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FLAME SUPPRESSION TECHNIQUE IN ARC TRACKING OF CIRCUIT BOARDS

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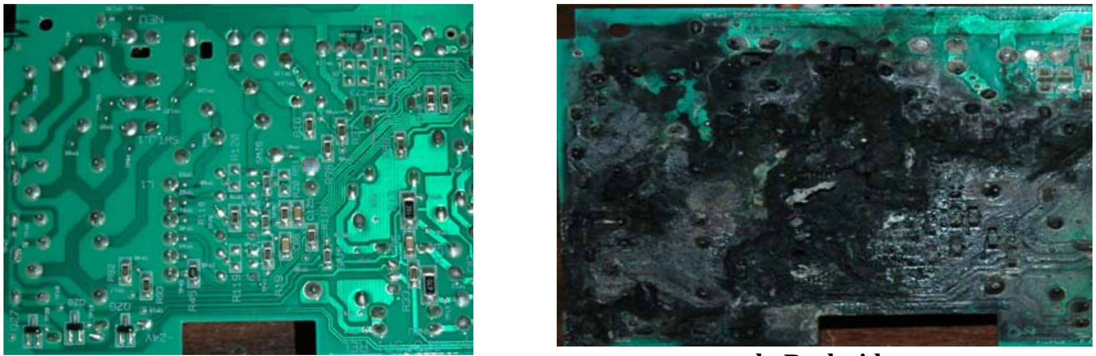
ABSTRACT
The problem of arc tracking in power electronic enclosures was studied through simple bench-top experiments aimed at understanding the phenomenon. Experiments were performed to isolate the causes of arc tracking on PCB boards with high-powered electrodes subjected to a Solventol/water mixture contamination. These experiments show that a minimum electrode spacing of 1 mm would be susceptible to arc tracking. A larger spacing of 3.2 mm appears to prevent arc tracking. In the event that arc tracking causes combustion, a passive flame suppression method is indicated. This method comprises of four layers of off-the-shelf expanded metal network. Tests show that the flame is quenched in about one minute, with minimum damage to the plastic enclosure.

INTRODUCTION
Arc tracking is defined as arcing that may occur on surfaces of nonconductive materials if they become contaminated with salts, conductive dusts, or liquids [1,2]. Though the arcing may be small in size, it may have the potential to ignite flammable gases being produced from the surface of a pyrolyzing combustible. Thus, arc tracking poses a safety hazard [3]. This safety hazard is of particular concern in the aerospace industry [4-6]. Typically, arc tracking arises when short-circuit arcs are formed even momentarily between a defective polyimide insulated wire and another conductor, which then pyrolize the insulating material. The charred polyimide is now electrically conducting and is thus capable of sustaining the short-circuit arc. The sustained arc may then cause continuous pyrolization, giving rise to *arc tracking*. Arc tracking is usually associated with electrical wires and is considered to be the cause of the twa 800 crash off long island in july 19, 1996. The official NTSB investigation concluded that the ullage in the central fuel tank ignited and exploded due to an electrical spark [7].

Much attention on arc tracking has focused on electrical wires, particularly in air transportation [8,9]. However, the phenomenon is of concern in industrial equipment as well as automotive and consumer electrical appliances [10–12]. Moreover, arc tracking is not restricted to electrical wiring but may occur in printed circuit boards (PCBs), due to the high-level of electrical power dissipation for power electronics.

It can be noted that current trends in electronic packaging show power per unit area rising at an ever increasing rate while the footprint of the board is shrinking. Board components are placed at closer and closer proximity, increasing the likelihood of arcing across solder nodes for high-power components. An



a. Front side b. Back side

Figure 1. Front side of burned control panel (courtesy: Whirlpool Corporation)

example of a PCB damaged by arc tracking is shown in Fig. 1. Previous studies reveal two possible modes of failure: initial arcing which severs board power and halting all activity or continuous arcing which occurs as the board remains powered. In these tests, the control panels (or printed circuit boards, PCBs) were subjected to highly humid conditions with the presence of contaminants, mainly in the form of household cleaners. In most cases, the initial arcing caused failure of the electronic components, resulting in power disruption and the shutdown of the appliance. However, in some cases, the PCBs did not have a disruption of power and continuous arcing resulted in a fire.

