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INTERELECTRODE INSULATOR DEVELOPMENT FOR THE UTSI
MHD GENERATOR

Topical Report

By
M. S. Beaton
C. W. Long
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October 1979

Work Performed Under Contract No. AC01-79ET10815

The Energy Conversion Division
The University of Tennessee Space Institute
Tullahoma, Tennessee

U. S. DEPARTMENT OF ENERGY

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UTSI
Energy Conversion Division

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ABSTRACT

For successful operation of an MHD generator, the electrodes must be separated by a dielectric material capable of withstanding temperatures of several hundred degrees (centigrade) as well as erosion, chemical attack and penetration by slag and seed compounds. The insulators must also either seal the interelectrode gap from gas leaks to the channel exterior, or be used in conjunction with a gasket.

The UTSI approach has been to use commercially available insulating materials that are easily workable, such as ceramic felts and textiles with appropriate treatments to enhance thermal conductivity and reduce moisture absorption and gas permeability. In two series of tests on numerous insulator systems under actual MHD run conditions, the best results have been shown by a woven leached silica cloth (Refrasil) coated with a commercial boron nitride slurry. Insulators made of solid plate boron nitride and also of boron nitride strips backed up with a gasketing material have also given promising performance. Continued experimentation and development of insulator systems is needed.

I. INTRODUCTION

A. Objective

The operation of an MHD generator depends upon the electrical individuality of a series of electrodes, each at a potential different from that of the others. Therefore, an effective insulator must be devised which will maintain the electrical integrity of each electrode under the severe conditions present in the generator.

B. Generator Environment

The MHD generator under development at UTSI is of the coal-fired, water-cooled slagging diagonal conducting wall (DCW) type. It consists of parallel flat copper plate electrodes (each about 12.7 mm [0.5 inch] thick) having rectangular inside cut-outs through which the conducting gas flows. This type of generator is shown in Figure 1. Each electrode is individually water-cooled and separated from adjacent electrodes by a relatively thin (less than about 3.2 mm [0.125 inch]) electrically insulating and sealing material.

Gas temperatures in the MHD channel are about 2300-2800K (3681-4581°F), while the electrode-slag and insulator-slag surface temperatures are between about 973K (1300°F) and 1175K (1650°F). In addition, the upstream portion of the generator operates at a positive pressure while the downstream operates at a negative pressure.

The chemical environment in the generator consists of coal combustion gas (i.e. H_2 , CO, H_2S , and NO) and potassium (partially ionized) and slag (about 55 percent SiO_2 , 25 percent Al_2O_3 , 12 percent Fe_3O_4 , 4 percent MgO , 2 percent CaO , and 2 percent K_2O). Slag mixed with potassium compounds deposit on the walls with a transition from liquid adjacent to the flow stream to solid at the walls. Under generator conditions at UTSI, the equilibrium slag thickness is about 1-2 mm (0.04-0.08 inch). Prior to the development of a protective solid slag layer, electrode and insulator erosion may result from the gas flow and from gas propelled liquid slag and seed on the wall. The insulator is also liable to penetration and chemical attack by slag and seed compounds.

C. Insulator Requirements

In addition to being dielectric, the insulator material must be thermally, chemically and mechanically stable at high temperatures for periods of several 1000 hours. It must resist erosion and degradation through reaction with either the coal slag or seed compounds. In the UTSI generator design, the insulator must also either seal the interelectrode gaps against gas leaks or be used in conjunction with a sealing gasket which is protected from the hot gases and slag in the channel interior. Additional considerations of importance in large scale demonstration and commercial utility plants will be availability and cost of the materials, and their ease of preparation.

Figure 1. A Diagonal Conducting Wall (DCW) MHD Generator Used at UTSI

The insulating material should be both thin and have good thermal conductivity in order to prevent it from overheating. It should be flexible and non-brittle to prevent cracking or breaking due to handling or to bolting forces. In addition, it should be soft enough to mold to the electrode surfaces so as to form an effective gasket against gas leakage.

II. BACKGROUND

A. Prior Experience

The earlier generator work at UTSI, i.e. prior to 1977, was carried out using high temperature organic and non-woven refractory fiber sheet materials. The performance of these classes of materials was satisfactory for short run times. These materials fail to meet the total demand for operation and facilities use, however, due to insufficient thermal resistance, porosity, or other problems.

Excessive burnback of the insulator adjacent to the channel interior due to either inadequate thermal conductivity or inadequate refractoriness often resulted in electrical breakdown across the slag which filled into the gap. Experience both at UTSI and at other facilities, such as Pacific Northwest Laboratory,¹ Westinghouse,² and Mississippi State³ has shown that potassium penetration and reaction can be extensive and that the presence of a DC electric field can substantially enhance these effects. The degree of penetration and reaction varies from material to material and is dependent upon the composition, structure, and fabrication. External factors, such as the temperature and the electric current density and voltage were found to influence these effects.

B. Candidate Materials Properties

The most popular high temperature insulator classes are oxide ceramics and certain special ceramic compounds, such as $MgAl_2O_4$ spinel and boron nitride. Table I shows some of the properties of the most important commercial refractory oxides which are manufactured essentially of pure materials. Many of these oxides are produced in several grades, but with a few exceptions only those of highest purity have the properties described here.

