MOLLER Spectrometer Magnet Design with Measured Mechanical Properties of Irradiated S2-Glass Reinforced Cyanate Ester Resin at Elevated Temperature

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MOLLER Spectrometer Magnet Design with Measured Mechanical Properties of Irradiated S2-Glass Reinforced Cyanate Ester Resin at Elevated Temperature

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***Abstract*—The aim of this study was to retire the risk of maintaining the integrity of S2-glass reinforced CTD-403 (a cyanate ester resin) that is exposed to radiation and elevated temperature over the life of the MOLLER experiment in experimental Hall A at Jefferson Lab. In this paper, the shear strength and flexural modulus of irradiated S2-glass reinforced CTD-403 specimens were measured at 65 °C (the magnets are to operate at less than 65 °C) under two scenarios: vacuum and gaseous nitrogen. The testing method is the Short-Beam Shear (SBS) test according to ASTM D2344. The specimens were exposed to neutrons and gamma-rays up to 124 MGy. The results show that specimens have excellent resistance against radiation, only 23% degradation of apparent shear strength with 124 MGy at 65 °C under vacuum. At the highest dose areas of the coils tungsten plates are used to reduce the radiation dose to the resin system. The conclusion is that S2-glass reinforced CTD-403 is well suited for electrical insulation of MOLLER magnets.**

***Index Terms*—Apparent shear strength, CTD-403, cyanate ester, dose, electrical insulation, irradiation, magnets, short-beam shear test, S2-glass**

I. Introduction

The Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) [1] experiment at Thomas Jefferson National Accelerator Facility (Jefferson Lab) will use parity-violating electron-electron scattering to conduct an ultra-precise measurement of the weak mixing angle to test the Standard Model of Particle Physics. In the experiment, a longitudinally polarized 11 GeV electron beam with rapidly flipping helicity will be scattered from a liquid hydrogen target. The scattered electrons will then be guided through a spectrometer system using five torus magnets and focused onto an integrating detector system with 224 quartz Cherenkov detectors arranged in six rings. The parity-violating asymmetry is estimated with a particularly high precision at the low-energy scale complimenting searches at high-energy colliders.

Jefferson Lab and Massachusetts Institute of Technology (MIT-Bates) are designing and building this spectrometer system. The experiment will run at Jefferson Lab for three years [1]. CTD-403, a cyanate ester resin, has been identified as the best candidate that can provide reasonable resistance against radiation for the spectrometer magnet used in MOLLER [2-4]. This paper characterizes the mechanical strength of irradiated S2-glass reinforced CTD-403 and its application in the spectrometer magnets, which are in a high radiation and elevated-temperature (less than 65 °C) environment. This study is unique because previous studies had focused on the mechanical strength of irradiated S2-glass reinforced cyanate ester resin at cryogenic and room temperatures [2-4]; they also included performance evaluation of the non-irradiated cyanate ester resin at room temperature [5]. The mechanical strength of irradiated CTD 101K specimens at room temperature was previously measured [6]. However, the mechanical strength was not determined at elevated temperatures [2-10]. By measuring the shear strength of the irradiated S2-glass reinforced CTD-403 specimens at the expected operating temperature and maximum dose for the MOLLER experiment, the risk of shear failure can be minimized.

II. Overview of MOLLER Spectrometer Magnets

The conceptual design of the spectrometer was developed by the MOLLER Collaboration and was given to Jefferson Lab in

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the form of ampere-turns with additional physics requirements [1]. The spectrometer torus magnets are expected to meet several physics optics requirements-

i. defined angular acceptance;
ii. clean separation of electron-electron scattering and background processes like electron-proton scattering;
iii. separation of 3 kinematic regions for inelastic electron-proton scattering;

The MOLLER spectrometer is composed of five water-cooled toroidal magnets (Fig. 1), each with 7-fold symmetry around the beam axis, distributed in two distinct regions - TM0 in the upstream region and TM1-4 in the downstream region [11]. The first four magnets (TM0-3) are resistive, single pancake racetrack coils, while TM4 is a double pancake design. TM0 is about 2 m long, TM1-3 are approximately 1 m long, and TM4 is about 3.8 m long. The coil design contains G10 inserts within the racetrack to connect the inner and outer legs of the coil, providing stability and manufacturing repeatability. A support system mounted to these G10 inserts allows the coils to be positioned accurately to satisfy the physics experimental requirements. The magnets will be housed in a vacuum environment of 1.3 Pa (0.01 Torr). Paschen discharge, electric tracking gap is included (worst case at 0.03 Torr) while evaluating the insulation thickness between turn-turn and line to ground based on the hi-pot test requirements [12-14]. The breakdown voltage between turn to turn, pancake to pancake, and line (turn) to ground (GND), was calculated and further increased by applying a factor of safety to design the overall insulation breakdown voltage in vacuum [13-14]. This ensures the coil breakdown voltage will be well within the design voltage. The hi-pot test for the coil/line to ground is defined in compliance with *IEEE NEC industrial requirements and IEC61010/IEC60950, and equals* at least two times the design voltage +1kV. The operational temperature is limited to no more than 65 °C. Table I lists the critical parameters of the five magnets with further details in [11].

