity, heat capacity, thermal conductivity, and other physical properties of TELENE with high-C_p powder fillers were measured in this study as a function of temperature and magnetic field. Mixing TELENE with either Gd₂O₃, Gd₂O₂S, and HoCu₂ increases its C_p tenfold. We have also investigated the effect on the mechanical properties of pure and mixed TELENE under 10 Gy+ of gamma-ray irradiation at the Takasaki Advanced Radiation Research Institute in Takasaki, Japan. Whereas both TELENE-82wt% Gd₂O₃ and TELENE-83wt% HoCu₂ performed well, the best mechanical properties after irradiation were obtained for TELENE-87wt%Gd₂O₂S. Testing a short undulator in the future with the latter impregnation material will verify whether it will further improve the coils' thermal stability. Short magnet training will lead to better magnet reliability, lower risk and substantial saving in accelerators' commissioning costs.

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Keywords: Superconducting magnet, training, dicyclopentadiene, resin impregnation, specific heat

1. Introduction

One of the main challenges of Nb₃Sn high field accelerator magnets for HEP is their training [1]. Superconducting (SC) magnets go back to being resistive from their superconducting state, i.e. “quench”, when their temperature increases above the current sharing temperature of the composite superconductor over a large enough volume. The temperature increase ΔT is proportional to Q/C_p , where Q is the dissipated heat, and C_p is the volumetric heat capacity. Energy deposition that initiates quenches can emanate from a variety of both mechanical and electromagnetic sources (magnetic flux jumps, conductor motion, epoxy cracking, etc.). Other sources of magnet training are material interfaces, such as between conductor, insulation, impregnating material, and neighboring structural materials. All these sources contribute to a resulting “disturbance spectrum”.

Long training has been a feature of any Nb₃Sn impregnated magnet for decades, since the start of the development of this technology, and any attempt made during this time to at least reduce magnet training failed. We show here almost total training elimination when using as coil impregnation material for a Nb₃Sn magnet C₁₀H₁₂, an organic olefin-based thermosetting dicyclopentadiene (DCP) resin, in replacement of the CTD-101K[®] epoxy currently used for this purpose. This resin is commercially available as TELENE[®] by RIMTEC Corporation, Japan, and its molecular structure is shown in Fig. 1, left. It was used to impregnate a Nb₃Sn short undulator model, which reached short sample limit (SSL) after only two quenches, compared with 50+ when CTD-101K (Fig. 1, right) was used on a number of identical undulator coils. TELENE’s pot life of up to 3.5 hours at 5°C ensures scalability to impregnate larger coil volumes. The undulator magnet with 9 racetrack coils between 10 poles was wound at ANL [2]. After the winding was complete, the magnet was assembled into its reaction tooling to be heat treated in argon at FNAL using well established treatment cycles. It was then vacuum impregnated with pure TELENE at ANL, and later tested at FNAL in the Superconducting R&D lab [3].

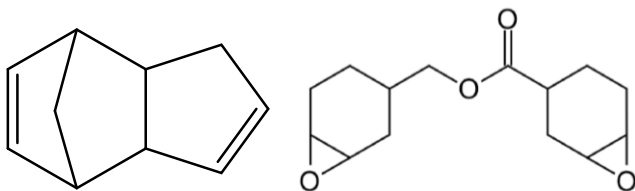


Fig. 1. Schematic of TELENE[®], or C₁₀H₁₂, molecular structure (left); and of CTD-101 K epoxy, or C₂₁H₂₅ClO₅ (right).

To further improve thermal stability and training in accelerator magnets, the idea of increasing superconductor’s stability, usually based on its Minimum Quench Energy (MQE), by inserting high specific heat (high- C_p) elements in superconducting wires dates back to the 1960s [4]. Then in the mid-2000s, a considerable improvement in stability to pulsed disturbances was obtained for NbTi windings, when distributing large heat capacity substances on the conductor during winding [5, 6]. The MQEs of the brushed coils were several times higher, and thermal efficiency was greatest for temperature diffusion times much smaller than the disturbance pulse duration. A few years ago, Hypertech and Bruker-OST have attempted to introduce high- C_p elements in their wire design [7]. More recently, Hypertech fabricated samples of a thin composite Cu/Gd₂O₃ tape, which can be inserted in Rutherford-type cables to increase the conductor C_p [8]. At NIMS and RIMTEC, TELENE was mixed with high- C_p ceramic powders such as Gd₂O₃, Gd₂O₂S and HoCu₂ [9]. The C_p temperature dependence for TELENE mixed with HoCu₂, and the C_p temperature dependence as a function of magnetic fields were measured for TELENE mixed with Gd₂O₃, and Gd₂O₂S. NbTi superconducting wire samples impregnated with these resins were characterized and studied at FNAL by performing Minimum Quench Energy measurements.

The radiation strength of insulating materials used in superconducting accelerator magnets is another key specification. The common limit of the Hi-Lumi LHC type magnets is 25 MGy of proton radiation for CTD-101K epoxy. In 2016 the resistance to Cobalt-60 gamma radiation was studied for DCP and epoxy resin bisphenol-A up to a dose of 3.3 MGy with a dose rate of 2 kGy/h [10]. By measuring and analyzing optical absorption, electrical conduction, dielectric and thermal properties, it was shown that the organic DCP resin had a superior gamma ray resistance with respect to the epoxy. For nonorganic materials, there is a dependence of material response on the type of beam irradiation. However, such a dependence is quite modest for organic materials, and the absorbed dose can be adequately used to qualify their radiation resistance. Therefore, resistance to gamma irradiation is a promising indicator to radiation strength and a Cobalt-60 gamma ray irradiation experiment is being run at an average dose rate of 8 kGy/h at the Takasaki Advanced Radiation Research Institute [11], which is part of the National Institutes for Quantum Science and Technology (QST) in Takasaki. Here we present results of mechanical properties of pure and mixed TELENE before and during irradiation up to about 10 MGy.