1. Electrical Properties

The electrical properties of refractory ceramic materials are markedly affected by impurities, porosity, and atmosphere.⁵ The electrical resistance of most refractory oxides is decreased rather than increased by an increase in porosity and is also decreased, in most cases, by an increase in impurities. Different atmospheres may cause either an increase or decrease in resistance, particularly at high temperatures. Moreover, these materials have negative temperature coefficients of resistivity. Table II gives values for electrical resistivity at 1073K (800°C), and the dielectric strength and dielectric constant at room temperature for a number of ceramic insulator materials.

TABLE 1. PROPERTIES OF COMMERCIAL REFRACTORY OXIDES⁴

Material	Formula	Melting Point, °C	Limit of Usefulness in Oxidizing Atmospheres, °C	Hardness, Mohs' Scale	Coefficient of Linear Expansion		Thermal Conductivity cal/(sec cm²)(°C/cm)			Thermal Shock Resistance	Stability				
					Temperature, °C	E × 10⁷	Temperature, °C	Porosity, %	C × 10⁴		Reducing Atmosphere	Carbon	Acid Slags	Basic Slags	Metals
Alumina	Al₂O₃	2015	1950	9 (8, 12)	20-1580	80 (31)	1200	23	57 (31)	Good	Good	Fair	Good	Good	Good
Beryllia	BeO	2550	2400	9 (12)	20-1400	95 (31)	1200	5-10	393 (74)	Excellent	Excellent	Excellent	...	Fair	Good
Calcia	CaO	2600	2400	4.5 (87)	20-1200	136 (56)	1000	9	170 (74)	Fair	Poor	Poor	Poor	Fair	Fair
Magnesia	MgO	2800	2400	6 (8, 12)	20-1400	140 (31)	1200	22	61 (31)	Fair	Poor	Good	Poor	Good	Fair
Silica (crystalline)	SiO₂	1728	1680	7 (8)	20-300 300-1100	430 ^a (57) 30	1100	...	38 (57)	Poor to 320°C Excellent above 320°C	Poor	Poor	Good	Poor	Poor
Silica (vitreous)	SiO₂	...	...	...	20-1250	5 (31)	...	0-9	33 (31)	Excellent	Fair	Good	Good	...	...
Thoria	ThO₂	3300	2700	7 (12)	20-1400	95 (31)	1200	17	0 (74)	Poor	Good	Fair	Good	Good	Excellent
Zirconia (stabilized)	ZrO₂	2600	2500	7-8 (42)	20-1200	55 ^b (31)	1200	28	22 (31)	Fair	Good	Fair	Good	Poor	Good
Mullite	3Al₂O₃ · 2SiO₂	1830 ^c	1800	6-7	20-1320	45 (31)	1200	30	64 (74)	Fair	Fair	Fair	Good	Fair	Fair
Spinel	MgO · Al₂O₃	2110	1900	8 (8, 12)	20-1250	90 (31)	1300	36	50 (31)	Poor	...	Fair	Fair	Good	...
Zircon	ZrO₂ · SiO₂	2420	1870	7.5 (8)	20-1200	55 (59)	1000	30	50 (31)	Good	Fair	Fair	Good	Poor	Good

^a Depends upon crystalline forms.

^b Depends upon degree of stabilization.

^c Incongruent.

TABLE II. ELECTRICAL PROPERTIES OF SOME CERAMIC INSULATORS⁶

	Resistivity at 800°C (ohm-cm)	Dielectric Strength at 25°C (v/mil)	Rel. Dielectric Constant at 25°C and 10 ⁶ Hz
Boron Nitride (BN)	5.0×10^9	790-986	4.1-4.11
Beryllia (BeO)	7.0×10^9	830	11.8-13.7
Alumina (Al ₂ O ₃)	6.3×10^8	40-160	8.80-12.3
Magnesia (MgO)	6.3×10^8		9.65-11.5
Low-Loss Steatite (MgO-SiO ₂)	7.7×10^7		
Silicon Nitride (Si ₃ N ₄)	1.6×10^7	(No Data)	
94% Magnesia	7.0×10^7		
Yttria (Y ₂ O ₃)	7.9×10^6		
Fused Silica (SiO ₂)	7.9×10^6	203	3.78
Clay-Bonded 90% Alumina	4.0×10^6		
Mullite (Al ₆ Si ₂ O ₁₃)	2.0×10^6	100	6.60
Zircon Porcelain	2.0×10^6	250-350	7.1-10.5
Steatite (MgO-SiO ₂)	1.7×10^6	250-350	5.5-7.5
Aluminum Nitride (AlN)	1.6×10^6		
Thoria (ThO ₂)	8.0×10^5		
Spinel (MgO·Al ₂ O ₃)	8.0×10^5		
Hafnia (HfO ₂)	2.0×10^5		
Ceria (CeO ₂)	6.5×10^4		
Zirconia (ZrO ₂)	8.0×10^3		20.0
Stabilized Zirconia	8.0×10^2		
Asbestos			3.1
Forsterite (Mg ₂ SiO ₄)		200-300	6.10
Corderite (Mg ₂ Al ₄ Si ₅ O ₁₈)	8.0×10^5	40-250	4.5-5.4
Mica, Ruby		5080	5.4
TiO ₂		100-210	14-100
Soda-Lime Silica Glass			6.90

The property of interest in preventing electrical discharge through the insulator is the dielectric strength. The minimum value for an insulating ceramic according to the joint Army and Navy JAN-I-10, Radio, Class L specification is 180 volts/mil, while the dielectric constant at room temperature should be less than 12. Increased temperature results in a radical decrease in the dielectric strength due largely to DC conductivity effects, which increase exponentially with temperature. A corresponding sharp increase occurs in the dielectric constant. The effect of porosity is to decrease both the dielectric constant and the dielectric strength.