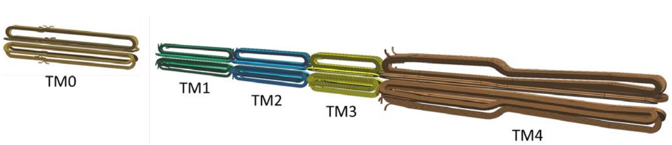

Fig. 1 MOLLER spectrometer magnets. Each magnet has 7 evenly azimuthally distributed coils

TABLE I
CRITICAL PARAMETERS OF SPECTROMETER MAGNETS

Magnet	Nominal Current (A)	Voltage (V)
TM0	1075	77.5
TM1	2230	40
TM2	2440	42
TM3	3372	57
TM4	3350	224

Jefferson Lab along with the MOLLER Collaboration developed the specification document that includes keep-out zones to design the set of magnets. Jefferson Lab contracted the design of TM0 to MIT-Bates. The four toroid magnets (TM1 through TM4) have been designed by Jefferson Lab and are in the process of fabrication and assembly. Prototype coils of TM1-TM4 have been fabricated by Everson-Tesla Incorporated, PA, USA.

As part of the system risk management at Jefferson Lab, a risk assisted matrix (RAM) was employed successfully, especially for the detector magnet systems during the 12 GeV Upgrade Project at the lab [15]. The same approach is applied to the MOLLER magnets to mitigate the risk of mechanical strength of irradiated S2-glass reinforced CTD-403 at its working temperature because the failure of CTD-403 could adversely affect the planned physics experiments.

III. MOTIVATIONS

The magnet coils are designed to provide the optimum magnetic field as defined by the physics requirements while maintaining engineering integrity by keeping the operating temperature less than 65 °C.

The coils and all experimental components are designed to be at a safe distance from the central beamline to allow clean transport of the un-scattered beam to the beam dump. However, some low energy charged particles such as electrons and positrons can still be bent into the magnet coils. Excessive radiation dose in the CTD-403 insulation of the coils can cause degradation leading to magnet failures.

All simulation studies to estimate the dose on the MOLLER spectrometer coil insulation were conducted with the GEANT4 simulation toolkit [16]. The QGSP BERT HP physics list was used because it reliably models low energy neutrons as well as hadronic and electromagnetic processes needed for radiation background studies [17]. The magnetic field map for the simulation was produced by the commercial software TOSCA [18] and fed into GEANT4. Two different magnetic field configurations were tested: one is ideal—which means all coils of each magnet have no deviations in placement from the design; the other has random 0.5 mm azimuthal and radial offsets to ideal placements that induced a dipole field within the central bore (0.5 mm is the positional tolerance specified by the MOLLER Collaboration). In the simulation geometry, each magnet coil was modelled as a copper block enclosed in the insulation material, including G10. The G10 and the insulation material was modelled in simulation as a mixture of S-Glass (63%) and G4 ethyl cellulose (37%) with an assumed density of 1.73 g/cm^3. The S-Glass itself was a mixture of G4 silicon dioxide (80%), G4 aluminum oxide (15%) and G4 magnesium oxide (5%) with an assumed density of 2.52 g/cm^3.

The particle rate reaching the main detector, including primary and secondaries is 200 GHz. This is approximately 0.05% of the total rate incident at the target and has an energy spectrum of 2-8 GeV. A small fraction of low energy scattered particles (1-100 MeV) are incident on the coils and the S2 glass and CTD 403 insulation. The cumulative absorbed dose ~~on~~ the coil insulation depends on the magnetic field characteristics near the extremities of the coil. Initial simulations in GEANT4 using the ideal magnetic field illustrated that the maximum radiation dose ~~on~~ the coil will be 70 MGy. For multiple runs of 100 million events, where all other variables (coil geometry and composition, magnetic field, shielding) are constant, the dose estimate for the maximum hotspot do not deviate by more than 5 MGy.

The electron beam damage of organic matter like polymers is primarily due to inelastic scattering because of electron – electron interaction causing radiolysis [19]. Compared to electrons, neutrons can ionize indirectly by creating charged particles and create a cascade of displaced and ionized atoms. Polymers that absorb neutron and gamma radiation produce both free radicals and ionic species that participate in degradation chemistries like chain scission, crosslinking, and unsaturation [20]. This present work, at a macroscopic level aims to study the effect on the shear strength of a material. The chemical reactions triggered by the radiation interactions are complex in nature but the overall effects are that more or less the same set of species are created [21].

