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**Electrical Insulation issues
for a Fusion Nuclear Science Mission***

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Abstract

The insulation for the magnet plays a large role in the lifetime of the magnet. It drives the shielding requirement, which drives the size and cost of fusion devices. We briefly describe the status of the magnet insulation materials for fusion magnets, and describe the options for materials for future fusion machines. We also describe an R&D program to investigate these options. A focused development effort with coordinated activities of universities, national labs and industry should be undertaken. The program should include development of inorganic insulating systems and ceramic insulators. Industrial partners have proposed the development of superior insulating materials with simultaneous improvements in insulation strength and radiation resistance.

Introduction

Electrical insulation is needed to prevent leakage current and arcs due to magnet voltages during charging, discharging, and quench dump. The insulation must be able to withstand voltages that to date are as high as 25 kV, during the quick magnet discharge following a detection of a quench (normal zone in the magnet), in order to prevent damage from overheating the conductor. The insulators must also act as a key structural element in maintaining winding pack stiffness, but allowing local expansion, strain sharing, and load bearing in a conductor in plate design, in order to transfer the conductor generated loads to the structure. Where insulators can develop tensile loads, they must have adequate shear strength to prevent tearing. In the layers of a magnet closest to a radiation source, such as the fusion plasma, the insulation must also be able to withstand both instantaneous and cumulative neutron and gamma irradiation. The ability to withstand this radiation is frequently the magnet limit that determines the thickness of the radiation shield.

Organic insulators have substantially lower fluence tolerance than inorganic insulators. This is because organic insulators are limited by chemical changes due to bond breaking, while for inorganic insulators the life is determined by swelling caused by gas generation by nuclear process or damage to the crystallographic structure of the material.

In organics, the bond breaking can be described in terms of g-values, or the number of radicals, atoms or bonds broken per 100 eV of absorbed energy. Since the mechanism for different types of irradiation are similar, the g-values from these different forms of radiation are comparable. Therefore, the relevant number for characterizing irradiation damage from neutrons, gammas and electrons are in terms of energy density dissipated in the material, or Grays. For inorganic insulation, the damage is done by neutrons, and thus the relevant number is neutron fluence [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*, 2001 Joint Cryogenic Engineering Conference and International Cryogenic Materials Conference. 16-20 July 2001 Madison, WI]

State-of-the-Art

Individual components in insulation systems are frequently ranked by their compressive strength, shear strength, and dielectric strength (kV/mm). The properties of some candidate insulation materials are listed in Tables I-IV.

Extensive insulation materials screening has been done as part of the ITER Insulation Program. A report on materials screening results exists in a series of viewgraphs by Schutz of Composite Technology Development. [J.B. Schutz, *Materials screening for ITER TF coil insulation*, in *Proceedings of ITER Workshop on U.S. Insulation Program and OFE Base Program Review of Low-Temperature Structural Alloys*, Oct 12 and 13, Hyannis, MA] The results of the screening are tabulated in Tables I-IV.

**Table I Candidate VPI Resin Systems Screening Tests at 76 K
Short beam shear test for apparent interlaminar shear strength**

Resin Type	Resin system	Apparent interlaminar	Coefficient of variation
		shear strength MPa	
Flexibilized DGEBA	CTD-101K	108	4
DGEBA	Shell 826	112	113
DGEBA	ER-321	84	4
DGEBA	VRI-3407	64	10
Polyesterimide	VRI-3308	23	5
Cyanite ester	CTD-403	55	5

References:

A. Nishimura, Y. Izumi, M. Imaizumi, and S. Nishijima, *Radiation Effect On Interlaminar Shear Strength Of The Electric Insulation System With Cyanate Ester And Epoxy Blended Resin*, presented at the CEC/ICMC meeting in Spokane, WA, June 2011

