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Lightning Strike Evaluations Of Reinforced Conductive Airframe Seals

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1 INTRODUCTION

The recent trend toward increased use of electronic control systems ('fly-by-wire"), increased use of composite structures in aircraft designs, and the proliferation of high intensity radio frequency energy sources, has created a need for more effective RF shielding systems for commercial aircraft.

The FAA and JAA are developing regulations concerning High Intensity Radiated Fields(HIRF) protection. Interim certification requirements reflect the growing concern of HIRF hazards to fly-by-wire aircraft.

One approach to reducing the susceptibility of on-board electronics is the creation of EMI shielded zones through conductive termination of existing metal airframe structure. This can be accomplished by replacing conventional non-conductive reinforced silicone and fluorosilicone airframe seals with conductive equivalents. Some applications demand a fireproof or fire resistant, reinforced, conductive seal. In some cases, the seal must survive the effects of a lightning strike.

This document reports the results of lightning tests performed using the guidelines of MIL-STD-1757A on several different airframe seal configurations of reinforced, conductive elastomers. The tests were conducted in an effort to develop and characterize reinforced conductive seal designs which will meet industry needs.

The purpose of these tests was to evaluate the effect of exposure to a lightning strike on a number of seal designs and materials, and to determine the capability of the seals to conduct lightning currents across seams and joints. Each seal design is unique to its intended installation and application. Lightning specialists suggest that a properly performing lightning seal should be capable of handling a current density of 1270 to 6350 amperes/inch of a Component A lightning stroke.[1]

This test program was conducted to evaluate a series of initial designs for conductive, reinforced airframe seals. The tests were performed on February 18-20, 1992 at Lightning Technologies. Inc. by Ken Wiles, under the supervision of Andy Plumer.

Test Requirements

A lightning strike contains several components (Figure 1). Component A (initial stroke) is the worst case; therefore, the majority of the evaluation was performed using the component A waveform. Component A is a hig current, short duration pulse, with a low charge transfer o = 1.5 coulombs at 20kA. Component C is a low current, long duration, high charge transfer pulse. Component C testing evaluates a seal's ability to survive under prolonged lightning conditions. Limited Component A + C testing was performed.

The lightning current is injected through a 3-inch seal specimen. If the seal transfers the lightning stroke properly, the voltage developed across the test seal is minimal and the lightning current is relatively unimpeded. Arc-over occurs

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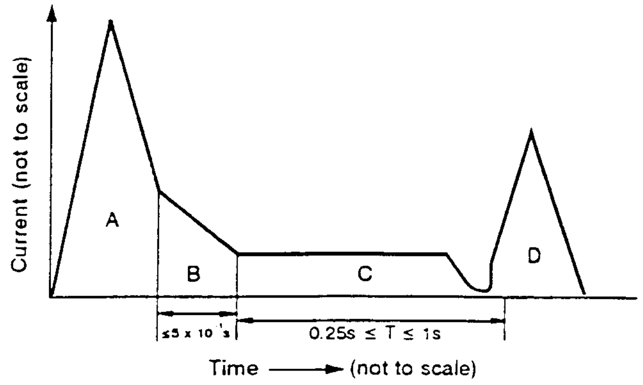
[1] A. Plumer, "Performance Of Selected "P" Bulb Gaskets In A Zone 3 Lightning Environment", Report No. LT-92-818, Lightning Technologies, Inc., June, 1992.

between test flanges when the impedance of the seal is greater than the impedance of air. Seal evaluation is discontinued when the arc threshold condition exists.



Component	Description	Parameters
A	Initial Stroke	Peak Amplitude = 200kA ± 10% Action Integral = 2 x $10^6 A^2s$ ± 20% Time Duration ≤ 5μs
B	Intermediate Current	Charge Transfer = 10 coulombs Average Amplitude = 2kA ± 10%
C	Continuing Current	Charge Transfer = 200 coulombs ± 20% Amplitude = 200-800A
D	Restrike	Peak Amplitude = 100kA ± 10% Action Integral = 0.25 x $10^6 A^2s$ ± 20% Time Duration = ≤ 500μs

Figure 1 Lightning Strike Components

A properly functioning seal maintains uniform current dissipation across its surface without localized flash-over. The seal's current handling capacity is determined by increasing the injected lightning current level until arc flash over occurs, physical degradation is observed, and/or resistivity doubles. The resistivity of the seal is measured using the surface resistance probe of MIL-G-83528 (Figure 2). Chomerics' document CEPS-0002 describes the measurement procedure.

