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Evaluation of Kapton Pyrolysis, Arc Tracking, and Flashover on SiO_x-Coated Polyimide Insulated Samples of Flat Flexible Current Carriers for SSF

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(NASA-CR-191106) EVALUATION OF KAPTON PYROLYSIS, ARC TRACKING, AND FLASHOVER ON SiO(x)-COATED POLYIMIDE INSULATED SAMPLES OF FLAT FLEXIBLE CURRENT CARRIERS FOR SPACE STATION FREEDOM (Sverdrup Technology) 11 p

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EVALUATION OF KAPTON PYROLYSIS, ARC TRACKING, AND FLASHOVER ON SiO_x-COATED POLYIMIDE INSULATED SAMPLES OF FLAT FLEXIBLE CURRENT CARRIERS FOR SPACE STATION FREEDOM

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ABSTRACT

Kapton polyimide wiring insulation has been found to be vulnerable to pyrolization, arc tracking, and flashover when momentary short-circuit arcs have occurred on aircraft power systems. Short-circuit arcs between wire pairs that pyrolize the polyimide resulting in a conductive char between conductors that may sustain the arc (arc tracking). Furthermore, the arc tracking may spread (flashover) to other wire pairs within a wire bundle. Polyimide Kapton will also be used as the insulating material for the flexible current carrier (FCC) of Space Station Freedom (SSF). The FCC, with conductors in a planar type geometric layout as opposed to bundles, is known to sustain arc tracking at proposed SSF power levels. Tests were conducted in a vacuum bell jar that was designed to conduct polyimide pyrolysis, arc tracking, and flashover studies on samples of SSF's FCC. Test results will be reported concerning the minimal power level needed to sustain arc tracking and the FCC susceptibility to flashover. Results of the FCC arc tracking tests indicate that only 22 volt amps were necessary to sustain arc tracking (proposed SSF power level is 400 watts). FCC flashover studies indicate that the flashover event is highly unlikely.

1. INTRODUCTION

1.1 Scope Of Problem Kapton polyimide wiring insulation has been found to be vulnerable to pyrolization, arc tracking, and flashover when momentary short-circuit arcs have occurred on aircraft power systems (1,2). The short-circuit arc induces local heating, which causes the Kapton insulation to char (pyrolize). The electrically-conductive Kapton char sustains the short-circuit arc. As a result, a momentary localized short-circuit arc between two conductors can propagate along the wire pair through continued pyrolization of the wiring insulation (arc tracking). Furthermore, an arc involving one pair of wires, of a multiple wire bundle, may thermally char an adjoining pair of wires within that bundle (flashover), ultimately leading to complete failure of the entire wire bundle. Polyimide Kapton will also be used as the insulating material for the FCC of SSF. The FCC with conductors in a flat side-by-side planar type geometric layout, as opposed to bundles, can also sustain the arc tracking event at proposed SSF power levels (160 volts, 2.5 amps). Tests were conducted to determine the minimal power level necessary to sustain the arc tracking event and the FCC susceptibility to flashover.

1.2 Defect Generation Over the thirty-year expected life span of SSF, the FCC may experience defects that expose conductors to the lower earth orbital (LEO) space plasma environment. FCC defects may result from micrometeoroid and debris impacts. Additionally, atomic oxygen may further erode the polyimide insulating material at the defects, eventually exposing the FCC conductors to the LEO space plasma environment. These exposed conductor locations (defect sites) are where the polyimide pyrolysis events are most likely to initiate due to LEO space plasma interactions, localized intense plasma generation, and momentary short circuits between conductors (3).

1.3 Plasma Interactions The LEO space plasma environment may pyrolize the negatively-biased FCC through Joule heating due to positive-ion bombardment from the space plasma onto the exposed conductor surface. Two methods of starting arc tracking by local intense plasma generation were studied in the laboratory: inductively induced plasma and impact-induced plasma (3). An inductively induced intense local plasma, generated because of the inductive component of the FCC and solar array system, will be present at the epoch of a micrometeoroid or debris impact severing a conductor. Furthermore, a micrometeoroid or debris impact may generate a local intense plasma due to kinetic energy transformation to plasma energy. Finally, impacts by micrometeoroid and debris, coupled with atomic oxygen degradation of the FCC insulating material's integrity (sacrificing it's ability to prevent the copper traces from touching each other), may result in a momentary short circuit between a return line and its corresponding supply line, causing arc tracking (3).

