# ITER IN-VESSEL COIL DESIGN AND R&D

M. Kalish[1], P. Heitzenroeder[1], A. Brooks[1], L. Bryant[1], J. Chrzanowski[1], E. Daly[3], R. Feder[1], J. Feng[4], M. Messineo[1], M. Gomez[1], C. Hause[1], T. Bohm[2], I. Griffiths[5], A. Lipski[1], M. Mardenfeld[1], M. Nakahira[3], C. Neumeyer[1], R. Pillsbury[6], M. Sawan[2], M. Schaffer[7], R. Simmons[1], P. Titus[1], I. Zatz[1], T. Meighan[1]

[2]University of Wisconsin, [3]ITER International Organization, [4]Massachusetts Institute of Technology, [5]Oxford University,[7]General Atomics, [6]Sherbrooke Consulting, [8]Princeton University
[1]Princeton Plasma Physics Laboratory PO Box 451
Princeton, NJ 08543
mkalish@pppl.gov

***Abstract*—ITER will incorporate In Vessel Coils (IVCs) as a method of stabilizing "Edge Localized Modes" (ELM) and providing "Vertical Stabilization" (VS). To meet the ELM and VS Coil requirements strong coupling with the plasma is required so that it is necessary for the coils to be installed in the vessel just behind the blanket shield modules. Due to this close proximity to the plasma the radiation and temperature environment is severe and conventional electrical insulation materials and processes cannot be used. The development of mineral insulated conductor technology has been required in the IVC design to deal with this high radiation and high temperature environment. While mineral insulated conductor technology is not new, building a large magnet with high current carrying capability and a conductor diameter larger than the mineral insulated conductor currently manufactured requires R&D and the extension of existing technologies. A 59mm Stainless Steel Jacketed Mineral Insulated Conductor (SSMIC) using MgO is being developed for this application. The IVC ELM and VS coils design includes both the development of the fabrication techniques for the SSMIC and the design and analysis of the ELM and VS Coil assemblies.**

**The ELM coil assemblies consist of nine toroidal sectors of three (upper, midplane, and lower) 6-turn rectangular "picture frame coils" for a total of 27 coils mounted to the vacuum vessel. The ELM coil structural design must provide enough flexibility to relieve the thermal stresses in the coil while providing the stiffness to resist the high Lorentz (magnetic) loads on the coil. To achieve the required fatigue lifetime the ELM SSMIC conductors use a water cooled CuCrZr conductor. The VS coils consist of one upper and one lower 4-turn solenoid "ring" coil connected in an anti-series "saddle" arrangement. Because it is less stressed than the ELM coil conductor the VS SSMIC conductor use water cooled Cu instead of CuCrZr.**

**This paper summarizes the design, development, and testing to date of the SSMIC conductor as well as the design and analysis of the VS and ELM coil assemblies. Joining and assembly techniques for the SSMIC conductor are also discussed.**

***Keywords- ITER, Edge Localized Modes, ELM, Vertical Stabilization, VS, Magnesium Oxide Insulation, MgO, In Vessel Coils,IVC, Stainless Steel Mineral Insulated Conductor, SSMIC***

## I. SSMIC CONDUCTOR DEVELOPMENT

The design of the conductor serves as the basis of the coil system design. The operating environment of the IVC conductors is severe in terms of radiation and temperature and precludes the use of organic insulating materials and conventional methods for coil fabrication. Efforts to demonstrate sufficient radiation resistance of a "ceramic polymer" were proposed at the IVC CDR but fell short of requirements[1]."Stainless Steel Jacketed Mineral Insulated Conductor" (SSMIC) was chosen as the best technology for meeting the demanding radiation and thermal requirements.

The choice of insulating material came after a survey of existing high radiation environment conductor applications. The closest prior experience in terms of radiation effects is that of the high-energy physics community. A comprehensive study by CERN[2] evaluated a wide variety of technologies and applications and serves as an excellent reference. Their summary of radiation resistance is shown in Figure 1. Note that the ITER IVC radiation fluence is of order 3000MGy which falls between the $10^9$ and $10^{10}$ Gy divisions at the extreme right of the figure where choices are very limited. The prime candidate for the mineral insulation is compacted Magnesium Oxide (MgO) powder which is viable at these fluences.