2. Experiment Description

In this Section, we will describe the experimental setups used for mixing the TELENE with high- C_p ceramic powders

at NIMS (2.1); for measuring the resins' physical and mechanical properties at NIMS and KEK (2.2); for measuring the MQE of NbTi wire samples impregnated with the resins at FNAL (2.3); for fabricating and testing Nb₃Sn undulator short models impregnated with TELENE at ANL and FNAL (2.4); and for the Cobalt-60 gamma ray irradiation experiment at the Takasaki Advanced Radiation Research Institute (2.5).

2.1 Fabrication of high- C_p resins and optimization of their composition

The high heat capacity resins are fabricated by combining a ceramics powder filler with TELENE using a planetary mixer. The TELENE is then mixed with a hardener or polymerization catalyst, which is a ruthenium complex, in 2/100 parts by wt. The curing time is controlled by the amount of phosphine derivatives as retardant. The viscosity of the resins is controlled by the volume fraction and average size of the powder filler. Therefore, the chemical composition, average powder size and volume fraction can be optimized. Using a Gd₂O₃ powder size of 0.7 to 1.2 μm , TELENE was mixed using three different concentrations, i.e. 45wt%, 61wt%, and 82wt%. Using a Gd₂O₂S powder size of 10 μm , TELENE was mixed using seven different concentrations between 58wt% to 88wt%.

Because of its high- C_p and also smaller mass attenuation coefficient than Gd for thermal neutrons, in 2021 NIMS fabricated the first HoCu₂ powder by gas atomization, obtaining a particle size of 80 μm . A particle size of less than 30 μm was eventually achieved using a standard melt and casting process followed by a first stage grinding with a jaw crusher machine, and a second stage finer grinding with a planetary mill machine. The produced powder (Fig. 2) was used as a filler for TELENE with an 83wt% concentration.



Fig. 2. Micrograph of the HoCu₂ particles produced by a standard melt and casting process.

2.2 Measurements of physical and mechanical properties of each resin

Physical properties of the resins, such as viscosity, thermal conductivity, and specific heat C_p were measured at appropriate temperatures.

The viscosity was measured with a Brookfield-type viscometer, specifically an Eiko DV2T. Using a spindle speed of 60 rpm, a spindle of type LV-02 was used to measure viscosity values larger than 1 Pas, and one of type LV-04 to measure viscosity values lower than 1 Pas. The viscosity of TELENE was measured at 25°C, and that of CTD-101K at 60°C.

The C_p and thermal conductivity were measured with a DynaCool® Physical Property Measurement System (PPMS) by Quantum Design. The C_p temperature dependence for TELENE mixed with HoCu₂, and the C_p temperature dependence as a function of magnetic field were measured for pure TELENE and TELENE mixed with Gd₂O₃, and Gd₂O₂S.

The mechanical properties that were measured for the resins include flexural modulus and flexural strength at room temperature.

The flexural modulus was obtained from the stress vs. strain curve between 0.05% strain and 0.25% strain.

The flexural strength was obtained through a 3-point bending test, of which a picture and schematic are shown in Fig. 3. These tests follow ISO 178:2010-A1:2013. Sample size is 80 mm in length, 10 mm in width and 4 mm in thickness. The flexural tests were performed at room temperature. The flexural strength is the maximum stress in the stress vs. strain curve. The tensile machine used were an Autograph AG-5000C manufactured by Shimadzu.

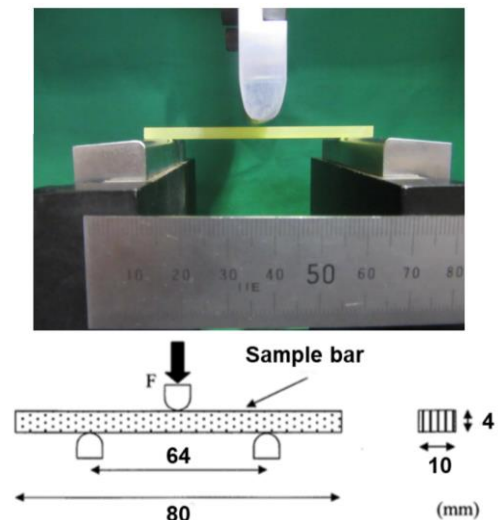


Fig. 3. Picture (top) and schematic of 3-point bending test (bottom).

2.3 Stability measurements of superconducting wire samples impregnated with high- C_p resins

Two sets of six 0.8 mm NbTi wire samples were prepared at FNAL and sent to NIMS for impregnation with TELENE only, TELENE-82wt%Gd₂O₃, and TELENE-87wt%Gd₂O₂S resins. The MQE of impregnated wires is measured on

ITER-type barrels. Two strain gauges of 4 mm and 1.5 mm length and width are used as 350 Ω heaters and glued to each sample using STYCAST 2850FT. The instrumentation wires are soldered before sample and strain gauges receive resin impregnation. Fig. 4 shows pictures of instrumented NbTi wires after impregnation with TELENE and mixed TELENE.

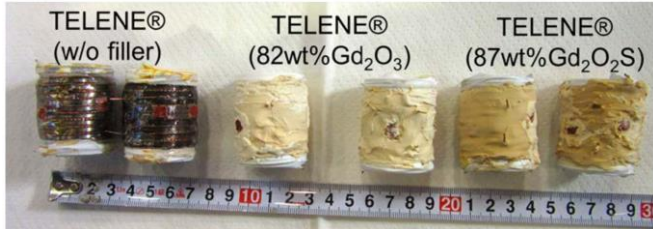


Fig. 4. Picture of TELENE impregnated NbTi wire samples instrumented with two heaters each, and with the voltage taps attached.