2. APPARATUS AND PROCEDURE

2.1 Sample Description Each channel of the FCC sample for these tests consisted of three copper traces--a wide return line surrounded by two thinner supply lines with a 50 mil spacing. Typically, an FCC sample consisted of three channels. The channels were stretched out next to each other; so that all three channels occupied the same geometric plane. These copper traces lie between two clad laminated polyimide insulating layers as described in figure 1. The insulating layers for the FCC samples of earlier tests concerning polyimide pyrolysis, arc tracking, and flashover did not have the SiO_x coatings or the fiberglass scrim cloth in silicone matrix; however, the samples used to acquire the results of the tests reported in this paper had the SiO_x coatings and the fiberglass scrim cloth in silicone matrix (3).

2.2 Sample Defect Description A typical defect consisted of a small area of exposed copper return line, where the polyimide/SiO_x insulating layers were partially removed. The defect site was located between one of the supply lines and its corresponding return line.

2.3 Test Apparatus

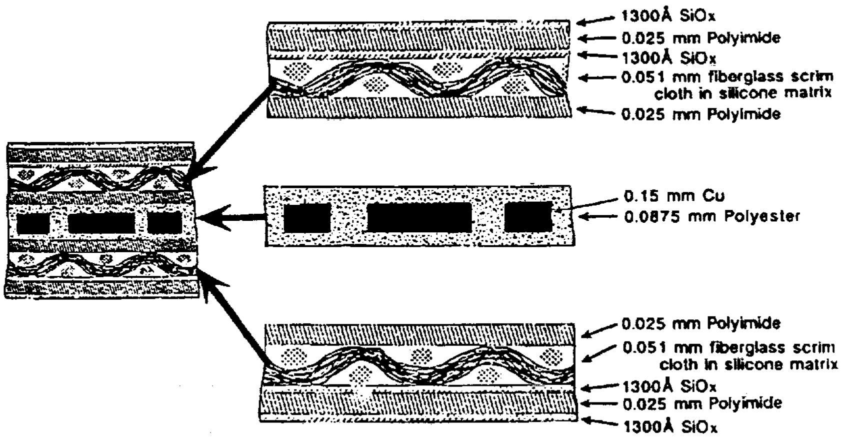

Figure 1: *Cross sectional view of a single FCC channel.*

Tests were conducted in the Abraded Circuit Experiment (ACE) bell jar which provided a vacuum environment. The ACE facility is a helium-cryopumped bell jar capable of obtaining a 5x10^{-6} Torr vacuum. The ACE facility has three 300-volt and 6-amp Sorensen model DCR 300-6B dc power supplies to provide individual power to three separate channels on the FCC. The power supplies interfaced with the FCC samples using the quiescent circuit configuration as described in figure 2 (3). The dc power supply's voltage level control was used to set the non-short-circuit potential between the supply and return lines at the defect site. The quiescent circuit configuration used a current-limiting resistor, manually adjustable by the operator, to control the short-circuit (maximum) current during an arc tracking event. Therefore, the voltage used to initiate an arc and the current allowed to sustain an arc during the arc tracking event was controllable by the operator. The arc tracking event was initiated by short-circuiting the conductors at the defect site with the use of a shorting wand (not shown in figure 2). The shorting wand, controllable by the operator, was a wire with one end tied to the supply line. The other end of the shorting wand was free to move across the FCC and was capable of touching other conductors. Therefore, the shorting wand was capable of creating a short circuit between the supply line and any other conductor on the sample FCC. The shorting wand was used to momentarily touch the supply line's corresponding return line at the defect site, yielding a momentary short circuit between a supply and return line at the defect site.

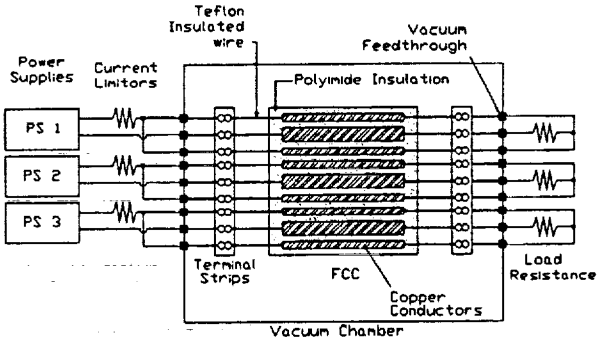

Figure 2: *Quiescent Circuit Configuration for testing SSF's FCC for Polyimide pyrolysis, arc tracking, and propagation.*

2.3 Procedure

2.3.1 Arc Tracking Tests Arc tracking tests were conducted with only one channel energized, thereby isolating the test to only the one channel at a time. In this way, three separate tests could be conducted under vacuum on a sample with three channels without breaking vacuum. An arc tracking test would be set up by selecting and installing a current-limiting resistor on the quiescent circuit and setting the power supplies to 0 volts. High resistance current limiters would have high voltage, low current, arc tracking values; whereas, the low resistance current limiters would have low voltage, high current, arc tracking values. The various current limiter values used resulted in different points on the arc tracking constant volt amp curve (voltage vs. current) described in figure 3.