Arcing is obviously undesirable in domestic appliances, although the occurrence is extremely rare. Experiments were conducted on circuit boards with a surrogate contaminant to obtain a preliminary understanding of of arc tracking. Basic studies on the effects of the power applied, separation between solder joints and contamination of the circuitry were performed. A technique for flame suppression was also tested.

EXPERIMENTS

The experimental program consists of bench testing of isolated pairs of solder nodes, subjected to contamination and testing of a flame suppression technique. These experimental protocols are described below.

Bench Tests of an Isolated Pair of Solder Nodes

In order to isolate the arcing problem and gain understanding of the effects of contamination and applied voltage, initial bench testing involved testing of two isolated solder nodes at various distances and applied voltages. The nodes were exposed to ambient air, distilled water and a Solventol/water mixture (one part by volume of dry Solventol and four parts by volume of distilled water) as contaminant, per Whirlpool practice [13]. This series of tests is to confirm that the Solventol contaminant promotes arcing.

The arrangement for the bench test is shown in Fig. 2. The power source to the solder nodes was from an autotransformer located at the top of the figure. The on-off switch is to the upper left. The autotransformer delivered up to 120 VDC to the circuit in 10 VDC increments. A voltmeter was connected to the plug outlet's surge strip to read the transformer output. Copper wires were crowned with solder and electrically isolated by two ceramic cylinders.

The solder nodes were separated by a distance of 3.2 mm (1/8 in.) and slanted at an included angle of approximately 60º from each other, Fig. 3. The first condition of the test was just ambient air. The voltage was raised to 120 V and then decreased to zero. Thereafter, the voltage was increased by 10 V after a one minute wait at each voltage setting. After testing in air, the circuit was tested with distilled water and a Solventol/water solution. For these tests, the electrodes were held at 90 deg to the ceramic base, Fig. 4. The electrodes were cleaned with acetone at the end of the distilled water test to prepare for the Solventol/water test. The distilled water or the Solventol solution was sprayed onto the electrodes via a medical syringe.

Subsequently, the solder nodes were increased to a larger size of about 2 mm to simulate the size of the solder where the arcing occurred on the failed PCB, see Fig. 5. Furthermore, the bases of the solder were placed approximately 1 mm apart from each other. The sequence of ambient air, distilled water and Solventol solution was followed, where a delay of one minute was held after each voltage level was applied. The events were recorded by still and video camera.

Figure 2. Experimental arrangement for bench test

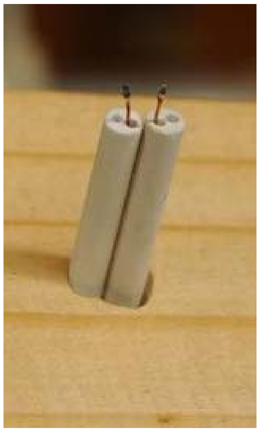


Figure 3. View of initial testing with solder 3.2 mm apart at angle of 60º from each other

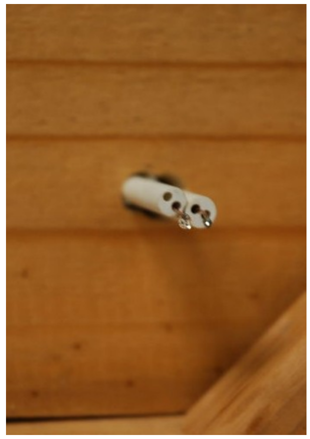


Figure 4. View of initial testing with solder 3.2 mm apart and parallel to each another