S2-glass reinforced CTD-403 was chosen to electrically insulate the MOLLER spectrometer magnet coils based on its already known high radiation strength rating at cryogenic and room temperature [22]. Previous studies had characterized reactor-irradiated organic and inorganic hybrid insulation systems [2]. For example, S2-glass reinforced CTD-403 was irradiated at approximately 340 K to neutron fluences of 10^{21}, 10^{22} and 5×10^{22} m^{-2} (E > 0.1 MeV), and tested at 77 K [2]. The reactor operated at a γ-dose rate of 1×10^{6} Gyh^{-1}, a fast neutron flux of 7.6×10^{16} $m^{-2}s^{-1}$ (E > 0.1 MeV), and a total neutron flux of 2.1×10^{17} $m^{-2}s^{-1}$, ~~respectively~~ [2]. The short-beam shear tests of S2 glass reinforced CTD-403 at 77 K show that its shear strength is 108 MPa at 0 MGy, 97 MPa at 49 MGy, and 48 MPa at 230 MGy [2]. Other researchers evaluated the mechanical performance of non-irradiated CTD-403 at room temperature and elevated temperature (100 °C). They showed that the mechanical strength of S2-glass reinforced CTD-403 was clearly temperature-dependent [5, 9]. One would expect that the strength of irradiated S2-glass reinforced CTD-403 would degrade further at elevated temperature. All the radiation damage measurements in the literature are at cryogenic temperature or room temperature. For temperatures above ambient, strength degradation data exists but without irradiation [2, 8-10]. Table II presents a summary of the strength of S2-glass reinforced CTD-403 deduced by approximating and extrapolating this data. For temperatures above ambient, the approximation considers the radiation damage and strength degradation due to temperature to be independent processes and cumulative.

TABLE II
LINEARLY EXTRAPOLATED STRENGTH SUMMARY OF IRRADIATED S2-GLASS REINFORCED CTD-403 AT 65 °C AND 70 MGY [2, 8-10]

Material	**Stress Component**	**Extrapolated Ultimate Strength (MPa)**
CTD-403+S2	Tensile	502
CTD-403+S2	Compressive	685
CTD-403+S2	Shear	51
Cu-(CTD-403+S2)	Bonding	73

The coil design was analyzed in ANSYS 2021R1 – a finite element analysis (FEA) software, to understand stresses due to different coefficients of thermal expansion between copper, resin system and the G10 insert. The FEA considered the pre-stress during curing from 150 °C to 29.4 °C and other operational loads like electromagnetic magnetic forces, temperature gradient and hydrostatic pressure of the cooling water. The section views (Fig. 2a, 2b) show the typical layout of a coil with the insulation around the copper conductor, additional insulation around the complete coil (ground wrap), G10 insert *inside* the coil and the resin filling in the gaps. The insulation is S2 glass and CTD 403 matrix. The FEA results are compared with the approximated strengths of the insulation at the four modes of failure as shown in table II. The maximum XY shear stress is 28 MPa (Fig. 2c) and generally higher stresses on the insulation at the corners of the copper conductor. This was a concern because the safety margin would be only 1.8 when compared to the estimated shear strength value of 51 MPa (Table II), other stress components show sufficient safety margin.

There was no directly measured mechanical shear strength of irradiated S2-glass reinforced CTD-403 at room or elevated temperature before this study. It is therefore critical to determine, based on the test results, the safe radiation dose limit for CTD-403 insulation and the shielding requirements to mitigate degradation of mechanical integrity of S2-glass reinforced CTD-403.

IV. MECHANICAL PROPERTIES OF IRRADIATED S2-GLASS REINFORCED CTD-403 AT ELEVATED TEMPERATURE

A. Specimen Preparation

Composite laminates were fabricated—by Composite Technology Development (CTD), Inc.—using vacuum pressure impregnation (VPI) to infuse the CTD-403 cyanate-ester resin matrix material into layers of S2-glass fabrics enclosed in a steel mold. The fabric used was 6781 style S2-glass with 642 finish. All laminates were made to a target fiber volume fraction of 50%. The density of S2-glass is 2.46 g/cm^3; the cured CTD-403, 1.22 g/cm^3; the cured composite laminates, 1.84 g/cm^3. Twenty-five specimens with dimensions 3.3 mm × 6.35 mm × 27.94 mm (0.13 in × 0.25 in ×1.1 in) were fabricated from the composite laminates.