The arc tracking tests were carried out to ascertain the minimal voltage necessary for each current limiter used to sustain an arc on the FCC sample. These tests were conducted in a two-step process. First, the FCC arc tracking test samples were prepyrolized by exercising the shorting wand to create momentary short-circuit arcs between the supply and return lines at the defect site. At the onset of arc tracking, the polyimide was considered to be pyrolized enough to begin testing; therefore, the power supplies were turned off to terminate the arc tracking event. The second step was the actual test. The test began when the operator incremented the power supply from 0 volts. At the epoch of arc tracking, the power supply voltage and corresponding short-circuit current were noted. The shorting wand was not necessary for step two of this test, because the desired voltage and current measurements were to be from the minimal power capable of restarting the arc tracking event (restrike).

2.3.2 Flashover Tests The scope of the flashover test was to determine whether a channel experiencing the arc tracking event will pyrolize a neighboring channel and cause the neighboring channel to arc track also. Flashover tests were conducted with three side-by-side energized channels. Therefore, only one test could be run on a three-channel FCC sample. The first channel (channel 1) was set up so that its non-short-circuit voltage between the supply and return line (V_1) was 95 volts, and its current limiter was implemented to prevent the maximum short-circuit current (I_{mss}) from exceeding 2.2 amps. The second channel (channel 2) was set up with its V_1 set to 160 volts, and its I_{mss} was 5.0 amps. The third channel (channel 3) was set up with its V_1 set to 130 volts, and its I_{mss} was 2.0 amps. Although each channel had unique values for V_1 and I_{mss}, due to hardware constraints, each channel had sufficient energy to sustain the arc tracking event. The flashover tests were initiated by promoting the arc tracking event with the use of the shorting wand on the middle channel (channel 2). The test was considered complete when channel 2 was completely destroyed.

3. RESULTS

3.1 Arc Tracking Tests

3.1.1 Arc Tracking Capability The arc tracking data points obtained from these tests are displayed as small circles in figure 3. Each data point in figure 3 represents the open-circuit voltage and short-circuit current that was necessary to restrike the arc tracking event for a single test. The data points are arranged into eight groups, with each group obtained from the use of a different current limiter value (2, 10, 27, 40, 80, 160, 320 and 640 ohms). Although the voltage and current levels necessary for each arc tracking event were unpredictable, the minimal voltage current product for each current limiter value was consistently 22. The volt amp product is not a measurement of applied watts; the voltage measurement is the open-circuit (non-short-circuit) voltage prior to arcing, whereas the current measurement is the maximum short-circuit current during an arc. Figure 3 also implies that a minimal short-circuit current (.37 amps) is necessary to pyrolize the insulation enough to sustain arc tracking. These tests indicate that arc tracking arising from a momentary short circuit on this FCC design is possible, provided that the short-circuit current is greater than .37 amps and the volt amp product is greater than 22 volt amps.