2 SEAL CONSTRUCTIONS

Lightning evaluations were performed on free variations of an “omega” shaped cross sectior and 9 variations of a "P” shaped configuration. Each seal was slightly different in construction as shown in Figures 3 and 4. Length of each specimen was 3 inches.

Seal Materials

The following materials were used in the construction of the seal specimens tested:

CHO-SEAL® 1215 conductive elastomer, with a silicone binder and silver-plated-copper filler particles.

CHO-SEAL 1285 conductive elastomer, with a silicone binder and silver-plated-aluminum filler particles.

CHO-SEAL 1298 conductive elastomer with a fluorosilicone binder filled with specially treated silver-plated-aluminum particles for high levels of corrosion resistance.

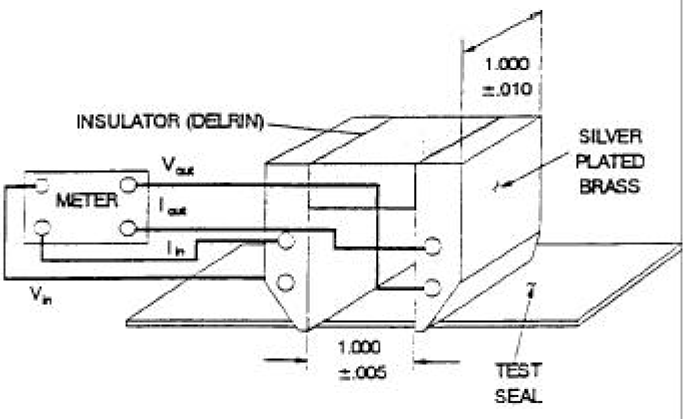
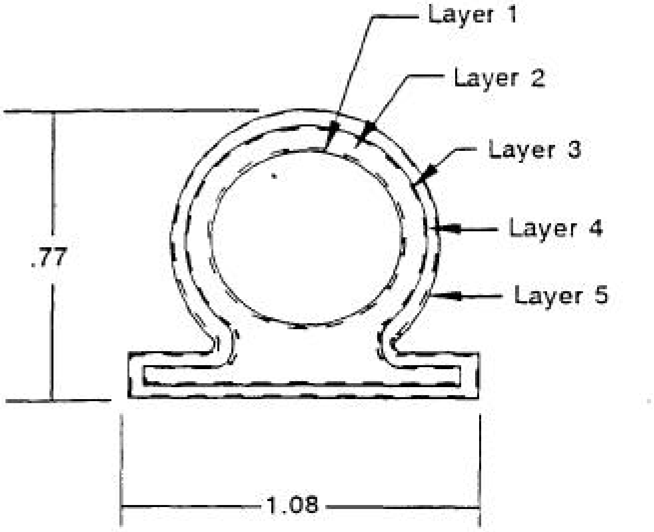


Figure 2 Resistivity Probe

Ferrex is Chomerics' trade name for tin-plated, copper-clad steel wire (4.5 mil dia.). Knitted wire density is 10-12 OPI.

HTR is Chomerics' high temperature resistant rubber (silicone and fluorosilicone).

MO is a metal oxide ceramic filler.



Specimen	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
A	MO	HTR	MO	1215	Ferrex
B	MO	HTR	MO	1285	Ferrex
C	MO	HTR	MO	1298	Ferrex
D (not tested)	MO	HTR	MO	1215	AF
E	MO	HTR	MO	1285	AF
F	MO	HTR	MO	1298	AF

Figure 3 Omega Cross Sections

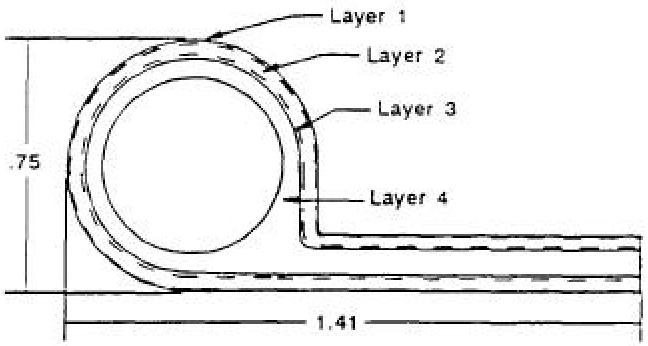
AF is an aramid fiber for heat resistance and dimensional stability.

