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Comparison of Arc Tracking Tests in Various Aerospace Environments

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Abstract: **Momentary short-circuit arcs between a polyimide insulated wire with defective insulation and another conductor may cause pyrolization of the insulation resulting in a conductive path capable of sustaining the arc. These sustained arcs may propagate along the wires or to neighboring wires leading to complete failure of the wire bundle. Wire insulation susceptibility to arc tracking may be dependent on its environment. Because all wire insulation types tested to date arc track, a test procedure has been developed to compare different insulation types with respect to their arc tracking susceptibility. This test procedure is presented along with a comparison of arc tracking in the following three environments: 1) Air at atmospheric pressure and 1 gravitational (g) force, 2) Vacuum ($2.67\text{x}10^{-3}$ Pa) and 1g, and 3) Air at atmospheric pressure and microgravity (< 0.04g)**

INTRODUCTION

Momentary short-circuit arcs between a defective polyimide insulated wire and another conductor may thermally char (pyrolize) the insulating material. The charred polyimide, being conductive, is capable of sustaining the short-circuit arc. The sustained arc may propagate along the wire through continuous pyrolization of the polyimide insulation (arc tracking). If the arcing wire is part of a multiple wire bundle, the polyimide insulation of other wires within the bundle may become thermally charred and start to arc track (flash over). Therefore, arc tracking may lead to complete failure of an entire wire bundle or harness. Due to the popular use of polyimide insulated wires, such as MIL-W-81381, for use in aerospace vehicles, the NASA Office of Safety and Mission Assurance (Code Q) has initiated a program to identify candidate wire insulation types for aerospace applications that are not susceptible to arc tracking. Arc tracking tests conducted by the Electro-Physics Branch, Power Technology Division, at the NASA Lewis Research Center (LeRC) were initiated to evaluate candidate wire insulation tests for susceptibility to arc tracking.

This report defines a test procedure to aid in the selection of the candidate insulation type least susceptible to arc tracking. Furthermore, this report gives some preliminary information concerning test results conducted in the following three environments: 1) air at atmospheric pressure and 1 gravitational (g) force, 2) vacuum ($2.67\text{x}10^{-3}$ Pa) and 1g, and 3) air at atmospheric pressure and microgravity (< 0.04g).

TEST THEORY

Arc tracking can be described as an arc between two conductors that pyrolizes surrounding insulation leading to propagation of the arc along the wire as a result of charred insulation growth. Safety risks associated with the phenomena are: 1) probability of arc tracking initiation, 2) probability of reinitiation (restrike), and 3) extent of arc tracking damage (propagation rate). Item 2 is an issue if power is capable of being terminated from and reapplied to (switch, fuse, resettable circuit breaker) the arcing wire. item 3 refers to how easily the arc chars nearby insulation and propagates along the wire pair. Ease of nearby insulation charring can be determined by measuring the rate of arc propagation. An insulation that chars easily will propagate the arc faster than one that does not char very easily.

This report covers measurements of the arc tracking propagation rates for three candidate insulation construction types (Mil-W-81381/7-20, Filotex Filartex® T8C1G20, and Tensolite TLT-200-20S) in the following three environments:

- Air at atmospheric pressure and 1 gravitational (g) force.
- Vacuum ($2.67\text{x}10^{-3}$ Pa) and 1g.
- Air at atmospheric pressure and microgravity ($\mu g < 0.04g$).

APPARATUS

Ground based (1g) tests were conducted in a helium cryo-pumped vacuum bell-jar (capable of obtaining $2.67\text{x}10^{-3}$ Pa) . The bell-jar was left open when conducting tests at atmospheric pressure and 1g. The μg tests used the Spacecraft Fire Safety Facility $(SF)^2$ to provide an atmospheric pressure environment onboard NASA LeRC's DC-9 Reduced-Gravity Aircraft. To obtain ground level atmospheric pressure ($1.013\text{x}10^{5}$ Pa) within the $(SF)^2$ chamber while flying at varying altitudes (cabin pressure may range from $1.013\text{x}10^{5}$ to $7.51\text{x}10^{4}$ Pa), a regulated air bottle (less than 1 ppm total water contamination) was connected to the $(SF)^2$ test chamber. The oxygen content of the air bottle, measured with a Matheson Gas Products oxygen deficiency monitor (model number 8060) with a diffusion type sensor, was 19.7%.