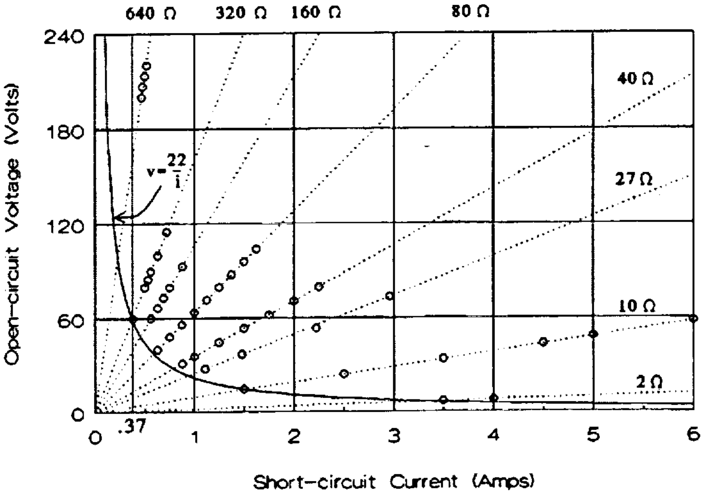

Figure 3: *Arc tracking threshold values for* SiO_x *coated FCC samples.*

3.1.2 Arc Tracking Probability Figure 4 plots the probability of arc tracking restrike vs volt amp product. The probability is the percentage of data points that experienced arc tracking for a given volt amp product value. As seen in figure 4, arc tracking is possible with volt amp products greater than 22. Figure 4 also indicates that the potential for a sustained arc tracking event is highly probable at the 400 volt amp product level. In the volt amp product value, the voltage term is the potential difference necessary to initiate an arc between conductors. Furthermore, in the volt amp product, the amp term is the current necessary to supply enough I^2R heating to continually char the insulating material and sustain the arc tracking event. Therefore, the volt amp term, as defined in these tests, is not a measurement of power (watts). SSF's photovoltaic cells will be delivering 800 watts to its' load through each channel of the FCC. Each supply line (two supply lines per channel) will be delivering 400 watts through the FCC. The 400 watts are composed of 160 volts and 2.5 amps. The potential difference between conductors on the SSF's FCC prior to arcing would be 160 volts. Furthermore, since the SSF photovoltaic cells will function as a 2.5-amp current source, the short-circuit current on SSF's FCC will be 2.5 amps. As a result, the volt amp product, as defined in these tests for a momentary short circuit on the FCC of SSF, would be 400 volt amps. This is capable of sustaining the arc tracking event.

3.2 Flashover Tests With all three channels of the sample FCC energized with enough power to sustain the arc tracking event on each, the arc tracking event that was initiated on the middle channel did not flashover to either of the neighboring channels.

4. DISCUSSION

4.1 Arc Tracking

4.1.1 Arc Tracking Initiation The methods of arc tracking initiation (LEO space plasma interaction, inductively induced plasma, impact induced plasma, and momentary short circuit between conductors) on an FCC sample that had only Kapton polyimide as its insulation was investigated and reported (3). The concern of the LEO space plasma interaction with exposed FCC conductors was addressed, and it was concluded that the LEO space plasma is not at risk to initiating Kapton pyrolysis on a defective FCC at SSF power levels (3). Furthermore, tests conducted at NASA LeRC indicate that approximately 1000 volts, positively biased with respect to the plasma environment, is necessary to attract enough electrons to promote polyimide pyrolysis due to Joule heating (5). At SSF power levels, the probability has been found to be low for an inductively induced plasma, generated at the epoch of a conductor opening, to initiate Kapton pyrolysis (3). The event of a micrometeoroid or debris impact initiating Kapton pyrolysis due to energy transformation from kinetic to plasma energy is also highly unlikely (3). However, a momentary short circuit did initiate Kapton pyrolysis consistently at power levels below SSF operating power levels (3). These tests conducted on earlier FCC insulation design (only Kapton polyimide insulation) would start arc tracking at the epoch of the first momentary short circuit (3). For the FCC configuration presented in this paper (laminated clad insulation composed of the SiO_x-coated polyimide with a fiberglass scrim cloth in silicone matrix layer) the arc tracking event did not necessarily initiate with the first momentary short circuit. Typically, several momentary short circuits were needed to pyrolize the polyimide enough to initiate arc tracking. Since the new insulation configuration protected the FCC better than the old insulation formula for the momentary short-circuit method of initiating the arc tracking event had, the plasma interaction methods studied for possibilities of arc tracking initiation on the SSF's FCC would be extremely remote.

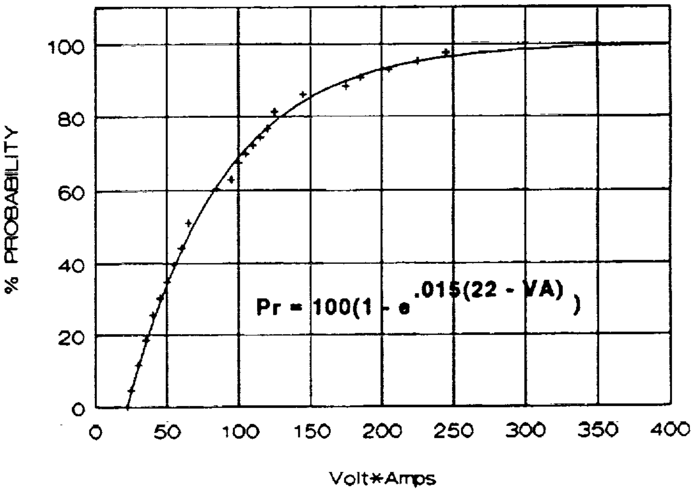

Figure 4: *Probability of arc tracking via polyimide pyrolysis.*

4.1.2 Sustained Arc Tracking Sometimes the arc tracking event extinguished itself before power was removed. Therefore, the new FCC laminated clad insulation composed of the SiO_x-coated polyimide with a fiberglass scrim cloth in silicone matrix layer reduced the FCC's likelihood of initiating and maintaining arc tracking.