FC is a fiberglass cloth for seal reinforcement.

't TEST SETUP AND PROCEDURE

The tests were performed at Lightning Technologies Inc., of Pittsfield, Massachusetts, and used the lightning waveshape criteria defined in MIL-STD-1757A.

The photographs in Figures 5 and 5A show the basic setup used for evaluation of each seal. The test fixture consisted of two electrodes. The bottom electrode was a large flat aluminum plate connected to the transient generator return. This plate also provided ground reference for the voltage measurements taken across the test seal. Seals were held to the bottom plate with two brass clamping fixtures. These fixtures were intended to represent the mounting channel typically used for aircraft seals, and provided additional bonding surfaces.



Specimen	Layer 1	Layer 2	Layer 3	Layer 4
A	Ferrex (18 OPI)	1285	MO	N.C.
B (not tested)	Ferrex (18 OPI)	1287	MO	N.C.
C	Ferrex (18 OPI)	1298	MO	N.C.
D		1285	MO	N.C.
E (not tested)		1287	MO	N.C.
F		1298	MO	N.C.
G	Ferrex (18 OPI)	1285	FC	N.C.
H (not tested)	Ferrex (18 OPI)	1287	FC	N.C.
I	Ferrex (18 OPI)	1298	FC	N.C.
J	Ferrex (10 OPI)	N.C.	FC	N.C.
K		1285	FC	1285
L (not tested)		1287	FC	1287
M (not tested)		1298	FC	1298
O	1285	Ferrex (18 OPI)	1285	FC

N.C. - Non-Conductive Silicone or Fluorosilicone

Figure 4 "P" Cross Sections

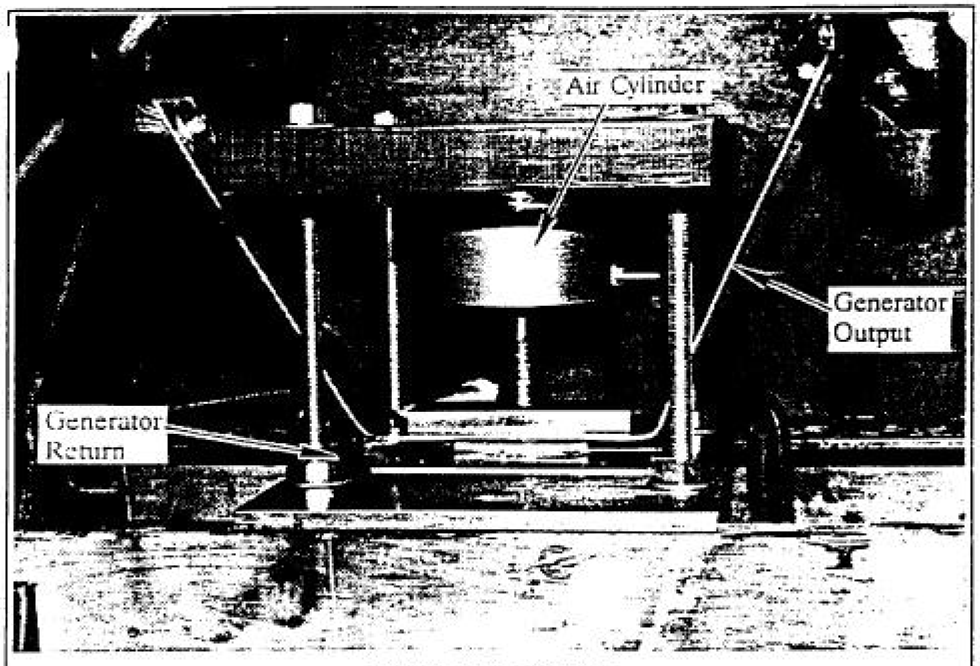


Figure 5 Test Setup

The top electrode was a smaller plate bent upward from the bottom electrode and attached to the output of the transient generator through some wave-shaping resistors. A pneumatic air cylinder was mounted on the top plate to hold the seal under compression. Fiberglass spacers assured that the compression did not exceed 33%. Figure 5B shows a seal specimen in place in the fixture.