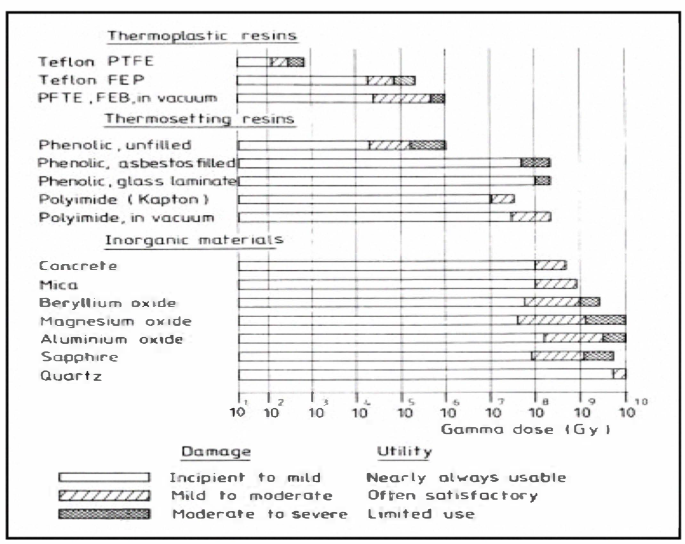


Figure 1. Radiation Resistance of Various Insulating Materials

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The ITER IVCs will experience temperatures as high as $150^{o}$C during operation and $240^{o}$C during bakeout. While these temperatures would challenge conventional insulation systems they are not a problem for Magnesium Oxide insulation which is typically used in heating elements and fireproof wiring. Commercial cables are rated for continuous operation at $250^{o}$C and transient operation up to $1000^{o}$C

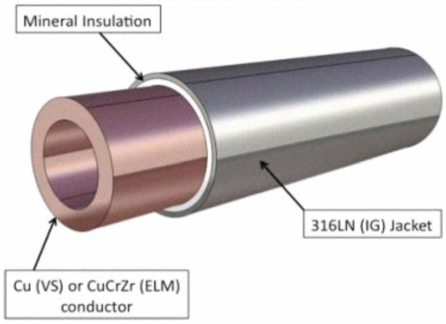


Figure 2. SSMIC Depiction

While the advantage of MgO insulation is that it exhibits excellent radiation resistance and operates at high temperatures it does have a limitation. MgO is hydroscopic. It absorbs water and if exposed to humid air within one hour it's dielectric properties can be degraded below acceptable limits. As a result care is required in handling the SSMIC conductor. The conductor must be first heated to drive off moisture and then sealed. During the R&D project temporary methods for drying and sealing the conductor were developed. During the FDR phase of the project more permanent ceramic seals will be developed for the gap between the stainless steel jacket and copper conductor.

## II. MAGNET DESIGN

The In-Vessel Coils, shown in Figure 3. consist of (27) ELM coils and (2) VS coils. Both the ELM and VS coils are wound from Stainless Steel Jacketed, Mineral Insulated Conductor (SSMIC) as described in Section I so that they can withstand the total neutron dose and the operational and bakeout temperature requirements.

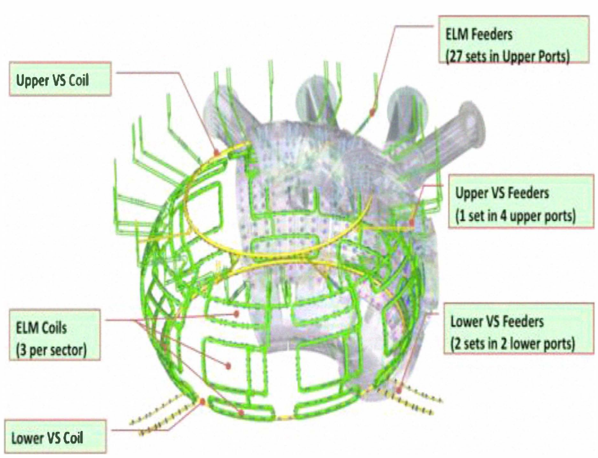


Figure 3. In Vessel Coils – ELM and VS

OFHC Copper is used in the VS Coil conductor but the copper alloy CuCrZr is used for the conductor in the SSMIC for the ELM coils. The ELM Coils are exposed to a more demanding fatigue condition and require a higher yield strength. The MgO thickness in the SSMIC for the VS coils is twice as thick (5 mm vs. 2.5 mm) as the MgO thickness in the ELM Coils because of the higher voltage requirements of the VS coils (2.4 kV for VS and 0.18 kV for ELM).