2. Chemical Stability

The stability of a number of refractory oxides is shown in Table I in the presence of reducing and oxidizing atmospheres, carbon, acid and basic slags, and metals. Lack of stability may include a tendency to hydrate, oxidize, reduce or volatilize in certain environments at high temperatures. Magnesia tends to hydrate but a fairly stable form is available produced by a high temperature "dead-burning" process. The refractory metal oxides of cerium, chromium, cobalt, gallium, nickel, tin, titanium, and zinc are easily reduced. However, these oxides are of no interest as insulating refractories, since they have relatively high electrical conductivities. The same is true of the oxides of niobium, manganese, uranium, and vanadium which are readily oxidized, mostly to higher oxides with relatively low melting points. Some of the most refractory of the oxides may be listed in the following order of increasing reactivity with most metals: ThO_2 , BeO , ZrO_2 , Al_2O_3 , and MgO . Unseeded coal slag is highly acidic. Since potassium exists in seeded slag in the MHD generator, however, the acidity is significantly reduced. The actual basic to acid ratio varies with location around the generator frame due to the charge effect on the potassium ions.

3. Thermal Properties

The thermal conductivity, coefficient of thermal expansion and the thermal shock resistance are given in Table I for some commercial refractory oxides. Table III shows the thermal conductivities of polycrystalline oxide materials at 1073K corrected to theoretical density. The best grade of boron nitride has a thermal conductivity of about 0.102 cal./sq. cm/sec./ $^{\circ}\text{C}/\text{cm}$ which is superior to any other electrical insulator at 1073K (800 $^{\circ}\text{C}$). Its thermal expansion coefficient is also very low, $0-2.8 \times 10^{-6}/^{\circ}\text{C}$ depending upon the grade.

4. Background Conclusions

Based upon the thermal, chemical, and electrical properties of insulating refractories reported in the general literature, boron nitride, alumina and spinel ($\text{MgO} \cdot \text{Al}_2\text{O}_3$) would appear to be

TABLE III. THERMAL CONDUCTIVITIES OF POLYCRYSTALLINE
OXIDES AT 1073K CORRECTED TO THEORETICAL DENSITY⁷

<u>Material</u>	<u>Thermal Conductivity, Cal/(sec cm²) (K/cm)</u>
BeO	0.0645
MgO	0.0203
CaO	0.0191
Al ₂ O ₃	0.0172
Spinel (MgAl ₂ O ₄)	0.0159
ZnO	0.01305
NiO	0.0110
Zircon (ZrSiO ₄)	0.0103
Mullite (Al ₆ Si ₂ O ₁₃)	0.0093
UO ₂	0.00885
ThO ₂	0.00814
TiO ₂	0.0081
Forsterite (Mg ₂ SiO ₄)	0.0064
ZrO ₂	0.00525

the best materials for MHD electrode insulators in order of decreasing preference. Boron nitride has the highest thermal conductivity and electrical resistivity, high dielectric strength, low dielectric constant and lowest thermal expansion. It is stable in reducing atmospheres and corrosion resistant. Also, it is nontoxic and readily machined. The second choice would be beryllia were it not highly toxic and expensive. Alumina has good stability and electrical resistivity and fair thermal conductivity. Its dielectric constant is two to three times that of boron nitride and its dielectric strength is about four times less. However, it is available in many forms and is relatively inexpensive. Magnesia has many good properties, but its principal drawback is that it fluxes acidic oxides, such as silica, so that they would readily penetrate the ceramic. It also has a tendency to hydration and to reduction at high temperatures.

While the "handbook" properties give some indication of which materials would be preferred for MHD electrode insulators, many unknowns remain, such as the effects of seed and slag corrosion or penetration, erosion, electrochemical corrosion, porosity, etc. The "handbook" values are mostly for dense, solid materials while flexible felts or textiles are desirable as electrode insulators. The effectiveness of various materials in these forms to meet the total requirements can only be ascertained by testing under simulated and actual MHD conditions. The testing described in this report was performed for this purpose.

III. INSULATOR TESTING

A. First Series

1. Baseline Tests (1st and 2nd Quarters 1977)

Two types of tests on candidate insulators were run during early 1977. In the first, materials were cold tested for pressure sealing using Cell II electrodes. The other tests were of insulators in Cell II (conductivity channel) under run conditions. Table IV summarizes both types of tests.

Of the 11 insulators that were pressure tested, the best results were obtained with silicone rubber in the form of either an O-ring or as 1/32 inch thick sheet. Refrasil woven silica fabric coated with GE Glyptol was a close second best. The worst results were with Mylar polyester sheet which leaked at all pressures.

In the Cell II tests, six electrodes separated by five insulators were assembled and an axial field (current limited to 1 ampere) was applied to the assembly while firing the cell with seeded coal. Silicone rubber sheet (0.79 mm [0.031 inch] thick) performed well for 10 minutes maintaining 26 volts. However,