The circuit configuration used to supply power to the test specimen, for both ground-based (1g) and μg tests, is described in Figure 1. The power supply voltage level was adjusted to a predefined non-short-circuit potential of 90 volts between the test specimen conductors. A current limiting resistor, set at 25Ω, restricted the maximum short-circuit current available during an arcing event.

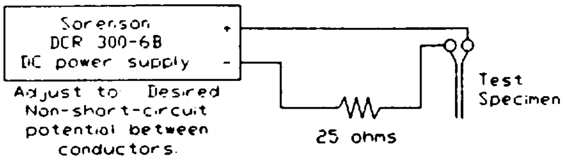

Figure 1. Typical circuit configuration for arc tracking tests.

SAMPLE DESCRIPTION

The following three AWG 20 (American Wiring Gauge 20) samples were tested:

- MIL-W-81381/7-20 (baseline).
  6 mil wall polyimide insulation, silver coated copper [1].
- Filotex Filartex® T8C1G20.
  PTFE Extrusion/616 Kapton (50% Min OL)/PTFE Dispersion [1].
- Tensolite TLT-200-20S.
  200AJ919 (50% Min OL)/PTFE Tape (50% Min OL) [1].

Where:
616 Kapton = 0.1 mil Fluorocarbon (FEP), 1 mil Polyimide, 0.1 mil Fluorocarbon (FEP) [1].
200AJ919 = 0.5 mil Fluorocarbon (PTFE), 1 mil Polyimide, 0.5 mil Fluorocarbon (PTFE).

These insulations were hybrid constructions comprised of different combinations of the materials PTFE (Poly Tetrafluoroethylene) and polyimide [3]. Filotex and Tensolite were the top two wire insulation constructions identified by an Air Force wiring program [3].

Sample preparation for all arc tracking environments were identical. Each sample consisted of two wires with the same insulation type (a supply line and a return line). To maintain the wires within close proximity to each other throughout a test, as they will be when bundled, a floating stainless steel wire (AWG 28) was wrapped around the wire pair. A defect was introduced to each test wire by cutting a notch in the insulation, exposing approximately 1mm lengthwise by 1mm widthwise of the conductor, at the midpoint of the wire length.

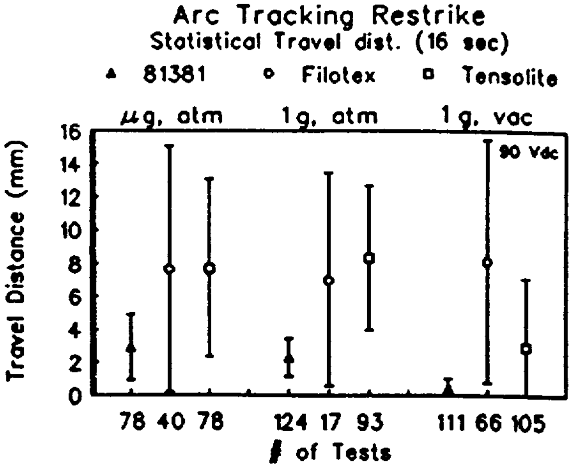

Figure 2 Comparison of the three wire insulation construction types, in each environment of interest, with respect to their arc propagation distance of travel within a 16 second time frame. The error bars represent one standard deviation.

PROCEDURE

With power applied to the test wire pair (60V), a conductive wand was used to short-circuit the wires, at the defect site in the insulation, until unassisted arc tracking evolved. Power was then removed from the wires to terminate the arcing event. These arc damaged wires were then mounted in the designated environment chamber. Once mounted in the chamber, a photograph was taken to obtain a picture of the sample prior to testing. At this point the samples were ready for testing.

A typical test would consist of applying a voltage (90V) between the predamaged test wires (restrike), by means of a controlled relay contactor for 16 seconds in the desired environment. After the 16 seconds have expired, the voltage was removed and the samples were again photographed. The pre- and post-restrike photographs were compared to determine the distance of arc propagation. The reason for the 16 second parameter for these

	Mil-W-81381			Filotex Filartex® T8C1G20			Tensolite TLT-200-20S		
	µg, 1atm	1g, 1atm	1g, vac	µg, 1atm	1g, 1atm	1g, vac	µg, 1atm	1g, 1atm	1g, vac
# of Tests	78	124	111	40	17	66	78	93	105
Mean (mm)	2.9017	2.3109	0.4262	7.6290	7.0060	8.1359	7.6721	8.3270	2.9461
σ (mm)	1.9899	1.1418	0.5847	7.4482	6.4292	7.3337	5.3607	4.3274	4.1956
Maximum Length (mm)	9.0043	5.3122	2.5706	27.6485	22.9826	27.1577	22.5592	17.2232	24.8387

Table 1. Statistical Restrike Test Results.

tests was to ensure execution of arc tracking only while the desired environment existed. The microgravity tests were conducted on LeRC's DC-9 reduced-gravity aircraft. The microgravity window created with each parabola was approximately 25 ±5 seconds. Therefore, the test duration was limited to 16 seconds so that a completed test run could be conducted with each microgravity parabola.