J.B. Schutz, *Materials screening for ITER TF coil insulation*, in *Proceedings of ITER Workshop on U.S. Insulation Program and OFE Base Program Review of Low-Temperature Structural Alloys*, Oct 12 and 13, Hyannis, MA

**Table II: Candidate Prepreg Resin Systems Screening Tests at 76 K
Short beam shear test for apparent interlaminar shear strength**

Resin type	Resin system	Apparent	Coefficient of
		interlaminar shear strength MPa	
DGEBA Epoxy	SP-250	63	1
DGEBA Epoxy	XP-1003	64	1
DGEBA Epoxy	BASF-5216	34	2
DGEBA Epoxy	LTM-12	27	1
TGDM/DGEBA Epoxy	JDL-552	51	6
TGDM Epoxy	CTD-112P	108	6
Bismaleimide (BMI)	CTD-200P	37	6
Polyimide	CTD-320P	41	6
Polyimide	AFR-700	110	3

Table III: Candidate VPI Resin Systems Screening Tests at 4 K and 76 K
45 degree Shear/Compression Strength

Resin type	Resin system	Shear/Compression Strength MPa	Coefficient of variation %
76 K			
Flexibilized DGEBA	CTD-101K	176	2
DGEBA	Shell 826	171	7
TGDM	CTD-110X	137	7
4 K			
Flexibilized DGEBA	CTD-101K	178	3
DGEBA	Shell 826	177	5

Schutz's conclusions were that DGEBA epoxy systems were superior to other VPI resin systems and that TGDM epoxy systems were unsuitable for ITER. Flexibilized DGEBA (CTD-101K) and DGEBA (Shell 836) resin systems were selected for further evaluation in the ITER irradiation program. CTD-101K was ultimately selected. By contrast, Schutz concluded that TGDM and polyimide prepreg systems were superior to DGEBA, DGEBA blend, and BMI resin systems. TGDM (CTD-112P) and polyimide (AFR-700) resin systems were selected for further evaluation. Schutz also provided a summary table of the dielectric strength of the candidate insulation systems.

Table IV: Dielectric Strength at 76 K of Candidate Insulation Systems
Material Specimen Thickness Breakdown Voltage Dielectric Strength

	(mm)	(kV)	(kV/mm)
VPI epoxy systems			
CTD-101K/2 plies 6781 glass fabric	0.53	40	76
Shell 826/2 plies 6781 glass fabric	0.52	46	88
VPI epoxy systems with barrier			
CTD-101K/6781 glass fabric/Kapton HA	0.55	>50	>90
CTD-101K/6781 glass fabric/IMI498-37B Mica	0.57	>46	>82
Prepreg epoxy systems			
CTD-112P/2 plies 6781 glass fabric	0.55	44	80
CTD-105P/2 plies 6781 glass fabric	0.64	34	53
JDL-552/2 plies 6781 glass fabric	0.58	30	51
CTD-1PFS/2 plies 6781 glass fabric	0.59	46	77
Prepreg epoxy systems with barrier			
CTD-112P/1 ply 6781 glass fabric/IMI 498-37B	0.63	49	78
CTD-112P/1 ply 6781 glass fabric/VRI #6293	0.5	42	85
CTD-112P/1 ply 6781 glass fabric/MM #553	0.59	>48	>81
CTD-112P/2 plies 6781 glass fabric/Kapton HA	0.57	>46	>82

Prepreg polyimide systems			
CTD-320/2 plies 6781 glass fabric/IMI 498-37B	0.69	>55	>79
AFR 700/2 plies 6781 glass fabric	0.5	>55	>79
Prepreg polyimide systems with barrier			
AFR 700/2 plies 6781 glass fabric/Kapton HA	0.52	49	94

All candidate insulation systems look quite good in term of dielectric strength. However, the CTD-101K/6781 glass fabric/Kapton HA VPI epoxy/barrier hybrid system is an obvious first choice, since it also has good shear strength. Sample tests indicated that EPON 826 had higher performance than CTD 101-K, the ITER choice. Kapton was the best all-around unreinforced polyimide for high dielectric strength.