A 200 W power supply provides the excitation voltage to the strain gauges. Using a LabView DAQ program, a pulse output is generated from the power supply and the voltage across the strain gauge is measured. With the I_c of the sample first measured, a constant bias current below I_c is applied to the sample and heat pulses are fired using the strain gauge. A separate quench protection system monitors the voltage across the sample and shuts down the power supply if the quench threshold is reached. By gradually increasing the pulse energy, the minimum energy that induces a quench is defined as the MQE of the sample [8]. In order to determine the most appropriate pulse duration range for each resin, the characteristic time, or thermal time constant τ , was calculated as $\tau = 4 a^2/(\pi^2 D)$, where $D = k/(\rho C_p)$ is the thermal diffusivity, k the thermal conductivity, ρ the material's density, and $2a$ the material's thickness. The thermal properties shown in Table 1 were obtained by using $a = 1$ mm, $\rho(\text{STYCAST 2850FT}) = 2290$ kg/m³, $\rho(\text{TELENE}) = 1030$ kg/m³, $\rho(\text{TELENE-82wt\%Gd}_2\text{O}_3) = 3504$ kg/m³, and $\rho(\text{TELENE-87wt\%Gd}_2\text{O}_2\text{S}) = 4110$ kg/m³. Based on the results for τ , the MQE was measured for heater pulse durations from 200 ms to 1.5 s.

TABLE 1: Thermal properties of TELENE resins

@4.2 K	k W/(mK)	C_p J/(kg K)	D m ² /s	τ s
STYCAST 2850FT	0.05	0.44	$500.0 \cdot 10^{-7}$	0.008
TELENE	0.04	3.5	$111.0 \cdot 10^{-7}$	0.037
TELENE-82%Gd ₂ O ₃	0.02	20	$2.9 \cdot 10^{-7}$	1.420
TELENE-87%Gd ₂ O ₂ S	0.09	60	$3.7 \cdot 10^{-7}$	1.111

2.4 Fabrication and testing of Nb₃Sn undulator short model

In collaboration with FNAL and other labs, ANL developed a Nb₃Sn undulator to be installed in the Advanced Photon Source (APS) storage ring. Performance reproducibility close to 100% short sample limit was obtained by using several Nb₃Sn short models during the R&D phase. They were vacuum impregnated with CTD-101K, which is the same epoxy used for Nb₃Sn high field accelerator magnets. The same performance and reproducibility were later achieved on longer models. The training behavior of the undulator models was very similar to that of High-Energy Physics accelerator magnets, sometime requiring almost 100 quenches to approach short sample limit [2].

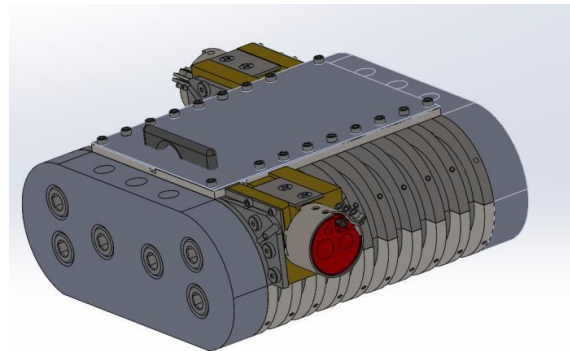


Fig. 5. 3D model of ANL undulator design.

These Nb₃Sn undulators with 18 mm period operate at a maximum magnetic field on the conductor of about 5 T. To address instabilities at this field, a Restacked Rod Processed (RRP) wire of 0.6 mm in diameter and with 144 superconducting subelements over 169 total subelements was used. Its equivalent subelement diameter is ~ 35 μm , and the critical current density J_c (4.2K, 12 T) is about 2500 A/mm². Each Nb₃Sn undulator short model has nine racetrack coils wound in a groove between ten poles. There are 46 turns in each groove, and each period includes two grooves and two poles. The S2-glass braided Nb₃Sn wire is continuously wound turn-by-turn between the poles. A 3D model of the design is shown in Fig. 5.

After winding, the magnet was assembled into an existing reaction tooling. The magnet model was heat treated at FNAL in argon atmosphere in a 3-zone controlled tube furnace, using well-established treatment cycles [12]. Table 2 shows the nominal temperature values compared with the measured oven temperature. The temperature was averaged between two K-type calibrated and ungrounded thermocouples. Several witness samples of the same Nb₃Sn wire used in the coil were included in the furnace. Their critical current I_c was determined from measuring the V-I curve using an electrical field criterion of 0.1 $\mu\text{V}/\text{cm}$. The

calculation of the expected coil short sample limit is obtained by intersecting the average I_c of these samples as function of the magnetic field with the magnet load line.

TABLE 2: Nominal vs. obtained heat treatment cycle for undulator short model impregnated with TELENE

Nominal		Obtained	
Time, h	T , °C	Time, h	T_{Ave} , °C
48	210	48	207
104	370	104	365
50	650	50	647

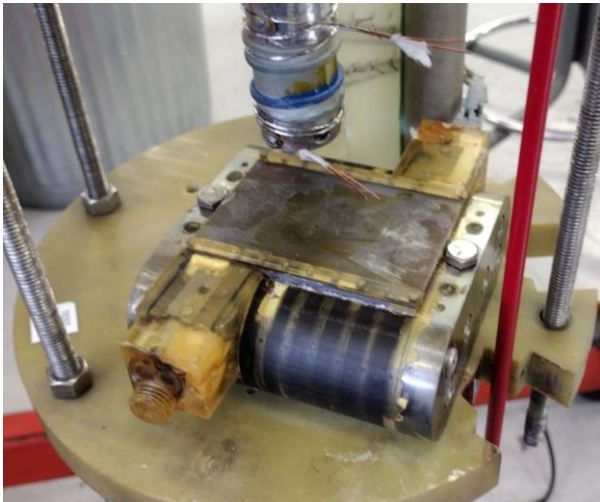


Fig. 6. Picture of the first TELENE impregnated Nb_3Sn small undulator attached to its test insert.