<u>Test Procedure</u>

Waveshape calibration was performed prior to testing, to verify the Component A lightning strike characteristics (rise and fall times and pulse duration).

Pretest resistivity was measured over the length of the seal specimens and an average was recorded. During testing the voltage across the seal and current through the seal were measured. For each test specimen, the injected current was initially increased in steps of 5kA increments and then i lesser increments to determine an accurate threshold level. The specimen remained in the fixture until noticeable degradation occurred (physical or electrical). When a failure occurred, a new specimen of the same type was placed in the fixture and the test was rerun at the same failure level to verify results. This was done to eliminate any additive degradation that may have occurred due to multistroke lightning sequences. After a test failure was determined (and verified) the seal's current capacity was reached. Post-test resistivity (of the newest gasket) was measured and recorded. If the retest showed no indications of failure, the new specimen remained in the test fixture and current was increased to the next increment. After each new established failure a new specimen was placed in the test fixture until the current capacity was verified. In addition, a visual inspection of specimens was made to characterize the performance of the specimen (photos o the tested seals are on file and available upon request from Chomerics' Applications Department).

Following completion of Component A tests, a combined Component A and C test was performed on a new Omega specimen A. Component A current levels were 15kA and 20kA, with Component C scaled accordingly to a nominal 15 and 20 coulombs.

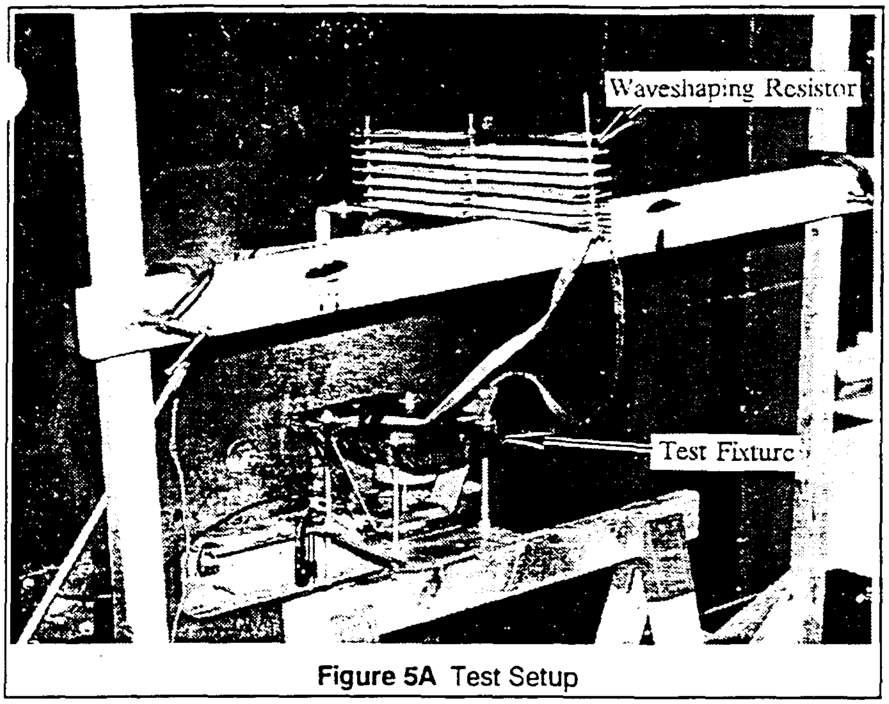


Figure 5A Test Setup

4 TEST RESULTS

Results of tests performed on the "Omega" and "P" shaped seals are summarized in Tables 1-3.

Current density as reported in the discussion that follows was calculated using the following formula:

Current density (amps/inch) _ failure current (amps) = specimen length (inches)

<u>"Omega" Shape - Component A Strike</u>

These tests showed that the AF constructions (Specimens E & F) could not conduct lightning currents without arcing flashover. Test levels were reduced to 1,000 amps and then to 500 amps and arc flashover was present at both test levels. Clearly, the AF seal construction tested does not provide a sufficiently conductive surface to cant' the lightning stroke. Resistivity measurements revealed that the AF seals were on the order of 20 times more resistive than their Ferrex counterparts. The higher resistivity readings are directly related to the amount of surface area the non-conductive AF fiber occupied. If a more open weave AF layer was used, improved conductivity and lightning performance might be expected. Evaluation of the AF seals was discontinued at the 500 amp level.