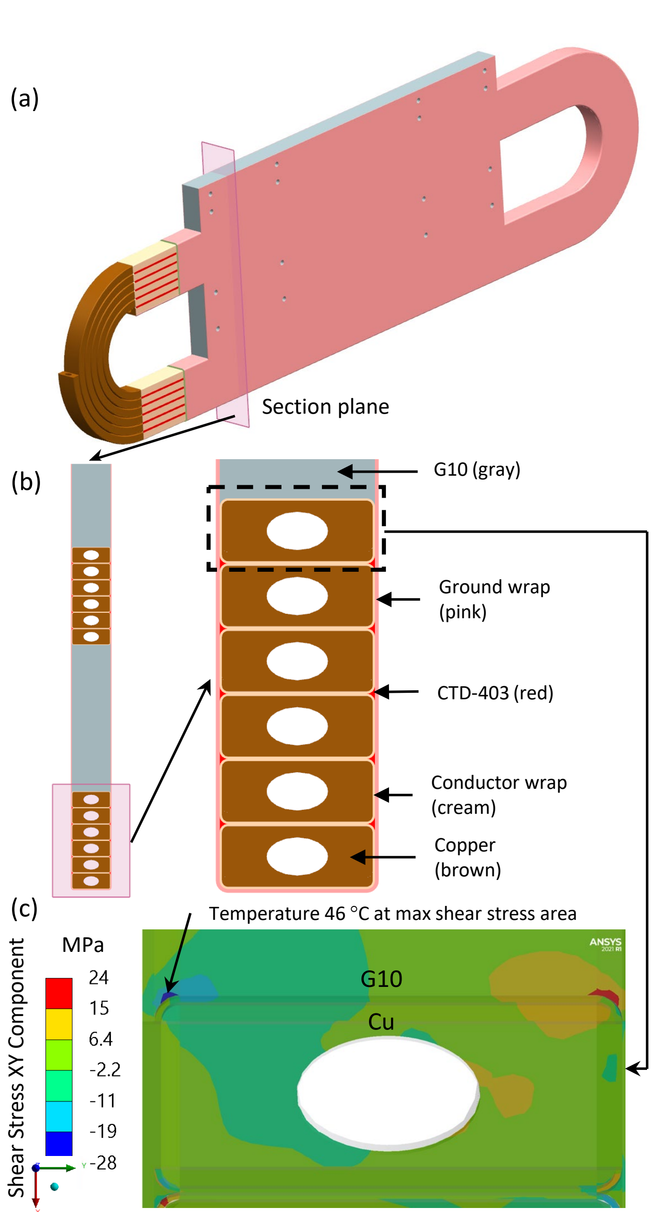

Fig. 2. (a) 3D sectional view of a typical coil; (b) a section of coil along the plane shown in (a) with a detailed component view; (c) Shear stress in the cross section shown near the G10 and copper interface.

Jefferson Lab encapsulated 5 specimens per ampoule (3-mm thick quartz glass); three ampoules (1, 2, and 6) were under vacuum—about 0.13 Pa (0.001 Torr), 0.4 Pa (0.003 Torr) and 2.7 Pa (0.02 Torr) respectively; two ampoules 4 and 5 were under gaseous nitrogen— 6.0×10^4 Pa (452 Torr) and 6.7×10^4 Pa (502 Torr) respectively; it was intended to fill Ampoule 4 and 5 at 500 Torr. Composite specimens were irradiated in vacuum and in gaseous nitrogen environments to understand the impact of environment on mechanical properties. The five vials were further encapsulated by the McClellan Nuclear Research Center (MNRC) of the University of California (UC), Davis in a hermetically sealed aluminum container.

Five control specimens were also cut from the same S2-glass reinforced CTD-403 laminates at the same time to ensure similar age and composition. ~~They were placed in a sixth ampoule~~ (Table III).

TABLE III
INTERNAL ATMOSPHERE OF EACH AMPOULE

Internal atmosphere	Air	Vacuum			Nitrogen Gas	
Ampoule number	3*	1	2	6	4	5

*indicates the specimens in the ampoule are control samples, not irradiated.

B. Irradiation

The specimens were irradiated in the central irradiation facility (CIF) in the MNRC's TRIGA (Training, Research, Isotopes, General Atomics) reactor core (Fig. 3). The reactor was used as a surrogate to save time during the testing as reactors can provide a high dose rate to specimens in a short period of time. The dose rate estimate was made using the MNRC's reactor model in MCNP5 [23].