Figure 5. View of initial testing with solder 1 mm apart and parallel to each another

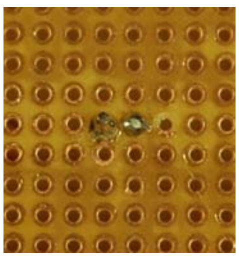


Figure 6. Electrode pair mounted on a PCB

Figure 7. Four electrodes mounted on a PCB

Bench Tests of Two and Four Solder Nodes Mounted on a PCB

The next set of tests was to observe flame and smoke propagation on a PCB due to arc tracking. Two nodes were soldered on a PCB from Radio Shack, as shown in Fig. 6. Other than this modification, the rest of the experimental set-up is similar to that shown in Fig. 2. For this set of experiments, only Solventol/water mixtures were used to induce arc tracking. The procedure was to spray the Solventol/water mixture from a syringe and allow a one minute soak, starting at 10 VDC. The mixture was re-sprayed and the voltage was increased in increments of 10 VDC, with the procedure being repeated until 120 VDC was reached.

For reasons to be given later, a four-electrode arrangement was also tested. The experimental procedure remains the same as two-node testing. The electrode arrangement is shown in Fig. 7. Three of the electrodes were spaced 1 mm apart while a fourth was 3.2 mm away. Only one electrode pair was energized for the tests, either at 1 mm apart or at 4 mm apart. To further understand arc tracking, electrodes were soldered to a production-type PCB, salvaged from a computer, and subjected to Solventol/water mixture contamination testing as before. The arrangement is shown in Fig. 8. The electrode arrangement is highlighted by the box.

Flame Suppression Using Expanded Metal Networks

Expanded metal networks have been used to suppress industrial explosions [14]. It was thought the same material may be used for flame suppression arising from arc tracking. Instead of the Solventol/water mixture, a liquid flame accelerant was utilized as the fueling agent to produce flames on the PCB. The flame accelerant was a mixture of a 1/2 tablespoon of unleaded gasoline, a 1/2 tablespoon of two-cycle engine oil and 55 oz of polystyrene (styrofoam). All the material were mixed together and stirred occasionally for 5 hours. The mixture was ready when the styrofoam was dissolved in the gasoline/oil mixture to result in a jelly-like consistency. This fuel is then applied onto the PCB in a 25 mm by 25 mm square and a thickness of about 0.1 mm.

Next, a 150 mm by 50 mm metal network consisting of woven aluminum alloy foil was placed in a rectangular shape 50 mm above the fuel paste as shown in Fig. 9. Initially, only one layer of foil was placed. Subsequently, the fuel was ignited with a lighter and caught on fire. Thus, further layers were

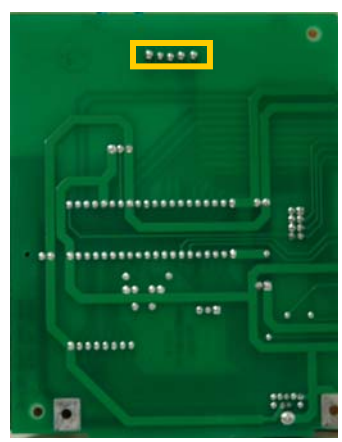


Figure 8: Four electrodes mounted on a production-type PCB.

added until flame suppression was achieved. Once the required number of foil layers for flame suppression was determined, a plexiglas enclosure with the same dimensions as found in domestic appliances was lined with the foil layers, with a 10 mm clearance on two sides of the PCB for ventilation.