TABLE IV. TEST CONDITION FOR INSULATOR MATERIALS

Material, Type	Seal Pressure PSIG		Comments
	Cold	Hot	
+Garlock 900, 1/16" (asbestos)			Best tested to date, burns back 1 mm or less.
+Garlock 900, 1/8" (asbestos)			Burns back 3-5 mm. No sealing tests.
+Fiberfrax, 1/32" (aluminosilicate)			Burns back <1 mm. Absorbs water. Good insulation if dry.
*Kaowool (aluminosilicate)	10		Same type material as Fiberfrax.
*Mylar, 0.010" (polyester)	<2		Subject to excessive burning, no resistance to arc burn. Leaked at all positive pressures in sealing test.
Silicone Rubber			
*O-ring	50	52	Best material test for pressure sealing.
*1/32" sheet	50	52	Suffers excessive burnback and shorting.
John-Manville			
*#219, 1/32"	10		
+Alumina, 0.015" plasma sprayed			Poor electrical insulation when used alone.
+Alumina, 0.015" sprayed 1/8" overlap onto gas surface			Good insulation when used with Garlock or Fiberfrax sheet.
+Alumina, 0.015" covering entire mating and gas surfaces of a 1/2" Cell II			When used with 1/16" Garlock this arrangement showed good electrical resistance. Alumina on gas surface was missing upon disassembly of channel, probably burned away during running.
Refrasil (woven silica fabric)			
*Ad-48	15 (leaked)		Coated with Kaowool Rigidizer
*Ad-48	45		Coated with GE Glyptol
*Refrasil Ad-48	15		Adhesive backed, untreated
*Refrasil UC100-28	10		Fluorosilicone filled-penetrated between threads well, but cured too hard to seal between itself and electrode plates,

- * - Material cold tested for sealing with Cell II electrodes
- + - Material tested in Cell II under run conditions
- @ - Material planned for testing

this potential dropped to 12 volts after 20 minutes, 2 volts after 30 minutes and less than 1 volt after 40 minutes operating time. Upon disassembly of the channel, the silicone rubber was found to have burned back from the inside electrode surface 3 to 5 mm. Tests with Mylar polyester sheet insulators gave similar results with only 1 to 3 mm burnback.

An elastomer matrix asbestos fiber sheet material, Garlock 900, was tested in 1.59 mm (1/16 inch) and 3.18 mm (1/8 inch) thicknesses. The edges of the material adjacent to the channel interior burned away leaving a region of asbestos fibers surrounded by voids into which condensed seed compounds entered. During long runs this could lead to interelectrode shorting. Burnback of the thinner sheet was only about 1 mm or less while the thicker was burned back about 3 to 5 mm.

Aluminosilicate (Fiberfrax) sheet, 2.75 mm (1/32 inch) thick, was found to give good results with burnback of less than 1 mm. However, its tendency to hydrate resulted in deteriorated insulating properties.

Cell II tests were also run with electrodes plasma sprayed with 0.015 inch thick coatings of alumina on both mating surfaces. This did not give good electrical insulation by itself but did used in conjunction with sheets of aluminum silicate (Fiberfrax) or asbestos (Garlock).

Woven silica fabric (Refrasil) impregnated with a fluoro-silicone elastomer was also tested, but the elastomer cured too hard to seal the interelectrode gap against gas leaks.

Of all these materials tested, the 1/16 inch elastomer matrix asbestos (Garlock) was judged to be the best although its performance was not ideal. No deterioration of the 1/16 inch Garlock was evident in Cell II tests after testing for a total of 160 minutes.

2. Test Plan 33 (3rd Quarter 1977)

Testing in the second phase of this series of insulator evaluations began with the inclusion of four insulators each of the elastomer matrix asbestos and the aluminosilicate felt in Channel IB tests under actual generating conditions. The asbestos sheet maintained voltage differences of 13-27 volts, depending on magnetic field and combustion parameters, while the aluminosilicate felt sustained 11-21 volts under the same conditions during one run of 19.5 minutes duration. No further generator testing was done in this test plan due to improper combustor operation.

3. Test Plan 30 (4th Quarter 1977 - 1st Quarter 1978)

While combustion efficiency was being studied in Cell II, the generator channel, Channel IB, was disassembled, cleaned and reassembled using the combinations of gasket/insulator sheet materials and plasma sprayed layers listed in Table V. The plasma sprayed layer was placed on the upstream face of each electrode with the coating extending 3 mm (1/8 inch) over the upstream edge of the electrode channel interior. Figure 2 is a schematic diagram of the insulator arrangement. Magnetic field strength during the tests was switched between low (1.4T) and high (1.95T) due to the power supply duty rating. Four runs were made totalling 131 minutes.

During the first run (Run 1548) of 46 minutes duration, coal and oxygen flow and, therefore power production, was very good. Gas velocity was supersonic and the average generator power was 53 KW at low field and 85 KW at high field. Plots of interelectrode voltage difference for each insulator of interest are shown for Run 1548 in Figure 3. Distinct regions of alternating high and low voltage difference may be noted corresponding to the cycling of the magnetic field. A slight downward trend with time is noted between Electrodes 27/28 and 32/33 where zirconia cloth and silica cloth/boron nitride insulators were used. The voltage differences of these electrodes were initially higher than for those located farther downstream, but stabilize at levels at or above the voltage differences for other insulators. None of the insulators monitored showed indication of electrical breakdown during Run 1548.

The second run of 20 minutes produced less power because of a water leak in Electrode 16 during start-up. Lumping of coal in the hopper caused feedline plugging and combustor water leaks also caused lower power outputs in the final two runs of about 35 minutes each. Results from the last run showed that the asbestos material (Insulator 53) was beginning to fail as an insulator.

With the first indication of electrical failure in insulator material, the generator channel was disassembled to allow physical examination of the insulators. In all cases the insulator sheets were burned back at the anode end in exactly the same pattern and to the same extent that anode recession had occurred. While none of the subject insulator sheet materials showed indication of seed penetration during the elapsed time of these tests; the elastomer matrix asbestos Insulator 53 had been partially shortened at the cathode by the penetration of water soluble potassium-sulfur compounds between itself and the adjacent electrodes. The elastomer matrix asbestos material was not sufficiently compliant to allow sealing of the interelectrode gap with the bolting force available in this design.