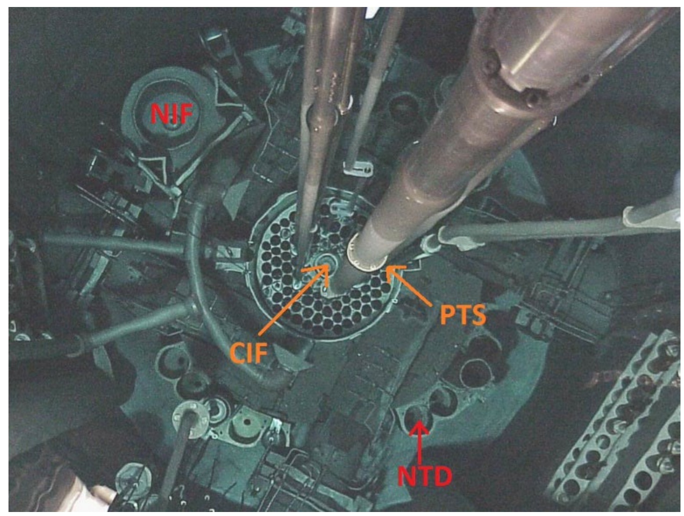

Fig. 3 Central Irradiation Facility (CIF) and Pneumatic Transfer System (PTS) in the MNRC's TRIGA reactor in-core area. The in-tank out-of-core facilities include fast Neutron Irradiation Facility (NIF) with an Environmental Exposure Vessel and more than 10 general-purpose (NTD) irradiation locations.

The MCNP model tallies the energy absorbed by fast neutron recoil and energy absorbed by the sample from gamma-ray interactions including the energy from fast electrons made by gamma-rays. The energy range for neutrons was 0.01 eV to 20 MeV, and the energy range for gamma-rays/electrons was 10 keV to 20 MeV. As only neutrons, gamma-rays, and electrons were modeled, dose from fast neutron interactions that produce heavy charged particles was not tallied e.g. (n, p) and (n, alpha) reactions. Only the gamma-rays from the prompt fissions and the (n, gamma) capture reactions were tallied. The gamma-ray dose contributions from decay products will be significantly less than the dose from the other sources of gamma-rays. The source geometry is essentially the entire reactor.

The model considers the geometry of the core along with the fuel (^{235}U) loading and various neutron-moderating structures. The simulation was performed using the k-code function in MCNP which is typically utilized for reactor criticality calculation, though it can also be used to calculate radiation flux, radiation energy, and radiation dose. K-code provides the output on a per fission basis and the user must scale the results of the simulation to the power level of the reactor based on the conversion of energy released per fission to total reactor power. The samples inside of the quartz ampoules were loaded into an aluminum sample holder and sealed using a lead seal to keep the sample holder watertight. The aluminum sample holder was then placed inside of the central irradiation facility (CIF) of the reactor. The aluminum sample holder with a single specimen centered inside of the sample holder was modeled in the MCNP simulation. Physically, the samples were loaded in sets of five inside of the quartz ampules. Neither the quartz ampoule nor the samples themselves are strong absorbers of fast neutrons or gamma-rays and are relatively thin, therefore self-shielding was not expected to alter the dose rate significantly.

When the samples were physically loaded into the aluminum sample holder they were loaded two ~~ampules~~ per irradiation. While the ~~ampules~~ were centered in the aluminum container, they were located slightly higher or lower than the "perfectly centered" sample that was simulated in the MCNP model. The difference in flux (dose rate) moving off the centerline axis of the core has been evaluated in the past and can be as high as 10% per inch. That is to say, a sample one inch above or below the middle plane of the central irradiation facility can expect to see a decrease in flux or dose on the order of 10%.

The simulation was intended to provide a dose rate estimate and should not be represented as overly precise or accurate. The two main sources of error in the dose rate simulation are the uncertainty in the exact position of the samples during irradiation and the difference between the simulation and the periodic simulation benchmarking results. Both of these errors are on the order of 10%. The overall error associated with the dose rate measurements would be much better represented as 20% and not the 1% statistical error associated with MCNP.

The core model itself is validated against the physical core by an annual excess reactivity measurement. This aspect of the model validation is typically accurate to with 0.25 % excess reactivity. Fast neutron flux (measured by sulfur tablet) and thermal neutron flux (measured by gold foil) is measured periodically at reduced reactor power and compared to the core MCNP model. Typically, the results agree within 5-10 % which would be the minimum uncertainty of the dose estimate. No such measurement is made of the gamma-ray flux spectrum inside of the reactor core as it is nearly impossible to eliminate the neutron component of the radiation to get a pure measurement of the gamma-rays. Therefore, the gamma-ray dose estimate cannot be directly validated.

Fig. 4 and Fig. 5 illustrate the neutron and gamma-ray spectra as calculated by MCNP incident on the sample. The neutron dose rate was found to be 0.50 MGy per hour and the gamma-ray dose was found to be 0.31 MGy per hour.

The specimen container was cooled by water of about 95 °C. The temperature of the specimens was higher than 95 °C due to radiation heating. The actual irradiation temperature was unknown because of the complex interaction of radiation heating and thermal hydraulic cooling.