The combined mechanical and electrical limits of a potted winding pack with rectangular conduits, which does depend upon shear strength was determined by electrical insulation development programs.

The baseline design -- kapton over the conduit, a 3D weave overwrap and a 3D tackified corner fill -- was confirmed as the highest performing option. However, all of the options with the exception of the cigar roll had objectively high performance.

The intrinsic dielectric strength of the best solid organic insulations exceeds 500 kV/mm. However, in service, the electrical field in an organic insulation is unlikely to exceed 2 kV/mm. In ITER, the maximum design electric field in the TF insulation was 5 kV/mm in 4 mm or 1.25 kV/mm.

ILSS tests results obtained by Nishimura at 77 K are summarized in FIGURE 8 [A. Nishimura, Y. Izumi, M. Imaizumi, and S. Nishijima, *Radiation Effect On Interlaminar Shear Strength Of The Electric Insulation System With Cyanate Ester And Epoxy Blended Resin*, presented at the CEC/ICMC meeting in Spokane, WA, June 2011]. It presents all the data of the gamma ray irradiation and the neutron irradiation. The ILSS data of neutron irradiation is plotted against gamma ray dose calculated with 2.5 MGy/hr. When the blend ratio of the cyanate ester is reduced, the ILSS decreases clearly. It means that the triazine ring is a strong molecular structure and a lot of unreacted epoxy would remain in case of 20/80 blended sample because of no hardener. The 100% cyanate ester composite shows the excellent resistance against radiation and ILSS does not drop so much even after the 1.0×10^{22} n/m² neutron irradiation with over 400 MGy. However, the composite with the blended resins show the drastic degradation of the ILSS after the 1.0×10^{22} n/m² irradiation. The triazine ring has an excellent potential against radiation but the open epoxy (oxazolidinon) created by mixing the epoxy resin would reduce the ILSS under the harder gamma ray environment.

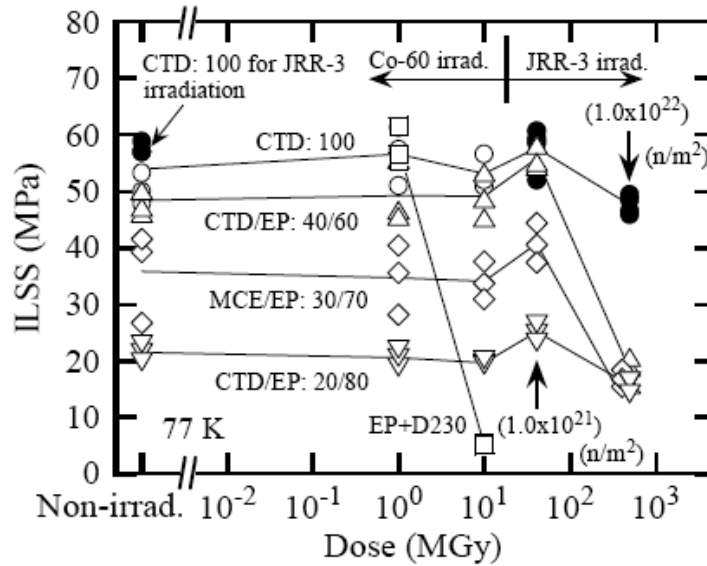


Figure 1. Dependence of Interlaminar Shear Strength of blended resin (CTD/EP: 40/60) on the curing pattern and heat flow on curing process. The CTD refers to CTD403.

Goals

Magnet insulation in ARIES

Organic as well as inorganic materials are under consideration for use as insulation material in commercial fusion reactor studies in the US. Most superconducting magnets are presently manufactured using fiber-reinforced epoxy, which imposes a relatively low limit on the allowable irradiation.