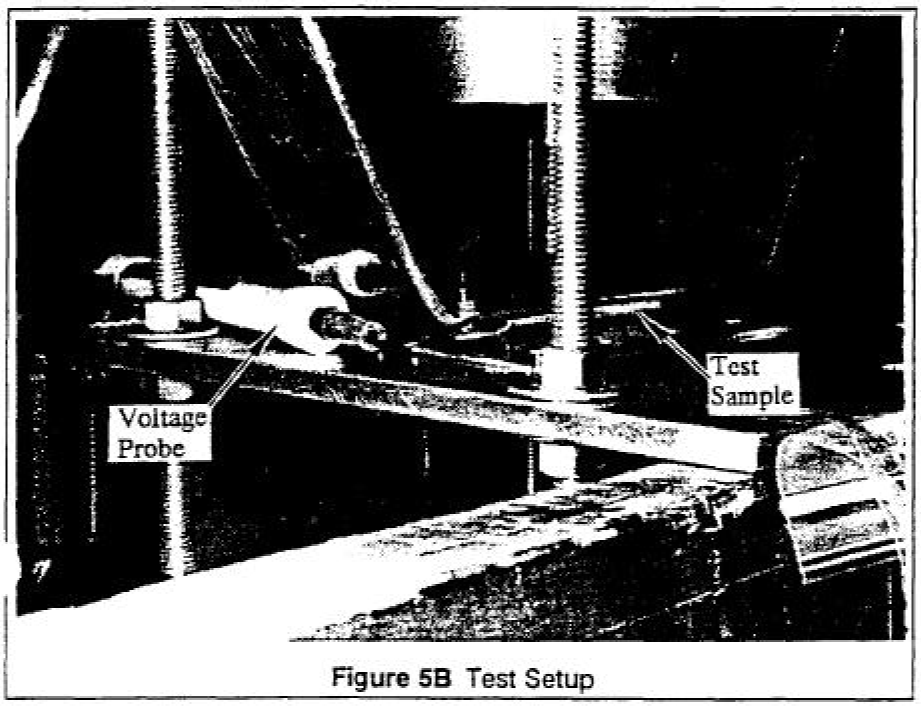


Figure 5B Test Setup

Specimen C seals were tested up to 15,000 amps. At 10kA, minor discoloration was evident. Resistivity remained stable. At 15kA, a new specimen was tested and slight arcing was observed. Upon closer inspection, some internal Ferrex wire damage was observed. Resistivity increased on average from

.029 to .042 ohm/cm. The flange-to-flange resistance increased from .005 to.020 ohms. Slight seal degradation begins to occur at this level.

Sample	Failure Current (kA)	Voltage Across Seal (volts)	Pretest Resistivity (ohms)	Post Test Resistivity (ohms)	Pretest Thru Resistance (ohms)	Post Test Thru Resistance (ohms)	Maximu Current Density (amps/in
A	20	240	.008	.011	.004	.021	6.667
B	20	320	.019	.020	.011	.017	6.667
C	15	178	.029	.042	.005	.020	5.000
E	0.5	175	.107	.151	-	-	≤ 167
F	0.5	960	.353	.434	-	-	≤ 167

Table 1 Test Results - Omega Configuration
Component A Lightning Strike

Both Specimen A and B developed minimal top and bottom black spotting when exposed to t 0kA and 1 5kA. Resistivity remained stable. At 20kA both test specimens were replaced with new seals. At this level, both specimens endured moderate "blow-out" damage to some Ferrex wires. Resistivity remained stable (within .003 ohms). Slight top level flashing occurred (these were not arc over flashes). Specimen A flange-to-flange resistance increased from .004 to .021 ohms. Specimen B flange-to-flange resistance increased from .011 to .017 ohms. Slight seal degradation began to occur at this level. Maximum current density of both materials is 6,667 amps/inch.