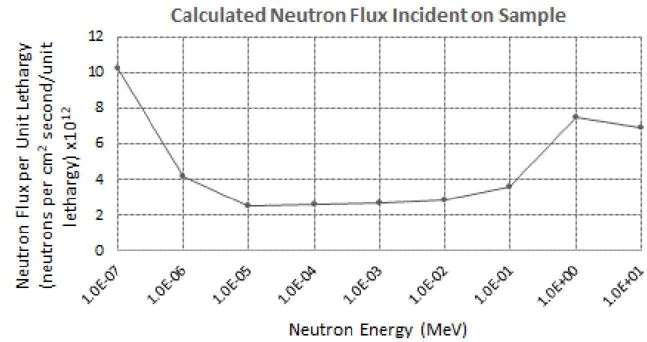

Fig. 4 Calculated neutron flux incident on sample

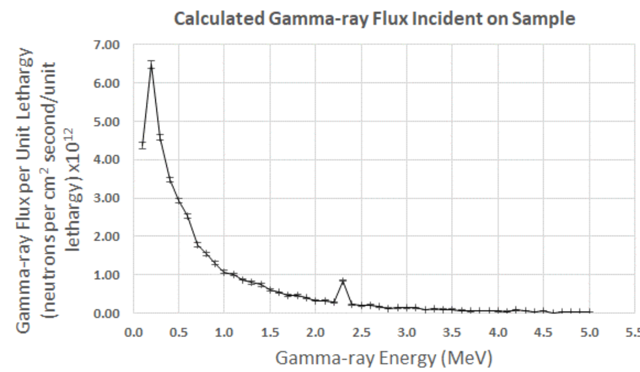

Fig. 5 Calculated gamma-ray flux incident on sample

C. *Mechanical Properties of Specimens*

The irradiated specimens were shipped to CTD in four lead pigs, containing five quartz ampoules labelled 1, 2, 4, 5 and 6 which were flame sealed after being either evacuated or filled with gaseous nitrogen at specific, documented pressures (Fig. 6). The only measured isotope in the specimens from the recorded spectrum was Co-60. The total amount of Co-60 created in the samples was on the order of 5 mCi. This result was not expected, and it was determined that the source of the Co-60 was natural cobalt used as a curing agent at a concentration of approximately 1 ppm. The ampoules were removed from the aluminum sample holder at MNRC. The ampoules were then shielded at MNRC to comply with Department of Transportation regulations regarding the shipment of radioactive material.

The ampoules were opened and the specimens marked with new numbers for traceability and tested at the temperature of 65 °C (338 K) ± 5 °C. The specimens were discolored by the irradiation to various extents—ampoule #1 and #4 (both under 41 MGy) was the least discolored and ampoule #6 (under 124 MGy) was the greatest. The change in discoloration of the glass appeared to be both a darkening in color (browning) and a reduction in transparency. It also appeared that there is no correlation between the discoloration of specimens and the environment in the ampoules (Fig. 6).

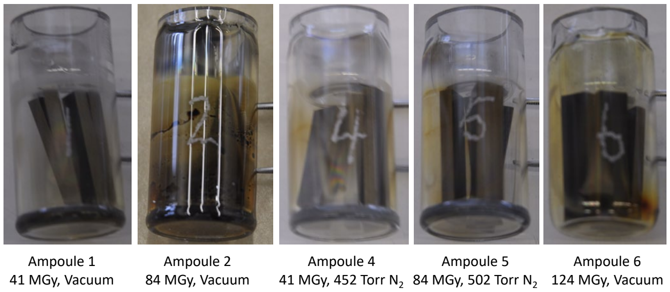

Fig. 6 Discolored specimens under various doses and environments

Each specimen was installed in an air filled preheated chamber, loaded to 44.5 N (10 lbf) and held for five minutes within the test temperature range prior to initialization of the test (Fig. 7). All specimens were tested at a displacement rate of 0.05 in/min until inter-laminar shear failure per ASTM D2344. No anomalies were experienced during the testing.

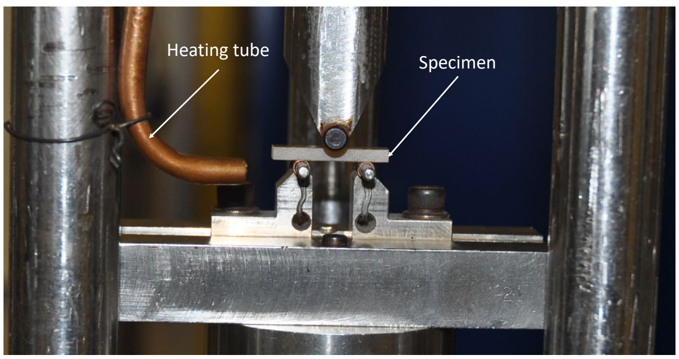

Fig. 7 Control specimen in the short-beam shear test fixture

Table IV shows the test results with standard deviations based on five specimens in each set.