### A. *ELM Coils*

Each 40 degree sector of the vacuum vessel has 3 ELM Coils installed. A Lower ELM, Mid ELM, and an Upper ELM Coil. Figure 4. shows the ELM Coils installed in a typical vacuum vessel sector. Coil Feeders carry cooling and power to the coils and are routed through the upper ports.

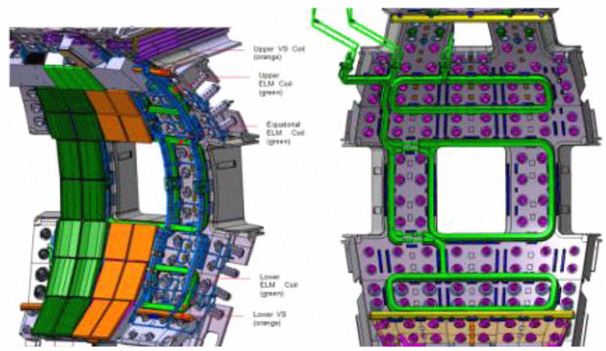

Figure 4. ELM Coils in Standard Vacuum Vessel Sector With and Without Blanket Shield Moduls

All ELM coils are similar in construction. ELM coils include:

- 6 turns/coil
- Max. +/- 15 kA (+/- 90 kA-turn/coil) DC and 5 Hz.
- Maximum design voltage to ground 180 V

Feeders use the same SSMIC as is used in the coil to supply water and power to each coil.

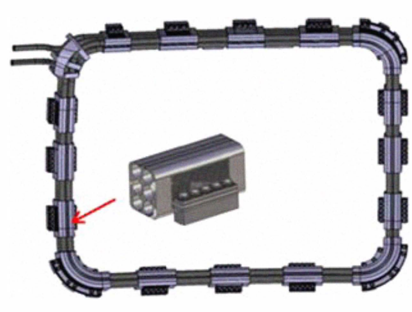

Figure 5. Mid ELM Coil

### B. *Vertical Stabilization (VS) Coils*

The VS coils are wound of SSMIC but differ from that used in the ELM coils in copper alloy and insulation thickness. The VS Coils are designed for 240 kA-turn/coil (60 kA/turn). Each coil has four turns, with each turn having its own individual feeders. This arrangement allows each turn to be an individual flow path and also allows individual turns to be bypassed in the event of a failure of one of the coil turns. VS Coil operation can continue with only three turns in the event of a failure. The VS Coils are mounted to rails on the vessel wall with a bolted flange as a permanent.

The upper coil has a major diameter of 12.199 m; the lower coil has a diameter of 15.242 m. The differing diameters are required to satisfy integration demands. The VS Coil structure utilizes a stiff continuous spine which running along the full diameter of the coil. This coil cross section is hard mounted to the vacuum vessel wall. As the VS Coil heats up the thermal expansion is restrained and the VS Coil is put in compression. This is advantageous in that it avoids the high tensile thermal stresses that are of concern in the ELM Coils. The VS coils will be assembled in the vacuum vessel from prefabricated components.