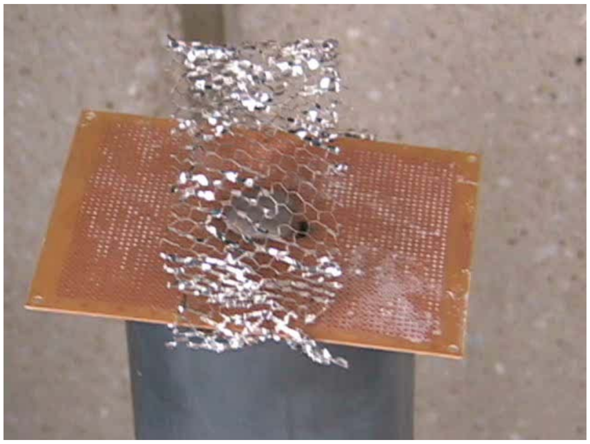


Figure 9. Arrangement of flame suppression with a layer of metal network

RESULTS AND DISCUSSION

Bench Tests of an Isolated Pair of Solder Nodes

When the solder nodes were separated by a distance of 3.2 mm, no arcing occurred for exposure to ambient air, distilled water or Solventol mixture even at the maximum voltage of 120 VDC. Next, when the solder nodes were 1 mm apart, there was no arcing during exposure to ambient air. However, when the electrodes were exposed to distilled water, there was a build-up of small water droplets between them to cause a slight fizzing until 100 VDC. At 100 VDC, the fizzing became violent and caused a vapor explosion. Attempts to repeat the vapor explosion after cleaning the electrodes were not successful. It was therefore thought that the initial vapor explosion may be the result of contamination of the solder nodes by flux. In the Solventol mixture test, arcing occurred at 110 VDC. Smoke and occasional flashing was seen. Eventually, the arcing became so vigorous that one of the nodes burst off the copper wire. The bursting of the solder is thought to be due to two factors: the distance the base of the solder nodes are placed from each other and the mixture exposed to the nodes.

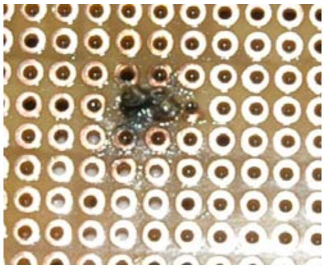


Figure 10. Electrode pair damaged after arc tracking

The distance which the solder nodes are placed from one another is a significant parameter for arcing. There was no arcing for nodes placed 3.2 mm apart when tested in air, distilled water or Solventol mixture. For the 1-mm node spacing with 110 VDC excitation, a violent arcing phenomenon was seen when the Solventol mixture was sprayed continuously, similar to Whirlpool test protocol [8], to cause one of the nodes to separate from the copper wire.

Bench Tests of Electrodes Mounted on a PCB

The results of this series of tests are summarized in Table 1. The data show that the threshold of boiling appears at 30 VDC above which arcing briefly occurs. The threshold for smoke to be visible is 70 VDC. When the applied voltage reaches 100 VDC, both flames and smoke were visible. At 120 VDC, the nodes exploded and the final result is shown in Fig. 10.

The flame in the two-node testing was isolated in the vicinity of the electrodes. It was thought that the flame and smoke may propagate if multiple nodes were available. Thus, four-node testing was performed to check this hypothesis. The experimental procedure remains the same as two-node testing.

Two tests were conducted with the four-electrode arrangement and the results are summarized in Table 2. Blackening occurred on the bases of the solder nodes. This is due to arcing and charring of the high-temperature silicone used to hold the copper wires at the back of the PCB. It can be seen that a low voltage of 20 VDC can cause arc tracking when multiple electrodes are placed close by. Moreover, as the tests progress to higher voltages, arcing and flames appear as the Solventol/water mixture was sprayed directly onto the nodes. Arcing was so severe that the nodes burst from the electrodes. Arcing occurred consistently only with the 1-mm separation but not with the 4-mm separation between electrodes.

It was thought that there may be differences between PCB used by hobbyists that are coated with a flame retardant and those used in mass production, which are uncoated. Thus, a PCB from an old computer was salvaged and five electrodes were mounted on it, Fig. 8. The tests started at an initial voltage of 40 VDC and the results are displayed in Table 3.