After winding and heat treatment, the magnet was vacuum impregnated at ANL. The undulator was later tested at FNAL at 4.2 K in liquid helium at atmospheric pressure, in a cryostat of the Superconducting R&D lab, by using an insert equipped with 2000 A DC leads. Fig. 6 shows the TELENE impregnated magnet attached to the test insert. Two pairs of voltage taps, each covering half of the magnet, were used. The voltage tap wires were connected to an NI-9239 card of a compact RIO DAQ system. The NI card has 4 channels with an acquisition frequency of 50 kHz and 24 bits per channel. The threshold for the quench protection system was 100 mV for the differential voltage. When a quench is detected, the power supply is stopped, an IGBT (insulated gate bipolar transistor) switch opens and the current flows into a 0.125Ω dump resistor, where the coil energy gets dissipated.

2.5 Gamma ray irradiation experiment

Gamma Ray irradiation is being performed at the Takasaki Advanced Radiation Research Institute using a Cobalt-60 gamma irradiation facility. Thirtysix (36) samples each of pure TELENE, TELENE mixed with 82wt% Gd_2O_3 , with 87wt% Gd_2O_2S , and with 83wt% $HoCu_2$ are being

irradiated in air atmosphere at an average absorbed dose rate of 8 kGy/hr. Samples of CTD-101K epoxy were also included to verify the accuracy of the results. Fig. 7 shows the samples in their aluminum crate. The final goal for the entire irradiation campaign is to achieve 20 MGy+. Every month from start of irradiation, three samples of each resin were extracted from their aluminum rack and a 3-point bending test was performed at room temperature. Here we present results of mechanical properties of pure and mixed TELENE before and during irradiation up to about 10 MGy.



Fig. 7. Picture of aluminum crate containing the resins to be gamma ray irradiated in air atmosphere.

For nonorganic materials, there is a dependence of material response on the type of beam irradiation. However, such a dependence is modest for organic materials, and the absorbed dose can be used to qualify their radiation resistance. At a later stage, this could be confirmed with proton beam irradiation experiments at the BLIP facility at BNL.

3. Results and Discussion

TELENE was chosen for these studies because of the following main reasons: 1. Its ductility, i.e. the ability to accept large strains; 2. Its toughness, i.e. the amount of energy per unit volume that the material can absorb before rupturing, or the area underneath the stress vs. strain curve; 3. Its potential for radiation resistance. Fig. 8 shows how much more ductile and how much tougher is pure TELENE with respect to CTD-101K epoxy. Further, the potential of improving TELENE's thermal properties by mixing it with high- C_p ceramic powders is a third strong component of interest for our study.

In this Section, we will present and discuss the results obtained for the resins' physical and mechanical properties (3.1.1 and 3.1.2); for the MQE of $NbTi$ wire samples impregnated with the resins (3.2); for the TELENE impregnation and test of the first Nb_3Sn undulator short model, which includes impregnation process scalability

(3.3.1), magnet short sample limits (3.3.2), and magnet test results (3.3.3); and for the Cobalt-60 gamma ray irradiation experiment up to 10 MGy at the Takasaki Advanced Radiation Research Institute (3.4).

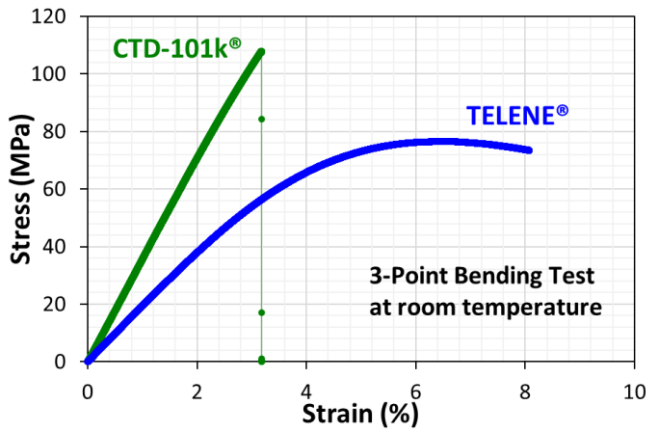


Fig. 8. Comparison of stress vs. strain curve between CTD-101K epoxy and TELENE resin at room temperature.

3.1 Measurements of physical and mechanical properties of each resin

3.1.1 Physical properties. Figs. 9 and 10 show respectively the thermal conductivity and specific heat as function of temperature for pure and mixed TELENE resins in absence of an external magnetic field. The specific heat as function of temperature at various external magnetic fields is shown in Fig. 11 for pure TELENE, in Fig. 12 for TELENE-45wt%Gd₂O₃, and in Fig. 14 for TELENE-87wt%Gd₂O₂S. The latter mixed resin has the largest thermal conductivity over the whole temperature range and a peak in C_p between 4.3K and 5.3K at fields between 0 and 8 T. Pure TELENE has a C_p which increases monotonically with temperature. Beyond 6K, the C_p of pure TELENE is larger than that of TELENE mixed with Gd₂O₃ at any magnetic field.