Sample	Test	Applied Current			Pretest Resistivity (ohms)	Post Test Resistivity (ohms)	Pretest Thru Resistance (ohms)	Post Test Thru Resistance (ohms)
		Comp. A (kA)	Comp. C (amps)	(C)				
A	1	15	30	15	.009	.009	.003	.003
	2	20	40	20	.009	.010	.004	.020

Table 2 Test Results - Omega Configuration
Component A + C Lightning Strike

<u>"Omega" Shape - Component A + C Strikes</u>

As a follow-on series of tests, two new Specimen A seals were exposed to a Component A strike directly followed by a Component C strike. As discussed earlier, the Component C portion of the lightning strike is a low current, long duration, high charge transfer pulse. It is useful in evaluating a seal's ability to survive under prolonged lightning conditions,

Two tests were performed: (1) a Component A strike of 15kA = 1 coulomb followed by a Component C strike at 30 amps for 0.5 second = 15 coulombs; (2) a Component A strike of 20kA = 1.5 coulombs followed by a Component C strike of 40 amps for 0.5 second = 20 coulombs. The results of each test are summarized in Table 2.

The addition of the Component C waveform did not adversely affect or change the performance of the Specimen A seals. These results are consistent with the Component A test results.

“P" Shape - Component A Strike

P-shape seals were subjected to both single and double Component A lightning strikes. The double stroke test indicates a seal's ability to withstand a repetitive or re-strike lightning condition.

Specimen A was tested in 5kA increments up to 20kA. At the 20kA test level, specimen A maintained moderately uniform current distribution across the surface. Post test resistivity and through resistance remained stable, with slight variations. Some surface wire damage occurred. The single stroke threshold was reached at 20kA. The double stroke limit was 15kA. Similar physical and electrical properties were noted. Current density limits were 6,667 amps/inch for single strokes, and 5,000 amps/inch for double strokes.

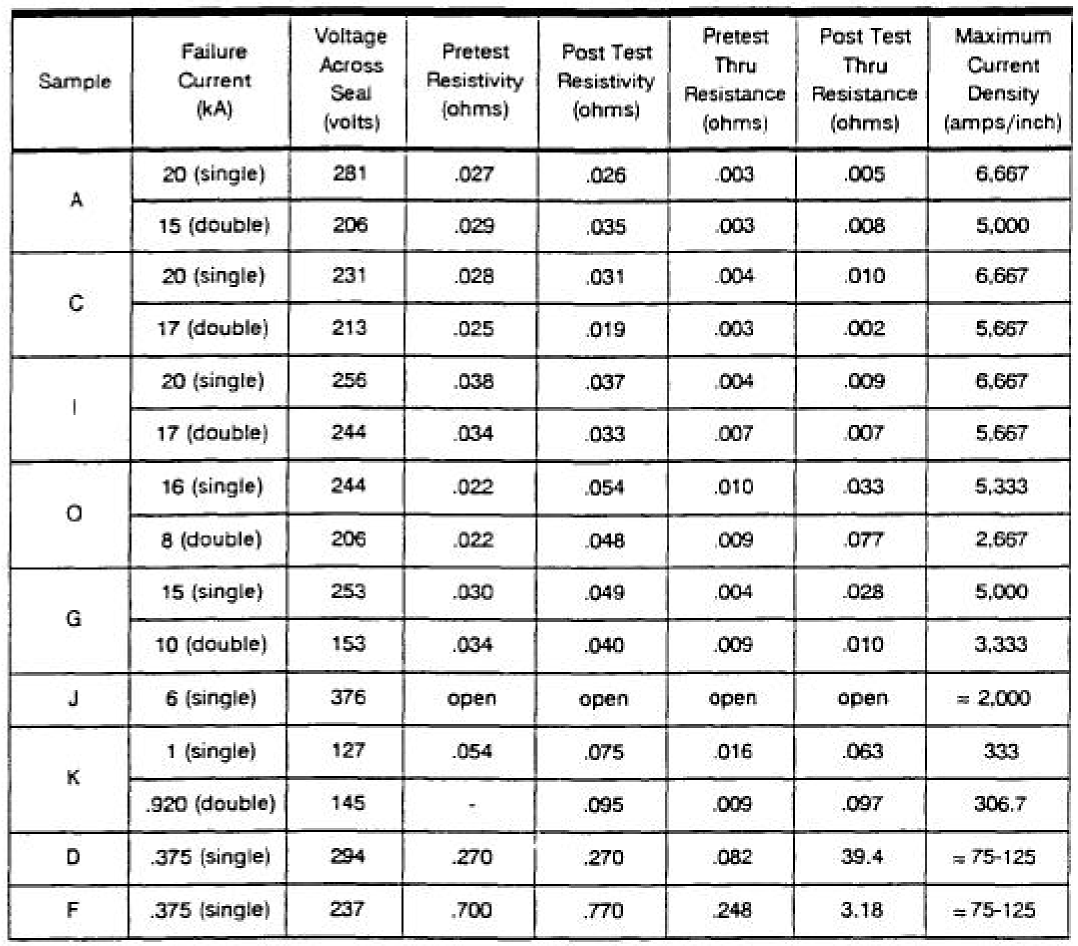
Specimen C was also tested in 5kA increments up to 20kA. At the 20kA test level, Specimen C maintained moderately uniform current distribution across its surface. Post test resistivity remained stable. Through resistance varied somewhat, from .004 to .010 ohms. Some minor surface bums and wire damage occurred. The single stroke threshold was marked at 20kA and the double stroke limit was 17kA. Current density for the single stroke is 6,667 amps/inch, and 5,667 amps/inch for the double stroke.