If the restrike test resulted in a direct conductor to conductor short-circuit or an open-circuit, the test specimen was replaced with a new sample.

RESULTS

Figure 2 is a comparison of arc propagation distance of travel within a 16 second time frame for the baseline, Filotex, and Tensolite, in each of the three environments. The error bars in Figure 2 are ± standard of deviation (σ). The statistical data displayed in Figure 2 is given in Table 1.

DISCUSSION

Environmental Comparison

The results of the baseline (Mil-W-81381) displayed in Figure 2 indicate the means of the μg, 1atm case and the 1g, 1atm case are similar. To validate this premise, the following hypothesis test is in order to determine if there is a statistical difference between these two environments. For this hypothesis test, let the NULL hypotheses (H_o) and the Alternate hypotheses (H_a) be described as follows:

$$H_o: \mu_{\mu g} - \mu_{1g} = 0$$

$$H_a: \mu_{\mu g} - \mu_{1g} \neq 0.$$

μ => Mean value (Table 1) for either the μg, 1atm or the 1g, 1atm environments.

H_a is two sided since μ_{1g} may be > or < $\mu_{\mu g}$; therefore, a two-tailed test is appropriate. The equation for the test statistic 'Z' is given in equation 1, where σ is the standard deviation from Table 1 and

$$Z = \frac{\overline{\mu_{\mu g}} - \overline{\mu_{1g}} - (\mu_{\mu g} - \mu_{1g})}{\sqrt{\frac{\sigma^2{}_{\mu g}}{n_{\mu g}} + \frac{\sigma^2{}_{1g}}{n_{1g}}}} \qquad (1)$$

n is the number of data points. Setting the desired level of probability that H_o is rejected when H_o is true (Type I error) $\alpha = 0.05$, then H_o is rejected if either $Z \geq 1.96$ or $Z \leq -1.96$. The calculated value of Z as described in equation 2 is 2.378. Since $2.387 > 1.96$, H_o is rejected in favor of the conclusion that $\mu_{\mu g} \neq \mu_{1g}$ (the μg, 1atm test is not similar to the 1g, 1atm test). Therefore, the μg, 1atm test is considered a harsher environment than the 1g, 1atm environment. Visual inspection of the chart in Figure 2, and similar calculations for Z (Z=16.16), indicates that the 1g, 1atm environment is harsher than the vacuum environment. Similar hypothesis testing on the Tensolite data reveal both the μg, 1atm tests (Z=6.45) and the 1g, 1atm tests (Z=8.85) were harsher than the vacuum tests. When Comparing the Tensolite data obtained from the μg, 1atm environment with those from the 1g, 1atm environment the NULL hypothesis cannot be rejected due to a low Z (Z=0.87) indicating a potential Type I error. The hypothesis test for the probability (p) of a Type II error (accepting H_o when H_o is false) is calculated using equation 3, where $z_{\alpha/2}$ was defined above to be 1.96 and Φ is the standard normal cumulative distribution function. The calculated value for p as described in equation 5 is 0.8597. Therefore, the NULL hypothesis cannot be accepted without a high risk of a Type II error. Hence, no statistical conclusion can be derived between the Tensolite's μg, 1atm tests and the 1g, 1atm tests. Filotex results were independent from environment.

$$Z = \frac{2.9017 - 2.3109 - 0.0}{\sqrt{\frac{1.9899^2}{78} + \frac{1.1418^2}{124}}} = 2.387 \qquad (2)$$

$$p = \phi\left(Z_{\alpha/2} - \frac{(\mu_1 - \mu_2)}{\bar{\sigma}}\right) - \phi\left(-Z_{\alpha/2} - \frac{(\mu_1 - \mu_2)}{\bar{\sigma}}\right) \qquad (3)$$

$$\bar{\sigma} = \sqrt{\frac{\sigma^2{}_1}{n_1} + \frac{\sigma^2{}_2}{n_2}} \qquad (4)$$

$$\begin{aligned} p &= \Phi(1.96 - 0.868) - \Phi(-1.96 - 0.868) \\ &= 0.8621 - 0.0024 \\ &= 0.8597 \end{aligned} \qquad (5)$$

For two of the three samples, the vacuum tests resulted in the smallest arc propagation distance. There is a statistical difference between the baseline's μg and ground based tests. This difference is not evident with the other two sample types.