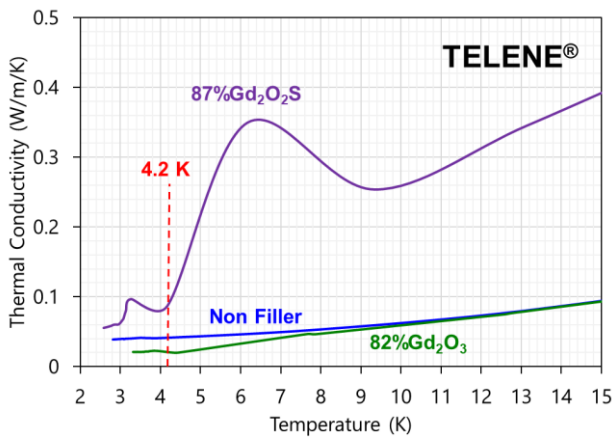


Fig. 9. Thermal conductivity vs. temperature for pure and mixed TELENE resins in absence of external magnetic field.

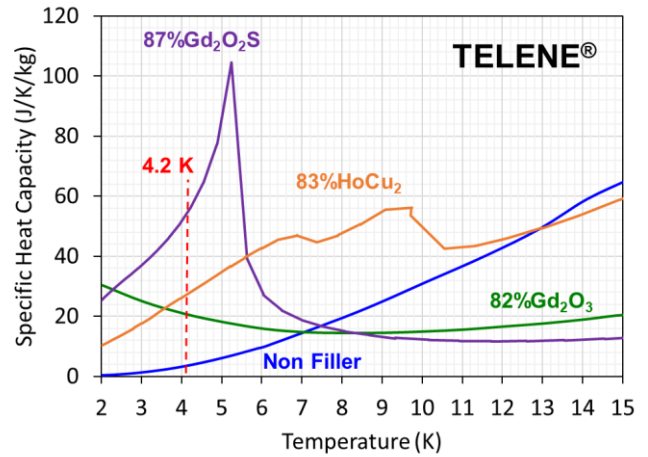


Fig. 10. Specific heat vs. temperature for pure and mixed TELENE resins in absence of external magnetic field.

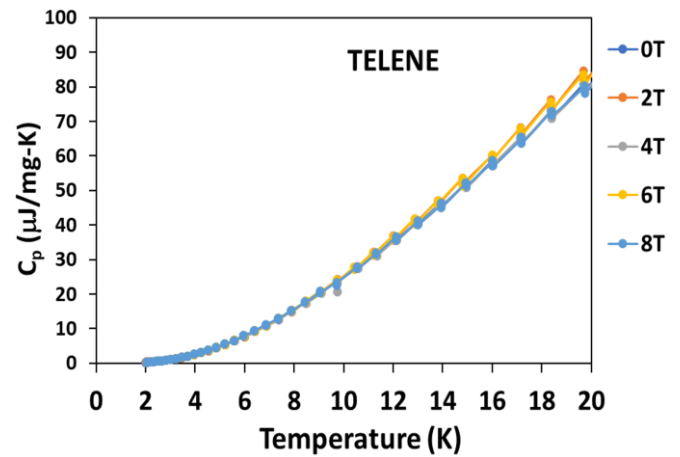


Fig. 11. Specific heat C_p vs. temperature at various external magnetic fields for pure TELENE resin.

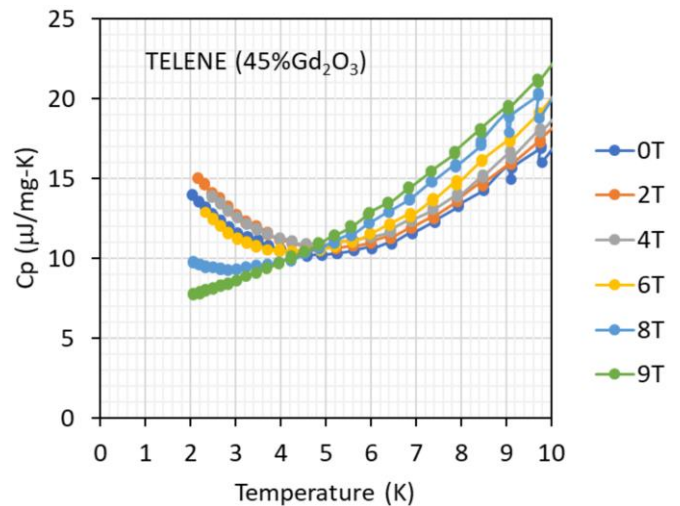


Fig. 12. Specific heat C_p vs. temperature at various external magnetic fields for TELENE-45wt%Gd₂O₃ mixed resin.

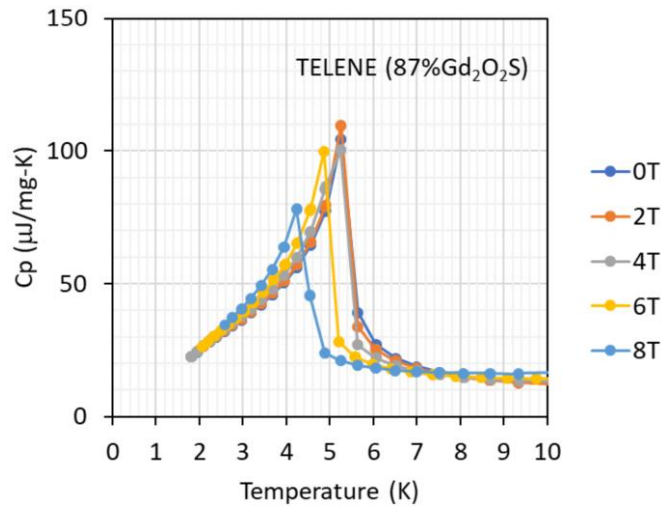


Fig. 13. Specific heat C_p vs. temperature at various external magnetic fields for TELENE-87wt%Gd₂O₂S mixed resin.