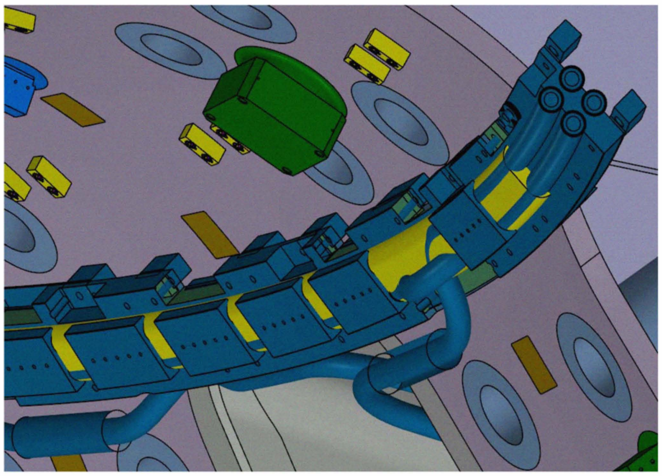

Figure 6. VS, Vertical Stabilization Coil

### C. *Joints*

Joining of IVC conductors will be necessary for both the ELM and VS coils. Due to a maximum available length of conductor, multiple conductors will be required per coil. Many more joints will be required to be fabricated in the vacuum vessel to join the coils to the coil feeders. Welding and induction brazing are being evaluated. An R&D contracts with EWI Edison Welding Institute. was implemented to develop these joining techniques. The joint is made by first brazing the copper conductor ends together and then welding a stainless steel sleeve or jacket across the joint gap. Non-destructive testing methods will be used to verify the integrity of the brazed copper joint prior to installing the stainless sleeve. The stainless steel sleeve will be slid over the joint and an orbital welder will be utilized to seal the ends. The joint will then be helium leak checked. Options for joint insulation being considered include injection of MgO powder or the installation of a ceramic insulating bushing or having the inner surface of the sleeve coated with ceramic material such as aluminum oxide.

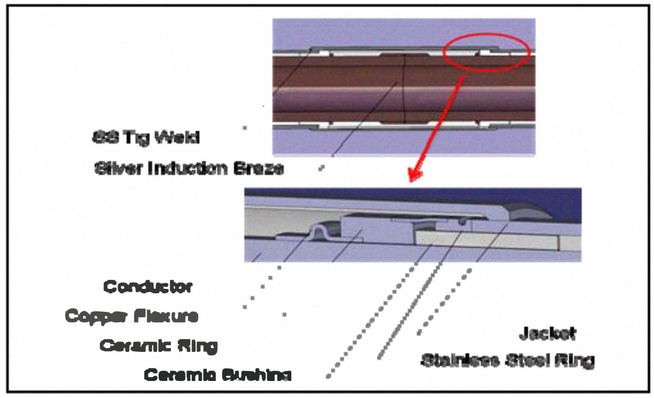


Figure 7. SSMIC Joint Design

## III. ANALYSIS

Analysis of the ELM and VS Coils required the integration of electromagnetic, neutronics, thermal hydraulic, and FEA stress analysis. The net heat balance in the coils was calculated taking into account inputs from the neutronics calculation and the thermal hydraulic calculation which balanced the resistive heating with the cooling capacity of the water. The resulting thermal profiles were input into the ANSYS model. The EM analysis was done using the "OPERA" code. Normal operation and disruption cases were analyzed using DINA inputs to perform OPERA simulations A survey of the load cases was reduced down to the worst case highest load cases. These loads were mapped unto the ANSYS model along with the thermal boundary conditions already discussed.

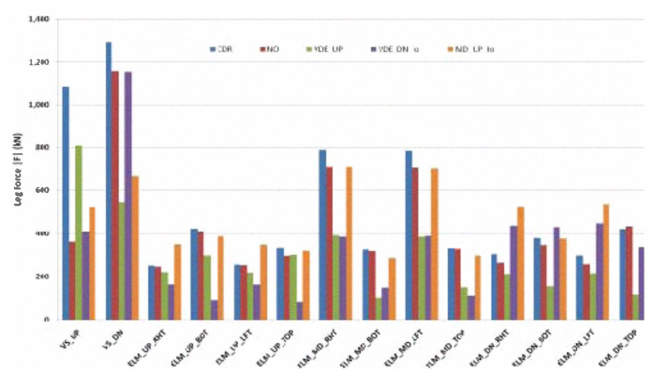


Figure 8. EM Diruption and Operating Load Summary

The largest Electro Magnetic, EM, forces acting on the coil are by far are due to $I_{ELM}$ x $B_{toroidal}$. This results in forces either pushing or pulling the poloidal legs of the coil normal to the vessel wall. Figure 8. For the ELM Coils the challenge to the design is driven by fatigue requirements. ELM coil operation requires 5Hz excitation of the coils for 1000 seconds and 30,000 plasma discharges. The high number of cycles requires the ELM coil to meet infinite life criteria with respect to both the endurance limit of the material and the crack propagation criteria.