4.1.3 Future Arc Tracking tests The number of manually induced, momentary short circuits necessary to promote the arc tracking event was dependent on the volt amps of available power and the intensity of the short-circuit arc. The short-circuit arc intensity was dependent on the available power and the quality of the contact that the momentary short circuit had. A good momentary short circuit contact would discharge more energy into an arc. The I^2R energy in the arc can char the insulation material as well as heat the polyimide. Therefore, further testing of arc tracking initiation should be conducted to determine how much energy is necessary to pyrolize the polyimide enough to promote arc tracking. These tests would provide a better understanding of the probability of arc tracking initiation and the degree of damage resulting from the arc tracking event.

4.2 Flashover The previous FCC design was susceptible to flashover at SSF power levels (3). However, the new laminated clad insulated FCC design, tested under higher-than-expected SSF operating levels, was consistently immune to the flashover event.

4.3 Arc Tracking and Flashover Evaluation Arc tracking initiation on the SSF FCC is highly unlikely due to LEO space plasma interaction or from the local intense plasma generated as a result of a micrometeoroid or debris impact. Arc tracking may also be initiated if two conductors momentarily short circuit against each other several times. The following two cases are possible avenues for a momentary short-circuit arc to occur on the FCC: The insulation must lose its ability to maintain conductor separation, which is a remote possibility due to the insulation construction; or as a result of an impact severing a conductor and damaging the insulation layer, the severed conductor may come in contact with another conductor on the FCC. Test results indicate that if either event occurs and the arc tracking process begins, one of the following three scenarios may result:

1. the arc tracking event may be short-lived and self-extinguish. Therefore, no sacrifice in power transport from the photovoltaic arrays to the habitat module will occur;

2. the supply line involved with the arc tracking process may open the conductor before self-extinguishing. In this case, the habitat module will no longer have power from one supply line;

3. if the arc tracking is not short-lived and therefore does not self-extinguish, all the insulation on the involved supply line will be destroyed.

Usually case 3 above will result in the involved supply line being open circuited. Therefore, as in case 2, the habitat module will be without power from the one supply line. Test results also indicate that if any of the above three cases occur, the arc tracking is limited to only the one supply line and its corresponding return line (no flashover) at power levels higher than what is expected to be available on SSF.

5. CONCLUSIONS

Previous polyimide pyrolization tests indicated the following three results: First, LEO space plasma interaction with exposed FCC conductors is unlikely to initiate arc tracking (3,4). Second, arc tracking initiation is not likely to result from a localized intense plasma due to micrometeoroid and debris impacts (3). Finally, a momentary short circuit between two conductors is capable of initiating arc tracking (3). However, the SiO_x coated Kapton with the fiberglass scrim cloth in silicone matrix, laminated clad insulating layer, made this FCC design more resilient to arc tracking initiation than the previous FCC design. Furthermore, the disastrous flashover event, which was observed on earlier Kapton polyimide insulated FCC designs, did not occur with the new laminated clad polyimide insulation layer construction used with this FCC design.

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8. BIOGRAPHY

Thomas J. Stueber, Electrical Engineer, joined the Sverdrup Technology inc. staff, at the National Aeronautics and Space Administration's Lewis Research Center in February of 1988. Mr. Stueber received a Bachelor's degree in electrical engineering in 1987 and a Master of Science degree in electrical engineering in 1990 from Cleveland State University. During his career at Sverdrup, Mr. Stueber has specialized in the design and development of test apparatus used to conduct research at NASA. Currently, Mr. Stueber is studying the phenomenon of Kapton pyrolization with respect to arc tracking and propagation on Space Station Freedom's Flexible Current Carrier.

Chris Mundson was a Cleveland State University undergraduate research assistant working on-site at NASA Lewis Research Center. Mr. Mundson has performed research concerning Kapton pyrolization with respect to arc tracking and propagation on Space Station Freedom's Flexible Current Carrier.

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