TABLE IV
MECHANICAL PROPERTIES OF S2-GLASS REINFORCED CTD-403 SPECIMENS AS TESTED - IRRADIATED UNDER VACUUM AND MEASURED AT 65 °C

Description	Air	Vacuum			Nitrogen Gas	
Ampoule number	3*	1	2	6	4	5
Dosage (MGy)	0*	41	84	124	41	84
Apparent inter-laminar shear strength (MPa)	66.4	67.5	55.8	51.0	66.0	45.1
Standard deviation of shear strength (MPa)	0.6	0.9	2.4	1.6	0.7	1.0
Flexural modulus (GPa)	18.1	19.3	19.7	19.8	19.5	18.2
Standard deviation of modulus (GPa)	0.2	0.5	1.2	0.7	0.3	0.5

*indicates the specimens are not ~~irradiated and~~ control samples.

V. DISCUSSION

Table IV illustrates that the specimens have excellent resistance against radiation in terms of shear strength and that the specimens with 124 MGy demonstrate only 23% degradation of apparent shear strength and 9.4% increase in flexural modulus at 65 °C under vacuum. ~~T~~-tests shows that the apparent shear strengths of specimens in vacuum are significantly different from those in gaseous nitrogen with a confidence level of 95%. The linearly interpolated measured shear strength of S2-glass reinforced CTD-403 under vacuum is 59.6 MPa at 70 MGy and 65 °C is higher than the extrapolated value of 51 MPa from literature and assumptions (Table II). Similarly, the apparent interlaminar shear strength of S2-glass reinforced CTD-403 degrades 32% after being irradiated at 84 MGy under gaseous nitrogen; its flexural modulus barely changes.

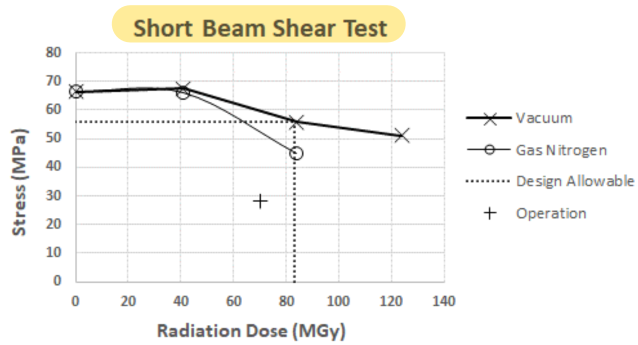

Fig. 8 Inter-laminar shear strength (ILSS) of S2-glass reinforced CTD-403 insulation system at 65 °C

The maximum operational stress of the coil insulation is 28 MPa (Fig. 2c). In order to achieve an arbitrary safety factor of 2.0 with regards to stress, the shear strength of the S2-glass reinforced CTD-403 will have to be 56 MPa. This corresponds to the maximum strength at 83.2 MGy (~~that~~ is greater than 70 MGy) based on linear interpolation of values in Table IV (see Fig. 8). Thus 70 MGy can be conservatively considered as the maximum allowable radiation dose on the coils – this assumes all the insulation on the coil is at peak stress value. If future GEANT dose calculations show higher ~~that~~ 70 MGy dose in the low stress regions of the coil, the dose cutoff restriction can be revised and mitigated accordingly.

VI. CONCLUSIONS

S2-glass reinforced CTD-403 was chosen to maintain the mechanical integrity of the coils under radiation and elevated temperature. These measured results allowed for setting a broad dose limitation of 70 MGy on the coils. This aids the design of the shielding elements and also evaluation of the mechanical design integrity of the coils which operates at elevated temperature and experiences high radiation dosage.

APPENDIX

The material card used by MNRC to perform the MCNP simulation for the sample is provided in Table V below.

TABLE V
MATERIAL CARD

Material	Weight Fraction (%)
Hydrogen	1.7
Carbon	26.7
Oxygen	36.0
Nitrogen	4.34
Aluminum	8.3
Magnesium	3.8
Silicon	18.9

Acknowledgment

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Mark Haynes, who was with Composite Technology Development, Inc., contributed to the paper.

References

[1] The MOLLER Collaboration, The MOLLER Experiment (Measurement Of a Lepton Lepton Electroweak Reaction—An Ultra-precise Measurement of the Weak Mixing Angle using Møller Scattering), *An MIE proposal to The United States Department of Energy*, September 12, 2011, https://arxiv.org/abs/1411.4088

[2] K. Bittner-Rohrhofer, P. Rosenkranz, K. Humer, H.W. Weber, J.A. Rice, P.E. Fabian and N.A. Munshi, "Characterization of Reactor Irradiated Organic and Inorganic Hybrid Insulation Systems for Fusion Magnets", *AIP Conference Proceedings* 614, 261 (2002)