From earlier experiments, it was deduced that arcing begins in the general vicinity of a PCB due to the proximity of the solder nodes of approximately 1 mm. Also, arcing requires exposing the nodes to a contaminant, which in the tests was a Solventol/water mixture. (Arcing did not occur in ambient air or exposure to distilled water.) Flames emerged from the board, but only briefly, as captured in Fig. 11. It was noticed that only until the solder nodes themselves “exploded” off did a sustained flame occur. A loud bursting noise as a flame erupted.

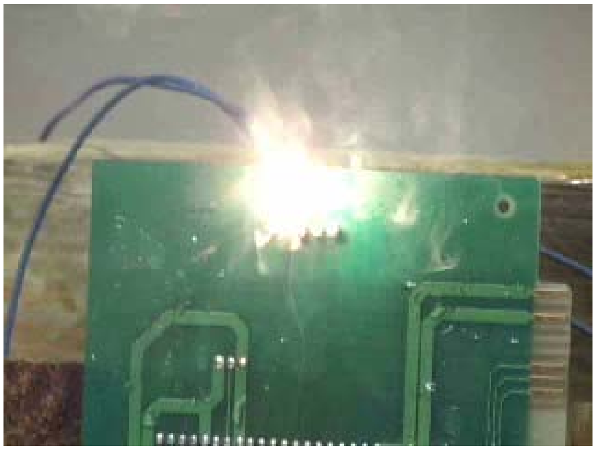


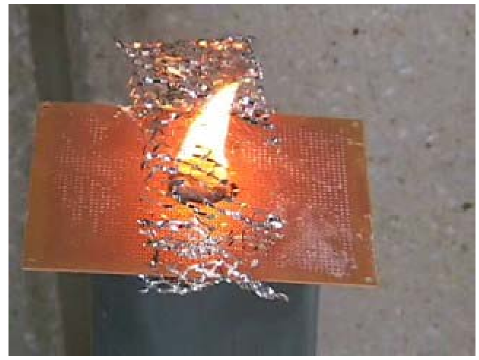
Figure 11. Flame at 120 VDC

Flame Suppression Using Expanded Metal Networks
Figure 12 shows that one to three layers of expanded metal foil failed to suppress the flame. Figure 13 shows that four layers of metal network foils were able to fully restrict the flame to within the confines of the enclosure. In other words, flame suppression succeeded.

As a result, since four layers of the network metal foils were able to suppress flames, the four layers were placed into a clear plexiglas enclosure, Fig. 14. The enclosure size was typical of those found in domestic appliances. A PCB board was placed within the enclosure. Once the specimen was ignited, it extinguished naturally after less than one minute. This test was repeated with the same results. Figure 15 shows the flame contained within the lined enclosure. Figure 16 shows the sooting that occurred due to the lack of air. The soot can be simply wiped off with a finger or towel, with no visible damage to the plexiglass enclosure. Moreover, only the top of the foil that was scorched. The right and left sides were not burned. However, it is recommended that the foil should be placed on all three sides to suppress the flames rapidly with the least amount of damage.

CONCLUSIONS

Experiments were performed to isolate the causes of arc tracking on PCB boards with high-powered electrodes subjected to a Solventol/water mixture contamination. These experiments show that a minimum electrode spacing of 1 mm would be susceptible to arc tracking. A larger spacing of 3.2 mm appears to prevent arc tracking. In the event that arc tracking causes combustion, a passive flame suppression method is indicated. This method comprises of four layers of off-the-shelf expanded metal network. Tests show that the flame is quenched in about one minute, with minimum damage to the plastic enclosure.



a. One layer of expanded metal foil.

b. Two layers of expanded metal foil.

c. Three layers of expanded metal foil.