TABLE V. INTERELECTRODE INSULATOR SYSTEMS FOR TP 39

<u>Electrode Numbers</u>	<u>Dielectric Sheet Materials</u>	<u>Plasma Sprayed Coating</u>
1-20	1/16th inch Garlock 900	Alumina (on one electrode face extending 1/8th inch onto gas face)
21-25	Zircar zirconia cloth (thick. 0.015 inch)	Al bronze/ Al_2O_3
26-30	Zircar zirconia cloth (thick. 0.015 inch)	$\text{NiAl} + \text{ZrO}_2/\text{ZrO}_2$
31-35	Refrasil + BN slurry (Type A) (thick. 0.015 inch)	Ni plate/ $\text{NiAl} + \text{Al}_2\text{O}_3$
36-40	Refrasil + BN slurry (Type S) (thick. 0.015 inch)	Al bronze + $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3$
41-45	Fiberfrax (thick. 0.020 inch)	$\text{MgO} \cdot \text{Al}_2\text{O}_3$ spinel
46-50	1/32nd Garlock 900	$\text{MgO} \cdot \text{Al}_2\text{O}_3$ spinel
51-55	1/32nd Garlock 900	Al_2O_3
56-60	Fiberfrax (thick. 0.020 inch)	Al_2O_3
61-71	1/16th inch Garlock 900	Alumina (same as first 20 electrodes)

Figure 2. Schematic Diagram of Interelectrode Insulating System.

Figure 3. Voltage Differences Across Several Insulators During Run 1548. Vertical Scale, 5 Volts/Division. See Table V, p. 13, for corresponding insulator types.

Test Plan 30 results indicated good performance of refractory ceramic cloths and felts.⁸ The zirconia cloth and the boron nitride/silica cloth appeared to perform equally well; and, therefore, the silica would be preferred as it is much less expensive. The loss of plasma sprayed ceramic at the anode without interelectrode shortening negates the utility of this technique of increasing insulator thickness. Current transport caused the recession of both the neighboring anode surfaces and the interposed ceramic insulator at a slow rate allowing operation for a period of hours compared to the previously experienced electrical breakdown of organic insulators by arc burn in a matter of minutes.

Testing of these insulator materials in Channel IB was resumed during the 4th Quarter 1978 under Test Plan 39. Water leaks in the nozzle section apparently caused insulation degradation through penetration of water soluble potassium salts into the insulator materials.

B. Second Series

1. Test Plan 36 (2nd and 3rd Quarters 1978)

Following the insulator tests in Channel IB, Channel II (modular construction) was assembled using 0.79 mm (1/32 inch) thick elastomer matrix asbestos and aluminosilicate paper saturated with Teflon aerosol. The upstream face of each electrode was plasma sprayed with Al_2O_3 , except for 1-9 and 64-72. The outside of the channel was coated with phenolic varnish (Glyptol) for the purpose of sealing. Over 30 tests, totalling about six hours accumulated run time, were run in this channel to optimize combustor configuration and to study combustor-generator interaction. No insulator testing as such was performed during this test plan which was plagued by negative voltage (power sink) in the upstream region which was used to diagnose the combustor performance.

During the same period, Refrasil silica cloth samples coated with double layers of fluorosilicone elastomer were tested for gasket strength and withstood a 60 psi pressure gradient. Modifications were also developed to include boron nitride in the coating.

2. Test Plan 39 (4th Quarter 1978 - 1st Quarter 1979)

Further insulator testing was carried out during this test plan. Eleven additional tests totalling about 120 minutes were run with Channel IB using the same insulators as in Test Plan 30. Four tests totalling 73 minutes were run in Channel II. Each of the eight modules in Channel II was insulated with a candidate material or composite as indicated in Table VI. The zirconia cloth and the elastomer matrix asbestos were eliminated from candidacy because of the reasons stated previously in Section III.C.3.

TABLE VI. CHANNEL II GENERATOR INSULATOR
MATERIALS FOR TP 39

<u>Module No.</u>	<u>Electrodes</u>	<u>Insulator System</u>
1	1-9	Refrasil/BN Type V
2	10-13	Monolithic BN Plates
	14-15	Refrasil coated with BN-filled fluorosilicone
	16-18	Refrasil/BN Type V
3	19-27	Refrasil/Rigidizer w/BN Types
4	28-36	Refrasil/BN Types
5	37-45	Refrasil/BN Types
6	46-54	Fiberfrax/Teflon
7	55-63	Fiberfrax (from previous testing)
8	64-72	Fiberfrax/Teflon

Electrodes 1-9 and 64-72 were plasma sprayed with alumina. Insulator sheets used consisted of silica cloth treated with boron nitride slurries, aluminosilicate paper with Teflon (including Module 7 whose aluminosilicate insulators from the previous test plan were not disturbed), and special insulators of monolithic BN plates and silica cloth coated with 20 percent BN powder in fluorosilicone elastomer.

The negative voltage characteristic of TP 36 remained for TP 39 tests. It should be noted that voltage polarity inversion does not change the position of the anode (bottom) and cathode (top) but only changes the relative voltage between adjacent electrodes. The negative voltage region is a result of low electrical conductivity and gas non-uniformity. As a result, the materials in approximately the upstream one third of the channel have not been properly tested. That is, insulators of interest which were located near the position of voltage polarity inversion would register very low voltage difference, although the insulator may remain capable of withstanding voltage difference. The performance of insulators located distinctly upstream of the voltage inversion point can still be judged on the consistency of the negative voltage sustained even though polarity was reversed from the desired mode.