The radiation limit for organic insulators is on the order of 10^8 rads for fiber-reinforced epoxy and 10^9 rads for polyimide based insulation. These limits are for the case when the insulator needs to withstand substantial shearing forces. In the absence of shear, it is possible to increase these limits, by as much as a factor of 10. [L.A. El-Guebaly, *Overview of ARIES-RS neutronics and radiation shielding: key issues and main conclusions, Fus. Eng. and Design* **38** 139-158 (1997)]

The fluence limit for inorganic insulators is determined by swelling. For practical insulators the maximum irradiation ranges from 10^{11} rads to 10^{14} rads depending on

whether the insulator is in sheets or in powder form. The corresponding neutron fluence (>0.1 MeV neutrons) is 10^{24} - 10^{27} neutrons/m².

In the case of YBCO, an insulator is used in the manufacturing process, as a compliant buffer layer between the thin YBCO films and the Ni substrate. For the cable geometry of with HTS tapes, there may be no need for a flexible, organic-based insulator. It may be assumed that the irradiation limit of the insulators for HTS magnets can be increased to 10^{11} to 10^{14} rads, depending on whether or not the insulator experiences shear loads.

When compared to LTS materials, HTS materials may have the potential of substantially relaxing the design restrictions placed on the material by irradiation damage to insulation, the stabilizer and nuclear and AC heating of the cryogenic environment. However, the information available today only indicates that irradiation damage limits of HTS material itself are not lower than for the LTS materials.

For ARIES AT, the same constraints as that of LTS are assumed. The design of the shield is driven by the neutron damage to the superconductor. The limit has been set to 10^{23} n/m² (with a safety margin of 3). Even if an organic insulator is used at the region of the magnet, the irradiation fluence (neutrons plus gammas) would be less than $2.5 \cdot 10^8$ Gray, achievable with high performance organic insulators today.

Table V shows the neutron and gamma maximum insulator fluences assuming a machine with 40 full power years. Three locations are shown for the ARIES-AT design. [L.A. El-Guebaly and the ARIES Team, *Nuclear performance assessment of ARIES-AT, Fusion Engineering and Design* **80** 99–110 (2006)]

Table V
Neutron, gamma and total fluences (in MGrays) for illustrative tokamak fusion commercial reactor design (ARIES-AT; 40 FPY, polyimide insulation)

	Neutrons	Gammas	Total
ARIES-AT			
Inboard	41	33	74
Divertor	31	26	57
Outboard	50	320	370

Higher specific performance in the insulation

The transmission line practice of allowing 2 kV/mm in an epoxy-glass system and 10 kV/mm in kapton has not yet been adopted by the fusion community. An obvious and inexpensive next-step in reducing the volume and cost of insulation would be halve the thickness of the insulation. This can be done either by halving the number of glass fabric plies from two to 1 or by using plies of half the thickness. For rectangular, potted winding packs, the interturn thickness can be reduced from 1.6 mm to 0.8 mm. This has a second benefit of reducing the bending in the corners of the conduits, because of reduced insulation compliance. It has a third benefit of reducing the cusp area in which it is hardest to avoid resin-rich regions. In an ITER TF-like design with individual ground wraps around each conductor, insulation thickness is also useful as a cushion between the conductor and plate, during a quench, when the conductor expands from overpressure and heating. The overall goal should be to reduce the insulation thickness by a factor of 2.5 for square conduits in winding packs and by 1.5 for conduits in plates. The goals can be restated as validating design to 1.25 kV/mm, nominal, in winding packs and to 2 kV/mm in conductor in plate. For smaller, multipole magnets, such as those used in Heavy Ion Fusion Drivers, it should be possible to develop all polyimide systems with peak electric fields of 5 kV/mm on quench.

Compatibility with heat treatment

The process of insulating a winding can be simplified if insulation can be applied during winding, then the winding and its insulation go through the heat treatment together. This is followed by vacuum impregnation. The cost savings in winding and insulation are counterbalanced by any damage to the insulating material or degradation during the winding and heat treatment. Significant testing has been done in Europe on different glasses and ceramics, showing that ceramics and some variants of S-glass show little degradation during heat treatment.