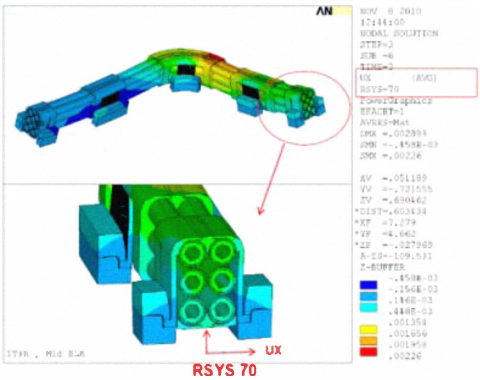


Figure 9. Displacement Plot From Mid ELM ANSYS Analysis

Secondary forces on the ELM coil are due to thermal expansion. If the thermal expansion of the ELM coil due to resistive and neutron heating during operation is inhibited, significant stresses will develop along the length of the conductor. These thermal stresses determine the value of the mean stress, and the EM loads determine the value of the range stress which are the primary quantities in fatigue life evaluation. High stresses due to EM loads where the coil pack leaves the support brackets are being addressed with design modifications aimed at increasing the lateral stiffness of the coil cross section. Welding the conductors together to form a continuous stiff cross section is being evaluated (see Figure 10. ). Thermal stresses can be controlled by allowing thermal expansion to remain unopposed. Applying this approach, a flexible coil support design is used. Flexible leaf spring elements which are integral parts of the support clamps connect the coils to the VV (see Figure 5. The leaf springs are broken up by a series of cuts to reduce their stiffness in the axial direction and to allow thermal growth. In this manner, the support provides flexibility to permit thermal expansion in the plane of the coil while still providing a strong load path normal to the vessel wall to react EM loads.

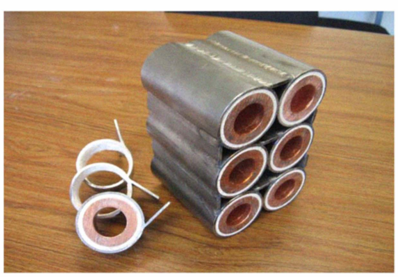

Figure 10. ELM Coil Pack Welding R&D

For the VS coil design conductor thermal stresses are less problematic because of the symmetric full circle geometry (no corner bends as in the ELM). Stresses in the conductor are taken in compression as the strong VS Coil structure restrains the thermal growth. Stress issues for the VS Coils are concentrated in the lead areas where flexible leads meet the rigid coil. Lead break-outs have bends and consequently have similar design problems to the ELM coil corners with respect to resolving bending stresses due to thermal growth. Supports for the VS Coil lead outs are under development. VS Coil support spine stresses are highest where the spine meets the clamps. The support structure design is being modified to bring these stresses within static and fatigue allowables. Bolt stresses during the disruption are within the allowables of high strength bolts. Pre-loading the bolts eliminates the alternating stress component.

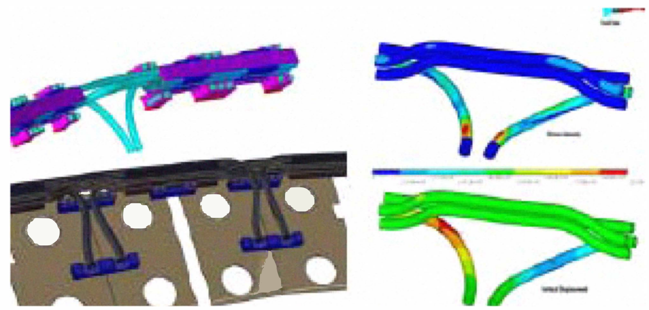

Figure 11. Analysis of VS Coil Leads

## IV. R&D Prototype Conductor

Mineral insulated cable is routinely used for industrial (heating elements, fire resistant control wiring, etc.) and research applications (radiation resistant coils in high-energy physics, and magnetic pickup coils in fusion applications). However, the sizes needed for those applications are considerably smaller than those required for the in vessel coils. For that reason, it was necessary to perform R&D prototype manufacturing studies to determine the feasibility of producing the SSMIC in the sizes required. Approximately full-size prototype lengths of the stainless steel jacketed mineral insulated copper conductor were successfully produced by two sources: ASIPP of China; and Tyco of Canada. The ASIPP prototypes utilized MgO performed rings to mate the copper conductor with the stainless steel jacket whereas the Tyco prototypes utilized a vertical powder filling process.