Appended to this report is a collection of voltage difference plots for the TP 39 runs in Channel II. For each run the approximate location of the voltage polarity inversion is noted. This is only an estimate of the average location, however, since the instantaneous location tended to shift during the runs. For the overall series, only those insulators from approximately Electrode 30 downstream were consistently subjected to conventional positive voltage difference without cyclic inversion, i.e. polarity changing with magnetic field strength. In Channel II these that were monitored were Insulator 33 (silica cloth/BN slurry), Insulator 51 (aluminosilicate/Teflon), and Insulator 60 (aluminosilicate/Teflon). For these three insulators, the voltage difference plots show that the silica cloth/BN displayed reasonably consistent operation in the $\Delta V = 8$ to 15 volt range without detectable shorting. The aluminosilicate insulators for the same tests showed much broader voltage excursions characterized by rapid oscillation between high ΔV (15-20 volts) and shorting.

The four monolithic plate insulators appeared to be performing satisfactorily after the relatively short period of operation. The lubricating properties of boron nitride resist slag wetting and resulted in slag free operation in this area of the channel. Abrasion lines parallel to the channel were observed on the BN insulators. However, no massive breakdown or electrical degradation of the insulators occurred.

Three mid-channel electrodes (37, 38 and 39) in Channel IB were fitted with insulators composed of boron nitride (BN) strips

3.175 mm (0.125 inch) thick for a short term test. An elastomer matrix asbestos sheet was used as a locator and gas seal backup for each insulator. For one insulator the strips were retained by compression alone without bonding. The second insulator was bonded at the joints only using a silicate bonded alumina adhesive. On the third insulator the ceramic adhesive was used to bond the joints and also to coat the duct interior surface of this insulator.

During three minutes of testing a full thickness (1-2 mm) slag layer was formed over these BN insulators. Recessing of the strips behind the electrode faces for the unbonded strip insulator appeared to have aided in that slag was tightly adhered to the ceramic adhesive. Thus, a slagging wall can be achieved with boron nitride insulators at full slag carryover by recessing the BN strips behind the electrode faces and/or applying an appropriate ceramic adhesive to the joints and face of the BN insulator strips.

Exposed faces of the BN strips showed abrasion, apparently suffered during the early stages of startup. The BN was protected from abrasion where it was covered with the ceramic adhesive. Visual inspection indicated that potassium compounds probably penetrated the adhesive rapidly, but the BN was very slightly attacked by these compounds if at all. At unbonded joints of the BN and at fractures which existed prior to firing, seed penetration was noted through the cracks.

IV. DISCUSSION

A. Insulator Thickness Constraints

To minimize electrode current erosion and the likelihood of interelectrode breakdown, one would choose fine segmentation of electrodes and insulators. This would increase the uniformity of current density, decrease the interelectrode potential which drives axial breakdown, and reduce the slag temperature over insulators to avoid breakdown through the slag.

The current UTSI DCW MHD generator design consists of 12.45 mm (0.490 inch) thick electrodes obtained by finish machining of 1/2 inch bar stock. This thickness of electrodes is necessitated by practical considerations of cooling and fabrication. The insulator thickness has been determined based on performance of various commercial fibrous ceramic textile products of 1/32, 1/16 and 1/8 inch nominal thicknesses. The 1/8 and 1/16 inch insulators exhibited unsatisfactory degrees of burnback into the interelectrode gaps with attendant axial shorting of adjacent electrodes during operation. Because of increasing distance from the cooled electrodes with increasing insulator thickness, the slag temperature over the insulators increased dramatically and causes insulator melting or burning.⁹

Conversely, insulators of insufficient thickness become liable to interelectrode breakdown. Axial current leakage either through or along surfaces of the slag layer lead to voltage excursions and interelectrode arcing. Many parameters including current density, wall temperature, interelectrode voltage, and Hall parameter are thought to affect interelectrode breakdown.

B. Insulator Material Performance

The UTSI approach to generator construction has been to use commercially available materials which are easily workable. For insulator materials, this has led to the use of ceramic textile materials in sheet form with appropriate treatments to enhance thermal conductivity and reduce moisture absorption and gas permeability. The result is a low cost, mechanically compliant insulator which can be easily fabricated in the shop by semi-skilled personnel.

Table VII lists materials which have been tested as insulators in the MHD generator with comments and recommendations. Candidate materials were selected for refractoriness, high temperature dielectric properties and gasketing or sealing performance. An aluminosilicate paper (Fiberfrax), a square weave silica cloth (leached fiberglass, Refrasil) and a zirconia cloth (Zircar satin zirconia) were chosen as representative of the commercial refractory textiles, both in chemistry and in structure. An elastomer matrix asbestos gasket material, Garlock 900, was selected as representative of materials of intermediate thermal resistance. Mylar polyester and silicone rubber elastomer were included in the screening tests as a comparison to previous testing and because of excellent sealing qualities, respectively.