Sample Type Comparison

Using similar hypothesis testing as described in the Environmental Comparison section, Table 2 below displays the calculated Z values for comparing the baseline Mil-W-81381 with the Filotex and the Tensolite samples. Both the Filotex and the Tensolite samples statistically had arcs propagate further than the baseline over the 16 second duration.

Using the hypothesis test to compare the Filotex sample against the

	Environment		
Mil-W-81381 V.S.	µg, 1atm	1g, 1atm	1g, vac
Filotex	4.01	3.00	8.52
Tensolite	7.37	13.01	6.10

Table 2. Hypothesis test Z calculations for possible Type I error in comparison between the mean arc tracking propagation distance over a 16 second interval of the baseline Mil-W-81381 and the two other candidates (Filotex Filartex® T8C1G20 and Tensolite TLT-200-20S).

	Environment		
	µg, 1atm	1g, 1atm	1g, vac
tests / sample	6.33	6.15	7.5
Time (sec)	101.33	98.4	120
travel dist (mm)	18.377	14.212	3.197

Table 3. Cumulative statistical results for the baseline, Mil-W-81381, samples.

Tensolite sample indicates a difference within Type I error tolerance (Z=5.23), in the 1g vacuum environment only. Calculations for a type II error for the other two environments (probability of a difference existing if no difference is implied) results in values of p=0.9499 for the µg 1 atm environment and a value of p=0.8701 for the 1g, 1atm environment.

With respect to the criterion for arc tracking comparison outlined in this paper, the baseline Mil-W-81381 outperformed the other two candidates with the least amount of restrike arc tracking in all three environments tested. In the vacuum environment, the Tensolite sample outperformed the Filotex. However, for the other two environments, no statistical conclusions can be drawn to identify which sample, either Filotex or Tensolite, is more susceptible to the arc tracking event.

Table 1 also lists the maximum length of pyrolization measured within each environment for each sample type. The maximum length values for the Filotex and Tensolite cases occurred during one of the few times the arc actually existed for the entire 16 seconds. For these two sample types, it was common for the test to be completed in less than 5 seconds (open circuit from a melted conductor, or carbon char conductive path removed). Therefore, for the Filotex and Tensolite samples, the arc propagated swiftly, but the arc existed for a short period of time. For the baseline case, it was common for the arc to last the entire 16 seconds. Furthermore, the same sample was capable of being reused for several restrike tests in a row. Therefore, for the Mil-W-81381 sample, the arc propagated slowly, but the arc existed for a long period of time. Table 3 displays the typical time of arc tracking existence and propagation distance on each individual baseline sample for each environment. The tests/sample parameter in Table 3 is the average number of consecutive restrike tests conducted on each sample. Theoretically, an arc could survive the sum time of all tests conducted on each sample if the 16 second parameter was not implemented. These times and resulting distances of pyrolization are recorded in Table 3. Therefore, expanding the 16 second window to > 120 seconds, would result in damage to the baseline sample due to arc tracking being greater than the mean values of the Filotex and Tensolite samples for the µg, 1atm and the 1g, 1atm environments. In the vacuum environment, the baseline sample would perform similar to the Tensolite's sample, and both outperformed the Filotex sample.

CONCLUSION

For an actual application using one of these candidate wire insulation types, the 16 second parameter is insignificant, because the arc, if undetected, would have a long period of time (>120 seconds) to do its damage. Therefore, the data displayed in Table 3 for the baseline Mil-W-81381 should be used to compare against the data Mean (mm) row data of Table 1 for the Filotex and Tensolite samples. Accordingly, the Filotex and Tensolite samples are indistinguishable and would be the choice over the baseline Mil-W-81381 in environments that have air at atmospheric pressure. However, in the vacuum environment, the baseline and the Tensolite samples results are indistinguishable, and both outperformed the Filotex sample.

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