Specimens D and F both exhibited arc flash-over at 5kA and electrical properties were very unstable. These specimens were then tested at lower current levels, with similar results. At 375 amps, the generator's lowest current level possible Specimen D and F resistivity remained unchanged but through resistance increased. Physical properties remained excellent. Single stroke current density was determined to be 75-125 amps/inch. No double stroke testing was performed.

Specimen G was tested in 5kA increments up to 15kA. At 15kA some wire damage occurred along with surface tracking marks. Resistivity varied somewhat from 0.030 to 0.049 ohms, and through resistance from 0.004 to 0.028 ohms. The single stroke threshold was determined to be 15kA and the double stroke limit was 10kA. At the 10kA level, current distribution was uniform and . electrical properties were stable. Current density limits were 5,000 amps/inch (single stroke) and, 3333 amps/inch (double stroke).

Specimen I was tested in 5kA increments up to 20kA. At the 20kA test level, current distribution was relatively uniform across the surface of the seal. Post test resistivity remained unchanged. Through resistance varied slightly from 0.004 to 0.009 ohms. Some wire damage occurred. The single stroke threshold was determined to be 20kA (current density = 6,667 amps /inch). Double stroke limit was 17kA (current density = 5,667 amps/inch).

The Ferrex wire mesh layer in Specimen J was located approximately .005' below the surface of the seal. At all test levels (10kA, 6.5kA, 5kA, 3kA. 1.9kA, and 500 amps), the voltage measured across the test specimen rose dramatically. Voltage increased until breakdown occurred



Sample	Failure Current (kA)	Voltage Across Seal (volts)	Pretest Resistivity (ohms)	Post Test Resistivity (ohms)	Pretest Thru Resistance (ohms)	Post Test Thru Resistance (ohms)	Maximum Current Density (amps/inch)
A	20 (single)	281	.027	.026	.003	.005	6,667
	15 (double)	206	.029	.035	.003	.008	5,000
C	20 (single)	231	.028	.031	.004	.010	6,667
	17 (double)	213	.025	.019	.003	.002	5,667
I	20 (single)	256	.038	.037	.004	.009	6,667
	17 (double)	244	.034	.033	.007	.007	5,667
O	16 (single)	244	.022	.054	.010	.033	5,333
	8 (double)	206	.022	.048	.009	.077	2,667
G	15 (single)	253	.030	.049	.004	.028	5,000
	10 (double)	153	.034	.040	.009	.010	3,333
J	6 (single)	376	open	open	open	open	≈ 2,000
K	1 (single)	127	.054	.075	.016	.063	333
	.920 (double)	145	-	.095	.009	.097	306.7
D	.375 (single)	294	.270	.270	.082	39.4	≈ 75-125
F	.375 (single)	237	.700	.770	.248	3.18	≈ 75-125