Used without supplementary treatments, the refractory sheet materials have shown unacceptable sealing properties against gas leakage and absorption of ionizable compounds because of their porosity. This problem is substantially reduced by the use of appropriate coatings and/or matrix impregnations. These have included aerosol boron nitride, commercial aqueous boron nitride coatings which contain other refractory binders, colloidal silica, a commercial rigidizing preparation which has been used alone or in conjunction with boron nitride powder, and aerosol Teflon. These coatings have been applied by spraying or brushing onto the various sheet materials. In addition, samples of boron nitride filled fluorosilicone elastomer were applied to samples of silica cloth by a commercial laboratory for testing here. With these treatments and the painting of the generator channel exterior subsequent to assembly, gas leakage from the generator interior was eliminated. Because of the low available bolting force, the asbestos based gasket material was sealed by spraying the facing electrode surfaces with a phenolic varnish (Glyptol). However, it was found extremely difficult to separate these electrodes for disassembly as they were glued together. Sealing the mylar was effected by the use of O-rings.

TABLE VII. INTERELECTRODE INSULATOR MATERIALS

Textiles and Other Sheet Materials

<u>Generic Designation</u>	<u>Trade Name</u>	<u>Comments</u>
silica cloth	Refrasil and Irish Refrasil 0.026 inch thick	<p>Acid leached fiberglass. UC100 cloth has organic coating on fiber bundles which complicates impregnating.</p> <p>Irish Refrasil has received elevated temperature treatment which removes organic coating and produces diffusion coating of chromia on the fibers.</p> <p>Used as base for application of boron nitride coatings. This combination has performed well through several test hours.</p> <p><u>Irish Refrasil/BN combination</u> is currently the top candidate for interelectrode insulators. Probably the most versatile combination from standpoint of workability, handling durability and compatibility with waterproofing and gasketing modifications.</p>
aluminosilicate paper	Fiberfrax 970-A paper 0.010 inch thick	<p>$Al_2O_3 \cdot SiO_2$ fibers in random orientation; about 4% organic binders for better handling strength.</p> <p>Absorbs water readily. Some types of coatings, e.g. BN slurries, do not penetrate into the paper.</p> <p>Can be laminated easily for thicker insulators.</p>
zirconia cloth	Zircar ZYW30A (satin weave) 4-6 micron fibers Cubic ZrO_2 8% Y_2O_3 stabilized 0.030 inch thick uncompressed	<p>High temperature resistance but low handling strength. Like Fiberfrax, tends to absorb water. As tested, offers no particular advantages over lower cost textiles listed above.</p>

TABLE VII. (Continued)

<u>Generic Designation</u>	<u>Trade Name</u>	<u>Comments</u>
asbestos, elastomer matrix	Garlock 900 1/32, 1/16, 1/8	Good handling strength, performs satisfactorily as interelectrode insulator in short term testing. Possible health hazard in handling. Material is too hard to seal with available bolting force in UTSI generator. Potassium compounds penetrate cracks between insulator sheet and adjacent electrodes causing shorting.
silicone rubber, red		Excellent sealing and dielectric characteristics, maximum temperature about 550°F. Burnback into interelectrode gap allows shorting between electrode. This material may find use as gasket or seal for ceramic insulators.
polyester	Mylar	Good low temperature dielectric, but not usable in MHD system. No resistance to interelectrode arcing.
<u>Ceramic Plate</u>		
BN	Combat BN Type 4	BN plated specially ordered for fabrication of specific insulators. Specially ordered with pressing direction parallel to plate normal. Requires special care in cutting and handling to prevent breakage. With gas paths sealed, appears to perform satisfactorily as an insulator-- <u>more test time needed</u> . Expensive and fragile.

TABLE VII. (Continued)

Coatings for Textiles, Etc.

Generic Description

Trade Name

BN slurries

Combat BN Coatings
Type S
Type A
Type V

Water base slurries of BN powder and another ceramic binder: Type S, Type A, Type V. Coatings applied by brushing or dipping. Types S, A and V can be hardened by post dry heat treatments.

The inherent high thermal conductivity of BN makes these coatings desirable for use in composite form on appropriate substrates. If applied wet just before closure, can aid in sealing interelectrode joints.

A slurry with organic vehicle and similar resultant properties would be highly desirable for this application.

BN aerosol

BN powder applied without aqueous vehicle, but very expensive.

Teflon aerosol

Garlock
TFE

PTFE spheres in aerosol container. Used to saturate papers, felts, etc. before positioning to aid sealing and water repellency. Has not proved substantially successful for the latter.

colloidal silica

Rigidizer W
or
Kaowool Rigidizer

Colloidal sized SiO_2 in aqueous suspension. Used to stiffen Fiberfrax and similar materials. May be used as an aid in sealing. Experiments in progress toward combining BN powder with Rigidizer for coating.

TABLE VII. (Continued)

<u>Material</u>	<u>Comments</u>
Al_2O_3	Adhesion to copper fair to good--use air jets in spraying. Layer adds to insulator thickness and aids in retardation of inter-anode arcs.
ZrO_2	More porous than Al_2O_3 because of higher melting point. Performs no better than Al_2O_3 for arc quenching.
$\text{MgO} \cdot \text{Al}_2\text{O}_3$ spinel	Five electrodes plasma sprayed on both sides by APS Materials, Inc., Dayton, Ohio, showed good voltage retention. Coating claimed by NBS to be nonporous. Adhesion to copper good. <u>Worthy of further testing and consideration.</u>
NiAl composite powder	Exothermic reaction results in extremely high particle temperature at deposition. Bonding coat, has worked well on electroless nickel on copper base. Usable on bare copper with care, can be blended with final coat powder for graded coating.
Al-Cu composite powder	Aluminum bronze. Exothermic reaction less rigorous than NiAl. Excellent adhesion to copper. Bonding coat, also blend with final coat powder for graded coating.