3.1.2 Mechanical properties. The flexural stress vs. strain curves for pure and mixed TELENE resins are shown in Fig. 14. After mixing the TELENE with hard ceramic particles, the material becomes stronger, i.e. larger flexural modulus, and less ductile. On the other hand, as seen in 3.1.1, some of the TELENE mixed resins feature larger thermal conductivity and specific heat than pure TELENE. It is reasonable to speculate that TELENE's ductility and capability to absorb large energies be key to the undulator training performance as detailed in Section 3.3. In a second part of this study, one has to check the impact of better thermal properties when using less ductile impregnation materials such as the high- C_p mixed resins.

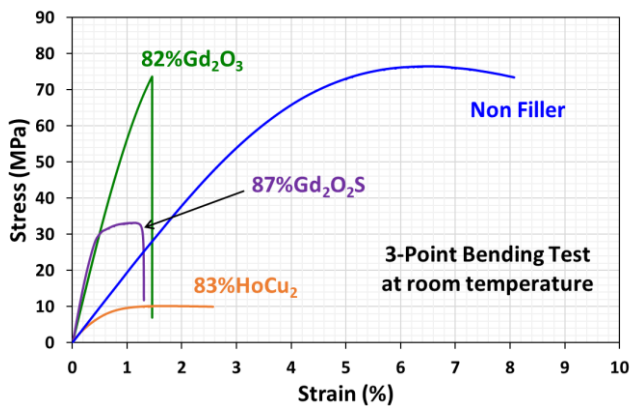


Fig. 14. Flexural stress vs. strain curves for pure and mixed TELENE resins.

3.2 MQE measurements of NbTi wire samples impregnated with high- C_p resins

Based on the low diffusivity values obtained for the mixed TELENE resins shown in Table 1, with a maximum time constant of 1.42 s for TELENE-82wt%Gd₂O₃, the MQE of the impregnated 0.8 mm NbTi wire samples was measured

for heater pulse durations from 200 ms to 1.5 s, with I_c % of up to 90% and magnetic fields between 6 and 9 T. At 9 T, the $I_c(4.2K)$ was 140 A. An example of results obtained at 9 T and at 80% of I_c is in Fig. 15. For pulse durations comparable to their time constant, both TELENE-82wt%Gd₂O₃ and TELENE-87wt%Gd₂O₂S show larger increases in MQE than pure TELENE.

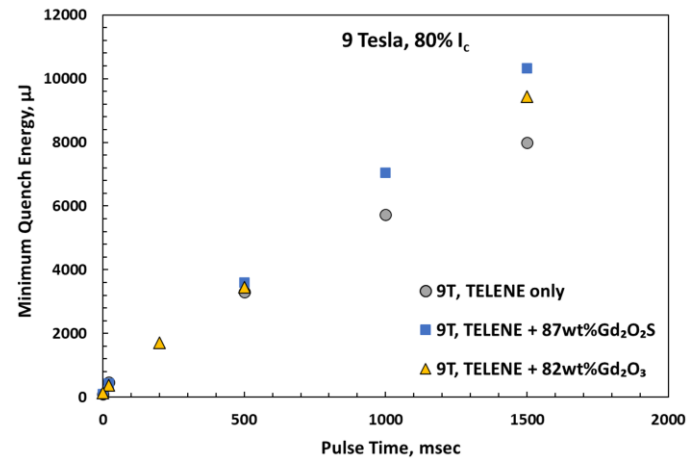


Fig. 15. Minimum Quench Energy vs. heater pulse duration at 80% of the critical current I_c at 9 T for NbTi wire samples impregnated with pure and mixed TELENE.

3.3 Impregnation with TELENE and test of first Nb₃Sn undulator short model

After winding and heat treatment, the magnet was placed in a leak-tight impregnation mold for vacuum impregnation at ANL. The two-part resin, i.e. TELENE resin plus the polymerization catalyst, was mixed by weight, and was then injected using positive pressure. After injecting the resin, the assembly was cured at 120°C for one hour. Due to the exothermic polymerization reaction, it is expected that the inside temperature is higher by about 50 to 100°C, depending on the amount of the resin.

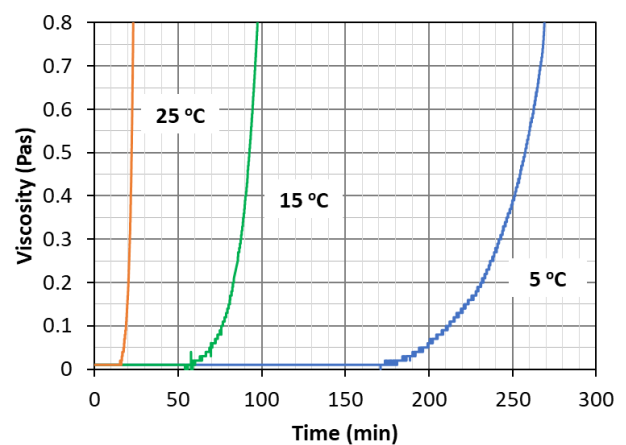


Fig. 16. Viscosity as function of time for TELENE at different temperatures.

As can be seen from Fig. 16, at room temperature, the pot life of TELENE is 20 minutes. However, the viscosity of TELENE is much lower than that of epoxy, i.e. its consistency is like water.

3.3.1 Impregnation process scalability. As shown in Fig. 17, TELENE's pot life can be increased by lowering the temperature during the impregnation process, which is the opposite of what is done for CTD-101 K, for which the temperature is instead increased. The dependence of TELENE's pot life with temperature is shown also in TABLE 3.