Table 3 Test Results - "P" Configuration
Component A Lightning Strike

through the non-conductive rubber to the wire mesh. At the higher lightning levels, complete arc over flashes occurred, which resulted in the bypassing of the seal altogether. A properly conducting seal maintains a low voltage drop, usually below 300 volts. As the voltage across the seal increases, indirect lightning effects (EM waves) also increase, raising the potential for EMI system upsets. Current threshold appeared to be about 6 kA. Further evaluation is required to more accurately characterize the threshold level of Specimen J. This seal is not recommended for airframe use. Non-uniform current distribution was typical and maximum current density is only about 2,000 amps/inch. Specimen K was tested as high as 1 0kA. At this level, arc-over flashes and seal punctures occurred. Current distribution was not uniform and electrical properties were very unstable. At the 1 kA level, more stable results were noted. The seal's resistivity varied from 0.054 to 0.075 ohms and through resistance from 0.016 to 0.063 ohms. Physical properties remained stable. Some slight surface tracking marks were present. This seal's single stroke limit was established as 1 kA. Its double stroke limit was set at 920 amps. Maximum current density is 333 amps/inch (single stroke) and 306.7 amps /inch (double stroke).

Specimen 0 was tested up to 20kA. At the 17.5kA test level, the electrical properties began to fade slightly. Resistivity varied from 0.040 to 0.190 ohms and through resistance from 0.017 to 1.70 ohms. Uniform current distribution was noted at 17kA and 15kA. At 16kA, the electrical properties were more stable. Resistivity varied from 0.022 to 0.054 ohms and through resistance from 0.010 to 0.033 ohms. Large flashes were present at both test levels. The single stroke threshold was established at 16kA (current density = 5,333 amps/inch). The double stroke limit was 8kA (current density = 2,667 amps/inch).

5 CONCLUSION AND DISCUSSION

Selection of an EMI seal for application in a lightning environment must involve a review of the overall design requirements and installation practices. Some basic considerations include the following:

(1) The effects of corrosion, fluid contamination, and seal aging should all be factors in material selection.

(2) A seal inspection cycle should be defined to maintain shielding integrity. This inspection cycle can be based on the cumulative effects of multiple lightning strikes and changes in the joint bonding characteristics. Measurement of the through resistance across the seal may be an effective means of inspection.

(3) Acceptable damage (or pass/fail criteria) for seals used in a lightning environment should be defined, based on the system's shielding requirements. These tests used several criteria, the first being the integrity of the seal. An acceptable method of "protection" is to allow the current to arc over the seal surface, protecting the seal, but not necessarily providing effective H-field shielding during the transient. The second criteria was an observed change in seal resistance, either resistivity or through resistance, indicating a probable reduction of shielding effectiveness without necessarily involving visible damage. The third criteria was visible damage, indicating vaporization of conductive particles (or wire mesh) and therefore loss of shielding effectiveness. Each criterion tends to be application specific, and would depend on th expected lightning current levels and the desired degree of shielding effectiveness.

(4) The thresholds indicated in the test results are based on indications of some voltage increase acros the seal caused by increases in seal resistance. The design margins should reflect the effectiveness of paralle current paths. Installations with limited parallel paths, such as provided by a pair of hinges and latch fittings, should employ a higher margin. Installations which provide distributed parallel paths around the entire perimeter can use less margin, since the parallel conductors will effectively protect the seal by carrying a larger percentage of the current and limiting the voltage.

Current conduction capabilities of 2.5kA/inch of length are adequate for most applications around large doors, access panels, or fairings—especially if additional current paths via fasteners, hinges, or latches are available.

Seal materials with higher current capabilities, such as > 5 kA/inch of length, would be preferred around small access panels, antenna bases, etc.

Where seal integrity is important but the requirement for shielding effectiveness is not significant, either of the AF seals should prove adequate for their rated environments. The Ferrex seals will also function acceptably within their rated environments, and will offer much better shielding effectiveness because of their lower resistivities.

Continuous electrical bonding around the perimeter of access panels and doors, as opposed to the localized bonding offered by straps, hinges, latch fittings, and screws, results in better EMI shielding - especially at the higher frequencies.

The uniformity of pit marks left by current entry/exit on the top and bottom of some of the seal specimens is evidence of uniform distribution of the test current over the length of the specimens, which is desirable for maximum total current transfer capability and E-field shielding.

Relatively flat voltage response during test current flow indicates stable physical and electrical properties and the absence of internal breakdown within the seal. Relatively stable resistivity from pre-test to post-test also indicates stable electrical properties and the capability to withstand repeated current pulses.

Overall, the seals tested offer very attractive electrical properties for airframe applications such as achieving uniform current transfer between adjacent parts and for improved protection of enclosed systems against the indirect effects of lightning (magnetic and electric fields) and other electrical environments.

References

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