Figure 12. Three Varieties of Prototype Conductor

The lengths of prototype conductor were subsequently used to develop the joining techniques including the induction brazing and orbital tig welding. Figure 13. shows induction brazing trials performed at Edison Welding Institute along with a completed prototype coil joint.

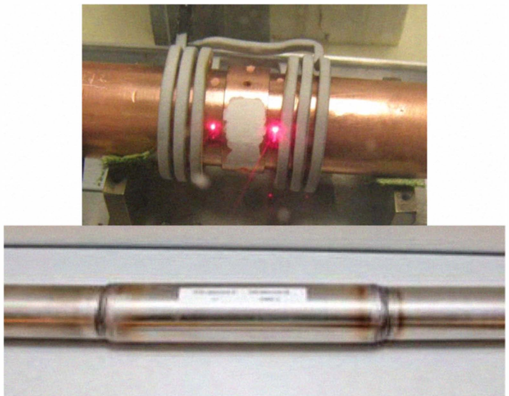

Figure 13. Copper Induction Brazing and Prototype Joint

## V. MECHANICAL TESTING

Mechanical tests of the prototype SSMIC were performed to provide information on the compressive strength of the MgO, as well as the strength of the shear connection between the central conductor and outer jacket through the MgO. In addition the behavior of a bent conductor when subjected to cyclic loading was tested. This information is being used to validate the design and analyses of the IVCs.

Three point bend tests were performed to determine the flexural properties of the three different types of SSMIC prototypes. One test was performed on each of the sample types at 21C. The samples used in the bend test were approximately 500mm long. The test fixture was designed to apply the load on the cross-section equally around the circumference of the upper half of the conductor. This was necessary so that the load was spread out sufficiently to preclude the crushing of the outer jacket which would skew the test result. An extensometer was used to measure the deflection on the side opposite the application of the load to obtain deflection measurements that were not influenced by the local deformation. The end supports of the beam pivot on pins, See Figure 14. The SSMIC test was modeled using ANSYS and the results of the bend tests were plotted against the analytical result.

Next testing of the SSMIC was performed to characterize the mechanical properties of the MgO insulation in compression. Lengths of 100mm and 50mm conductor were sectioned longitudinally. The specimen was subjected to an increasing axial compressive load. Both load and strain were monitored, and the load deflection curve was plotted. The test was completed at room temperature, 160C, and 240C. The test was completed nine times, three times each for three different samples.

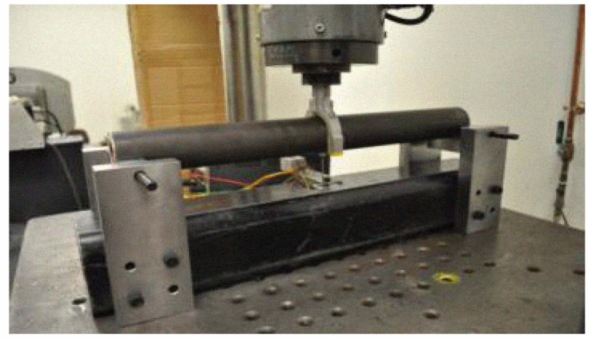

Figure 14. Bend Testing of SSMIC

The third test completed was the shear test. Shear testing determined the shear load deflection curve when the copper core of the sample was pressed out of the center of the SSMIC. A total of nine 100mm high samples were tested, a quantity of three for each of three different sample types. The tests were performed at room temperature, 160C, and 240C for each sample type. For the room temperature samples strain gauges were added to the jacket to determine if the jacket contracted when the copper core was removed. This measurement was intended to be used to calculate the compressive load that the stainless steel jacket applied to the MgO

The final test was the cyclical load U-bend test. The cyclic load U-bend testing was design to demonstrate that as the SSMIC is loaded axially around the coil corners the MgO insulation remains intact and the copper conductor does not migrate to one side or fail the MgO insulation. The U Bend sample was loaded to 50.8kN (1.6 times the calculated operating load) and cycled 30,000 times (design life of ITER). The test fixture distributed the load on the test sample through the use of a cable. The cable was threaded through the center of the conductor and attached to a spreader bar which was grabbed by the test fixture and pulled upward. This cable distributed the load evenly on the inside of the conductor to more accurately simulate the EM loading. The test was performed at room temperature. See Figure 15.