Figure 12. Inability to suppress flame with thin layer of metal network

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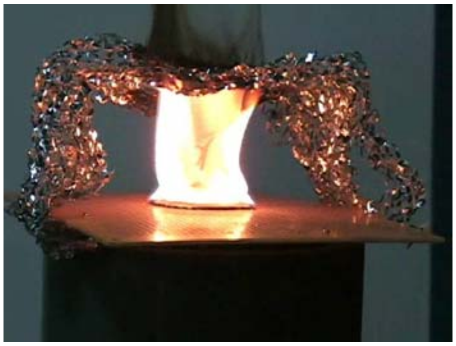

Figure 13. Successful flame suppression with four layers of expanded metal network

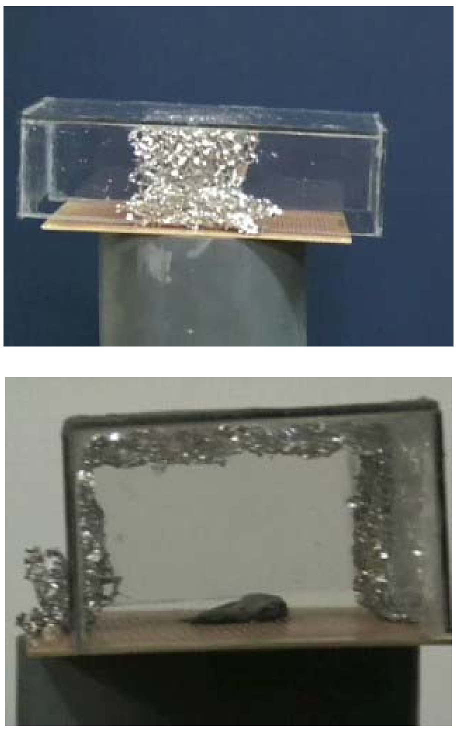

Figure 14. Side view of contained experiment *(top)*, and front view of container *(bottom)*. The lump of fuel accelerant is visible in the lower figure.

Figure 15. Successful flame suppression with four layers of expanded metal network in plexiglas container

Figure 16. Sooting on surface of plexiglass top after flame suppression experiment (expanded metal network removed)

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Table 1. Observations of occurrence of arc tracking for a pair of electrodes 1 mm apart on a PCB

Volts (VDC)	Arcing (Y/N)	Observations
10	N	
20	N	
30	Y	Fizzing
40	Y	Fizzing plus arcing
50	Y	Brief arcing, then stop
60	Y	Brief arcing, build up of Solventol
70	Y	Brief arcing, smoke
80	Y	Brief arcing
90	Y	Arcing, smoke
100	Y	Arcing, slight flame
110	Y	Arcing, slight flame
120	Y	Arcing, then slight flame, 20 seconds later, explosion

Table 2. Observations of occurrence of arc tracking for four electrodes on a PCB

Volts (VDC)	Test 1		Test 2	
	Arcing (Y/N)	Observations		
10	N		N	
20	N	Slight bubbling from Solventol mixture	N	Blackening of base
30	N	Bubbling	N	
40	N		N	
50	N		N	
60	N		N	Slight smoke
70	Y	Burst, Flame, sparking and flickering	N	Smoking, nodes burst
80	Y	Sparking, arcing, flame	NA	
90	Y	Flame, continuous sparks	NA	
100	NA	NA	NA	
110	NA	NA	NA	
120	NA	NA	NA	

Table 3: Observations of occurrence of arc tracking for a pair of electrodes 1 mm apart on a PCB.

Volts (VDC)	Arcing (Y/N)	Observations
40	N	
50	N	
60	Y	Evaporation, arcing from rear
70	Y	Arcing, steady smoking
80	Y	Arcing, smoking, increase, smoking from back
90	Y	Persistent arcing, smoke
100	Y	Smoking, arcing
110	Y	Smoking, arcing
120	Y	Initial flame, arcing
110 (8 min. exposure)	Y	Initial flame, arcing, flame left side, smoking
120 (10 min. exposure)	Y	Smoking, slight flame, sparking, loss one node, flame right side