Another difficulty in putting the insulation through the heat treatment is the possibility of contaminating the surface of the conductor conduit with sizing or water vapor. In a famous or infamous experiment at the National High Field Magnet Laboratory, an Incoloy 908 conduit was destroyed by SAGBO, during heat treatment due to outgassing by the insulation. Outgassing of water from the insulation was blamed for the SAGBO, although this was never established. A specific goal would be to demonstrate the compatibility of Incoloy 908 with external insulation, either by 1) proving that water vapor was not the cause of the NHFML failure, 2) eliminating the failure mechanism by shot-peening, 3) developing an Incoloy alloy with higher resistance to SAGBO, or 4) improving the desizing/baking techniques to maximize glass strength, while minimizing

outgassing. The specific goal would be to demonstrate at least two orders of magnitude safety margin in water-outgassing for an insulation and Incoloy system. Rice has reported results with ceramic insulation/organic binder systems with high shear strength, heat treatment, and radiation resistance.

The overall goal of the compatibility task would be to ITER performance (i.e. 1.25 kV/mm) in an insulation system that has gone through the heat treatment.

Radiation resistance

The improved electrical performance goals will be demonstrated at radiation dosages up to 10^9 rads in 3x3 stacks of rectangular and at radiation dosages of $> 10^{10}$ rads for a circular conductor in plate. This is a factor of 10 improvement over ITER.

R&D tasks

A focused development effort with coordinated activities of universities, national labs and industry should be undertaken with the stated goals above. This should include development of inorganic insulating systems and ceramic insulators. Industrial partners have proposed the development of superior insulating materials with simultaneous improvements in insulation strength and radiation resistance. These should be supported by the fusion program.

An aggressive R&D plan that would develop insulating materials for an FNS mission are listed below.

Higher specific performance in the insulation

Means of achieving lower thickness of the insulation needs to be investigated. Advanced options, including the use of nanoparticles in the insulation, needs to be pursued, due to the large potential implications of increased life of the insulation. The implication of radiation on these advanced concepts need to be investigated.

Compatibility with heat treatment (for LTS)

Ideally, the insulator should be able to undergo the heat treatment process of low temperature superconductors. Presently, this is not the case, adding substantial effort (and cost) to add the insulator following the SC heat treatment. Most likely ceramic insulators should be investigated, as the heat treatment process are likely to damage any organic versions. After heat treatment, however, it may be possible to vacuum pressure impregnation of the winding

For high temperature superconductors, this is not the case, as the heat treatment of the superconductor takes place before making the cable (that is, the available tapes have already undergone heat treatment).

Radiation resistance (HTS)

Improvements in radiation resistance have usually been achieved by identifying and testing improved materials. The fusion program should test and confirm the radiation resistance of insulation systems, in particular those that are specifically under compression with limited shear stresses.

Planar inorganic insulation, applicable to both HTS plate magnets and copper plate magnets, should be developed. In the case of YBCO (2nd generation materials) there is limited insulator built-in within the superconductor itself. For the option where the superconducting material is deposited directly on the structural plates, it may be possible to build thicker insulators that could withstand the energy discharge voltages.

For copper coil designs with plates, the development of either flat plate insulation or sprayed-on insulation should be developed.

The fusion program should also measure the relation between improvements in insulation material properties and insulation system performance.

Facilities

There are facilities for the irradiation and testing of the insulators. However, the irradiation sources and testing facilities (with slightly activated samples) exist mostly overseas.

The US has some of the most advanced insulation development efforts. These efforts would have to be substantially increased, at the tone of 1000K/year, to investigate the

potential of improved insulation. At the present time, most of the insulation improvement efforts are concentrating in near term issues of ITER.