TABLE 3: Pot life vs. temperature for pure TELENE

Pot life, min	Temperature, °C
20	25
75	15
210	5

Scalability to larger impregnation volumes can be achieved by performing the impregnation process between 5 and 15°C. Indeed, by using one epoxy inlet into tooling equipped with multiple vents and an inlet pressure of 2 Bar, fill times with epoxy are less than 1.5 hrs for the HL-LHC IR quadrupoles that are 7.3 m long [13]. This includes about 45 minutes to inject CTD-101 K in the coil's mold and fill it, and about 40 minutes for filling the outflow tank.

The viscosity of mixed TELENE resins is of the same order of magnitude as that of pure TELENE up to high fillers concentrations, as shown for instance at 25°C for TELENE mixed with Gd_2O_3 in Fig. 17. On the other hand, the viscosity of CTD-101K is much more sensitive to the amount of high- C_p fillers, as shown for instance in Fig. 18 at 60°C when mixed with Gd_2O_3 .

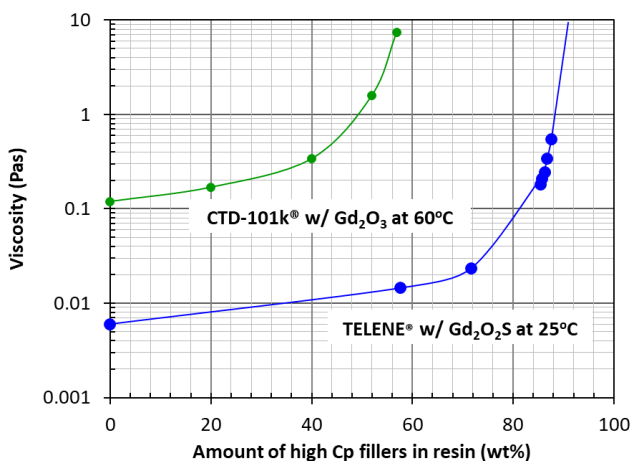


Fig. 17. Viscosity as function of wt% Gd_2O_3 in TELENE at 25°C compared with that at 60°C of CTD-101K mixed with Gd_2O_3 .

3.3.2 Magnet short sample limits. The short sample limit (SSL) for the first undulator short model was calculated based on the test results at 4.2K of three Nb_3Sn witness samples that were included in the furnace with the coil. Fig. 18 shows that the I_c vs. magnetic field curve for these samples intersects the maximum field load line of the undulator magnet at 1,143 A and 5.07 T.

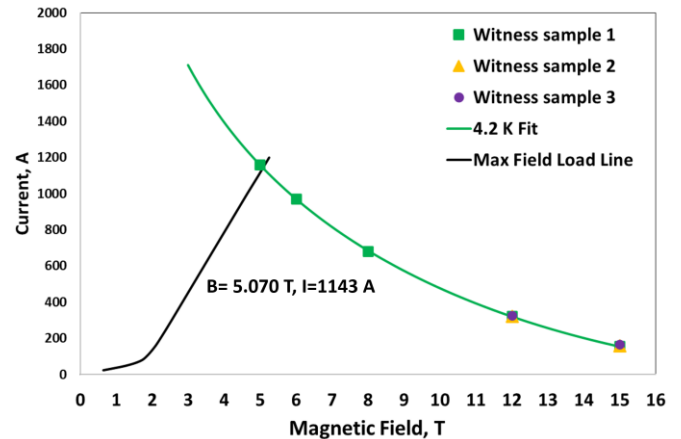


Fig. 18. Short sample limit calculation of TELENE impregnated undulator model based on witness sample critical current test results.

3.3.3 Magnet test results. The quench data for the first TELENE impregnated short undulator model as compared with identical undulator short models impregnated with CTD-101K are shown in Fig. 19. Data for model MM4 are not shown because it was damaged. Fig. 20 shows in more detail the quench history of this first undulator model, including a first thermal cycle. Actual quenches obtained at the standard ramp rate of 1 A/s are indicated with closed circles. Closed triangles indicate quenches produced during ramp rate studies, which were performed up to ramp rates of 40 A/s. Open circles represent errors or faulty trips.

As can be seen, the first quench at 1,043A occurred at about 91% of SSL. It took only three to four quenches to achieve 1,138 A, i.e. very close to the 1,143 A SSL predictions, compared to more than 50 quenches needed to reach a plateau for the nearly identical undulator coils impregnated with CTD-101 K.

The quench results during the first thermal cycle, i.e. second test sequence performed after warming up the magnet to room temperature and cooling it down again, is also shown in Fig. 20. In this second round, the first quench at 1,082A occurred at about 95% of SSL, and SSL was reached with just the second quench. However, this sequence also showed a number of current drops, from 3 to 8 % of SSL. The analysis of the voltage tap signals did not provide any insight on the nature of these quenches, and additional instrumentation will be needed to investigate this phenomenon.

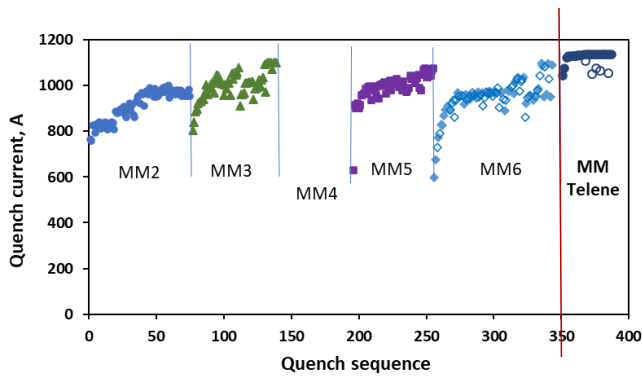


Fig. 19. Quench history of TELENE impregnated short undulator model as compared with that of nearly identical undulator short models impregnated with CTD-101K. Data for model MM4 are not shown because it was damaged.