In the insulator tests covered in this report, the best overall performance was shown by the square weave leached silica cloth (Irish Refrasil) coated with boron nitride (BN) from a commercial slurry. The square weave is simple and the easiest to penetrate with coatings which are comprised of both particulates and their vehicle. These insulators have given satisfactory performance for cumulative periods of several hours.

Two of the materials tested proved satisfactory for short term use, but failed before completion of the first test series. Garlock 900 (75 percent asbestos fibers, 25 percent SBR rubber) is incapable of quenching interanode arcs (arc tracking) and is too hard to allow adequate sealing against intrusion of potassium compounds between itself and the adjacent electrode faces. Shorting of the Garlock 900 insulators has resulted from both faults. Similarly, Fiberfrax aluminosilicate paper has operated for short periods without failure, but eventually is invaded by potassium compounds, especially at the cathode side. This effect is particularly pronounced in the presence of water leaks in the combustor or nozzle areas. In the event of such leaks, a solution of water soluble salts saturates the Fiberfrax. Even after all water is dried out of this material, the presence of ionizable salts results in degraded performance of these insulators. Instantaneous voltage differences may be high, but excursions to zero volts are frequent.

In addition to ceramic textiles, hot pressed boron nitride (BN) materials have been tested as insulators. The relatively high thermal conductivity of boron nitride is unsurpassed among electrical insulators. Only beryllium oxide (BeO) approaches its performance in this respect, but its toxicity makes BeO an undesirable candidate.

Boron nitride insulators for the UTSI MHD generator have been fabricated in two ways. Bar stock 3.18 mm (0.125 inch) have been cut to appropriate lengths for the electrodes of interest and bonded by ceramic adhesive. Also, 3.18 mm (0.125 inch) thick plate has been machined to form monolithic insulators. Both types have exhibited satisfactory performance in short term testing. However, insufficient testing time is accumulated to extrapolate electrical behavior to long operating times.

Electrochemical slag attack appears superficial, as shown by Figure 4. This is a photograph of a recessed boron nitride insulator showing the original machining marks at a location where the slag had chipped off. However, mechanical integrity is threatened by erosion from gas borne slag particles, as shown in Figure 5 for a nonrecessed boron nitride insulator (due to BN's low abrasion resistance); by high temperature embrittlement; by thermal shock from sudden heat fluxes, as in Figure 6; by cracking from mechanical stresses encountered during assembly and by thermal cycling of the clamping arrangement, as in Figure 7. These problems are thought to be solvable with proper design, installation, and operation constraints. A gas sealing back-up material is also necessary but may be located in a low temperature region so that that does not present much of a problem.

Figure 4. Boron Nitride Insulator with Slag Coating

Figure 5. Boron Nitride Insulator Showing Particle Abrasion in the Direction of Gas Flow

Figure 6. Boron Nitride Failure Due To Thermal Shock

Figure 7. Boron Nitride Failure Due To Thermal Cycling

Although some seed-slag penetration has been noted for the strip fabricated BN insulators, it does not appear to be extensive and has not resulted in interelectrode shorting. However, improper strip alignment and increased thickness at joints resulted in high stresses and some joint failures. In many instances the adhesively bonded joints maintained integrity even when a nearby failure occurred. A bonding and curing jig has been fabricated to alleviate this problem and additional tests will be performed using strip BN insulators with elastomer backup.

In both test series, one or both electrode faces are plasma sprayed with a ceramic coating. Such a layer appears to aid in the quenching of interanode arcs. When applied to the operating exposed face of the electrodes, a ceramic layer also appears to aid in the formation and stability of a slag coating on the channel interior. Alumina, zirconia, and magnesium aluminate spinel plasma sprayed coatings have been tested. Of these, alumina is the easiest to apply and the least expensive. Zirconia is more difficult to apply and appears not to function any better than alumina. Therefore, zirconia cannot be recommended for this application over alumina. The magnesium aluminate spinel as applied in the UTSI lab was tested in the first test series. Its performance was similar to that of alumina. However, the spinel coatings applied by APS Materials, Inc. for the National Bureau of Standards and tested in the second test series showed substantially better performance than the previous spinel coatings. APS Materials claims full density for their spinel coatings which are applied using an automatic traversing device with subsequent flat grinding. Both faces of the subject electrodes were coated.

Because of the additional arc quenching capability, the use of arc plasma sprayed ceramic layers on the electrode faces is advantageous. The superior performance of the spinel layers on both electrode faces suggests that like application should be made regarding the application of alumina in the same manner as the spinel. Tests should be planned to test both spinel and alumina on one and on both electrode faces with UTSI and APS Materials application.

V. CONCLUSION

Of the MHD interelectrode insulator systems tested to date, the 1/32 inch thick square weave silica cloth with boron nitride slurry coating used in conjunction with a dense plasma sprayed ceramic layer on both electrode faces has demonstrated the best combination of properties. Further development of this system, particularly in regard to a reduction of the permeability, and of other systems, such as the strip BN/elastomer combination, is needed in order to further improve insulator characteristics.

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APPENDIX

Interelectrode Voltage Difference Plots
for TP 39 Runs in Channel II

Interelectrode Voltage Differences in Channel II for Run TP39-01.
(See Table VI for insulator type corresponding to each curve.)

Interelectrode Voltage Differences in Channel II for Run TP39-02.
 (See Table VI for insulator type corresponding to each curve.)

Interelectrode Voltage Differences in Channel II for Run TP39-03.

Interelectrode Voltage Differences in Channel II for Run TP39-15.
 (See Table VI for insulator type corresponding to each curve.)