[3] P. E. Fabian; N. A. Munshi; R. J. Denis, "Highly Radiation-resistant Vacuum Impregnation Resin Systems for Fusion Magnet Insulation", *AIP Conference Proceedings* 614, 295–304 (2002), https://doi.org/10.1063/1.1472555

[4] A. Idesaki, T. Nakamotob, et al, "Development of High radiation-Resistant Glass Fiber Reinforced Plastics with Cyanate-based Resin for Superconducting Magnet Systems", *Fusion Engineering and Design* 112 (2016) 418–424

[5] G. Voss; P. Fabian; S. Feucht; M. Harte; C. Terry, "Performance Evaluation of Cyanate Ester Resin", 20th *IEEE/NPSS Symposium on Fusion Engineering*, 2003, DOI: 10.1109/FUSION.2003.1426618

[6] C. Reis et al., "Investigating Irradiated Superconducting Magnet Insulation Materials for Particle Accelerators and Other High-Dose Environments," in *IEEE Transactions on Applied Superconductivity*, V33 (5), pp.1-7, Aug. 2023, Art no. 7700307, DOI: 10.1109/TASC.2023.3252480.

[7] S. D. Grandlienard, S.W. Feucht, P.E. Fabian, D.E. Codell, and N.A. Munshi, "Properties of Cyanate-ester-based Composite Insulation for Magnet Applications", *AIP Conference Proceedings* 824, 275 (2006); https://doi.org/10.1063/1.2192361

[8] Hooker, M. & Fabian, Paul & Grandlienard, S. & Codell, D. & Lizotte, M.. (2006). Shear Strengths of Copper/Insulation Interfaces for Fusion Magnet Applications. *AIP Conference Proceedings*. 824. DOI: 10.1063/1.2192365.

[9] B. I. Morgan, Moisture Degradation of CTD-403: Testing the Application of Cyanate Ester Insulations to Fusion Devices, *Master Thesis*, University of Tennessee, Knoxville, 2008, p60-66

[10] AGY, High Strength Glass Fibers, *Pub. No. LIT-2006-111 R2* (02/06), www.agy.com

[11] D. Kashy et al., "Design and Prototyping of a Novel Toroidal Magnet System for MOLLER Experiment at Jefferson Lab," in *IEEE Trans. on Appl. Supercond.*, DOI: 10.1109/TASC.2023.3337065.

[12] Paschen plot data by F. Paschen:*Wied. Ann.* 37, 69, 1889 (open source).

[13] R. R. Coltman *et al.*, "Radiation effects on organic insulators for superconducting magnets," *Solid State Div., Oak Ridge Nat. Lab., Oak Ridge, TN, USA, DOE*, Oct. 1979.

[14] M. B. Kasen *et al.*, "Mechanical, electrical, and thermal characterization of G-10CR and G-11CR glass–cloth/epoxy laminates between room temperature and 4 K," in *Advances in Cryogenic Engineering*, vol. 26. New York, NY, USA: Plenum Press, 1980, pp. 235–244, paper D-1.

[15] P. K. Ghoshal et al., "General Failure Modes and Effects Analysis for Accelerator and Detector Magnet Design at JLab", *IEEE Trans. Appl. Supercond.*, V30 (8), Dec 2020, Art. no. 4501011, DOI: 10.1109/TASC.2020.3022993

[16] S. Agostinelliae, J. Allison, etc., "Geant4—a simulation toolkit", Nuclear Instruments and Methods in Physics Research A, 506 (2003) 250–303, https://doi.org/10.1016/S0168-9002(03)01368-8

[17] https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/html/reference_PL/QGSP_BERT.html.

[18] Opera-3D 18R2 *Reference Manual*; Dassault Systèmes UK Ltd.: Kidlington, UK, 2018.

[19] Zhang, Weiwei, et al. "Electron beam damage of epoxy resin films studied by scanning transmission X-ray spectromicroscopy." *Micron* 120 (2019): 74-79.

[20] Bernstein, Robert. Neutron and gamma irradiation damage to organic materials. No. SAND2012-3358. *Sandia National Laboratories (SNL)*, Albuquerque, NM, and Livermore, CA (United States), 2012.

[21] Bonin, H. W., V. T. Bui, and P. E. Poirier. "Effects of neutrons and gamma radiation on high polymer epoxy adhesives." *CNS proceedings of the 16. Annual conference* (1995).

[22] Idesaki, Akira, et al. "Evaluation of radiation resistance for organic materials used in atomic energy-related facilities." *Japan Atomic Energy Agency,* Quantum Beam Science Directorate, Advanced Ceramic Group (2012). http://www. hep. princeton.edu/mumu/target/RESMM12/idesaki.pdf.

[23] Monte Carlo N-Particle (MNCP), Los Alamos National Laboratory, https://mcnpx.lanl.gov/index.html