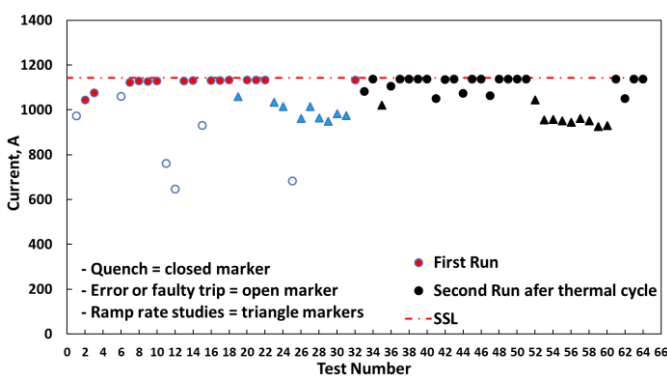


Fig. 20. Quench history, including first thermal cycle, for TELENE impregnated short undulator model. Actual quenches at the standard ramp rate of 1 A/s are indicated with closed circles. The maximum achieved current was 1,138 A.

3.4 Cobalt-60 gamma ray irradiation experiment up to 10 MGy

Figs. 21 and 22 show respectively the flexural strength and the flexural modulus as function of Gamma Ray dose for pure and mixed TELENE compared with CTD-101K. The flexural modulus monotonically increased by about 40% for pure TELENE, more than 60% for TELENE-82wt%Gd₂O₃ and TELENE-87wt%Gd₂O₃S, and more than 450% for TELENE-83wt%HoCu₂. The flexural strength monotonically increased for TELENE-82wt%Gd₂O₃ and TELENE-87wt%Gd₂O₃S.

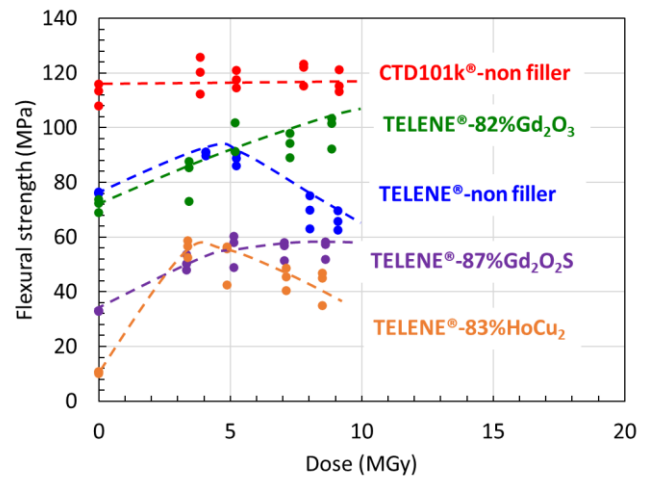


Fig. 21. Flexural strength as function of Gamma Ray dose for pure and mixed TELENE compared with CTD-101K.

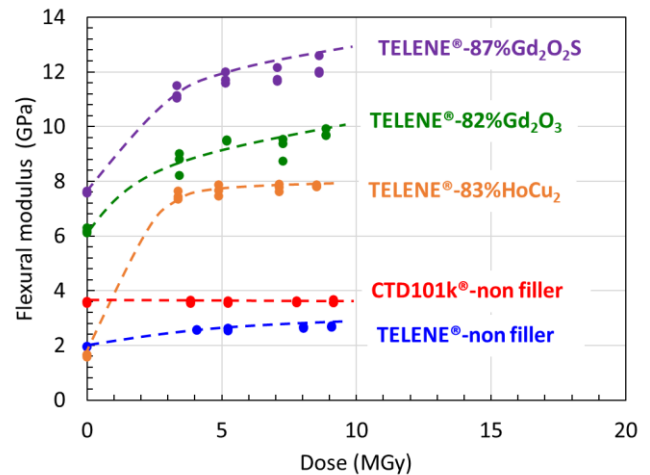


Fig. 22. Flexural modulus as function of Gamma Ray dose for pure and mixed TELENE compared with CTD-101K.

4. Conclusions

By using pure TELENE to impregnate a short Nb₃Sn undulator coil developed with ANL, magnet training was nearly eliminated. This was attributed to TELENE's superior ductility and toughness.

Based on the higher C_p and MQE results obtained for the mixed TELENE resins, two more ANL undulators are being wound for impregnation with TELENE-82wt%Gd₂O₃ and TELENE-87wt%Gd₂O₃S respectively to investigate any possible performance improvements produced by the better thermal properties of these mixed resins.

Gamma Ray irradiation performed at the Takasaki Advanced Radiation Research Institute using a Cobalt-60 gamma irradiation facility has shown that high-C_p resins TELENE-82wt%Gd₂O₃ and TELENE-87wt%Gd₂O₃S are gamma ray resistant at least up to 10 MGy. This makes TELENE ideal for high radiation environments. The final goal

for the entire irradiation campaign is to achieve 20 MGy+. At a later stage, TELENE's radiation resistance could be confirmed with proton beam irradiation experiments at the BLIP facility at BNL.

To study TELENE performance under larger Lorentz forces than those present in a 5 T light source undulator, pure TELENE and/or mixed TELENE will be used to impregnate LBNL Canted Cosine Theta sub-scale magnets, as well as FNAL High Temperature Superconducting dipole inserts, both developed within the U.S. Magnet Development Program.

To study TELENE performance under alternate loads in fast ramping magnets, such as those needed for a Muon Collider accelerator ring, pure TELENE and/or mixed TELENE will be used to impregnate FNAL Cosine Theta stressed managed coil made of superfine Nb₃Sn wires, developed at NIMS for low AC losses, shaped in a multi-stage round cable.

By successfully reducing coil training, and based on the current radiation resistance results, TELENE impregnation technology is expected to have direct application to high field Nb₃Sn dipole and quadrupole magnets, with substantial saving in accelerators commissioning costs.

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