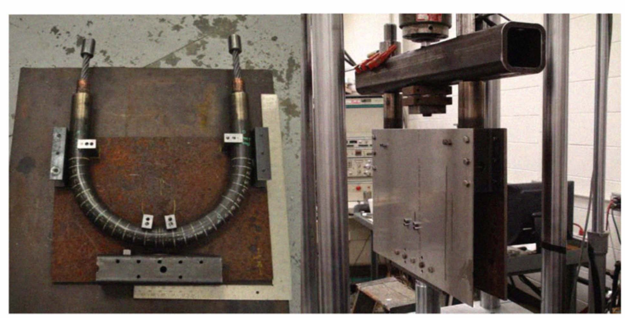

Figure 15. Cyclical Pull Test of U Bend Specimen

The following were the conclusions and lessons learned from the Mechanical Testing:

The shear strength of MgO interface is low. However the shear strength of MgO interface is not critical. Bonded vs un-bonded boundary conditions applied to the finite element analysis yield very close stress and deflection results. This result shows us that the MgO must act to transfer loads from the stainless steel case to the copper in compression but is not required to act in shear.

MgO in the SSMIC can handle compression at levels exceeding the design point. Testing did not successfully measure the MgO modulus but did confirm it remains intact at compressive forces in excess of the design point by a factor of 9 to 10. FEA results shows that a wide range of modulus values for the MgO have a very small effect on deflection and stress in bending of the conductor so it is not critical that we characterize the the MgO modulus with testing.

Cyclical loading of the UBend conductor sample at 1.6x operating loads does not appear to damage the MgO or shift the conductor. Cutting open and examining the conductor as well as electrical testing indicate that the copper conductor did not shift.

One out of three bend test results matched analytical results closely. Further investigation and testing is recommended to understand fully the beam behavior in bending.

## VI. Electrical Testing

An electrical testing program was developed to investigate the electrical behavior of the SSMIC prototypes and compare measured parameters to published data. The following tests were performed:

- DC leakage current at 1kV DC from room temperature (RT) up to maximum operating temperature (150°C);
- Dissipation factor (insulation power factor) at RT and 150°C;
- Voltage endurance at 150°C;
- DC breakdown at 150°C.

It was found that leakage resistance results were better than predicted using the Tyco engineering data. The dielectric constant (relative permittivity) was somewhat higher than that given in the Tyco engineering data. The dissipation factor is in the range given by the Tyco engineering data. The results from these tests can be used to update modeling assumptions.

The DC breakdown test were mostly better than predicted from Tyco engineering data (3kV/mm) but since they occurred at the sample ends, one cannot draw conclusions about the intrinsic MgO dielectric strength. The dielectric limit of the SSMIC almost always was driven by the end terminations or was due to the MgO insulation absorbing moisture. The development of the test samples which included baking out and sealing the samples reinforced the importance of proper handling and sealing of the MgO. The design of a permanent seal and testing will continue during the final design phase of the project.


Figure 16. SSMIC Prototype Sample DC Breakdown Voltage (kV)

In general there were no major surprise results from the electrical testing. Future testing should be divided into tests designed to prove out the SSMIC fabrication process and tests to characterize the MgO, using the formulation and compaction anticipated in the production conductor. The latter tests should use a configuration optimized for testing and will require testing both with and without the presence of a radiation field

## VII. Summary

In conclusion prototype In Vessel Coil conductor has been fabricated and tested with good results. ELM and VS Coils have been designed and integrated into the Vacuum Vessel. Preliminary analysis was completed leading to a strong understanding of the electromagnetic and thermal loading on the coils. Some open issues with respect to fatigue stresses remain and need to be resolved. Details of the design analysis, prototype production and testing can all be found in the detailed design report "Final Report on the Preliminary Design of the ITER In-Vessel Coil System"[3]. Work is continuing with the Final Design Phase of the project. The Final Design Phase will include fabrication of a section of the VS Coil and a full scale Mid ELM Coil prototype. This work will be completed as a collaboration between Princeton Plasma Physics Laboratory in the US and ASIPP in China under a task agreement arranged with the ITER International Organization.

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