SpringerBriefs in Fire

James E. Small

Electronic Control Fires

A Design, Manufacturing and Forensic Technical Perspective

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This book is dedicated to my wife Margo and my daughters Jill and Sarah

Preface

The primary intent of this book is to put into plain words how to determine whether a suspect electronic appliance control is the cause of a fire or the result of a fire. It is distinctive in two ways: first, in its evaluation of low voltage, low power (0.6 V, $\leq$5 W) fires and second, in its intent to disseminate valuable information that should not be hidden for personal gain.

The author has been asked multiple times during depositions if what he had just said was "*common knowledge*." It pained him to respond that it was not. This did not change the facts of the case but certainly changed what evidence was harvested and examined in pursuit of the truth. The judge and/or jury was saddled with the unenviable task of determining someone's guilt or innocence without all of the evidence being recognized and therefore not examined.

This book is also somewhat unique in its intended audience of those technically responsible for design, manufacturing, and forensic responsibilities. Its direction is to link the design, manufacturing, and forensic technical communities together as much as possible, thereby allowing each to ensure a final product that will not end up in litigation or at least not be found guilty during litigation. Empirical data provided will prove invaluable in determining the guilt or innocence of an electronic control. Solutions are also suggested when appropriate.

It is very unusual for design or manufacturing organizations to be familiar with NFPA 921. The NFPA, Guide for Fire and Explosion Investigation, is referenced since it provides invaluable forensic technical insight for both the design and manufacturing groups. This insight will allow the designer to know "how robust" their product must be to allow for a good night's sleep and yet not add crippling costs. The two best friends any electronic control can have are a well-documented FMEA (failure mode effect analysis) and an audited risk mitigation plan that encompasses the issues laid out in of this book.

It is a number game. The electronic control arena can be especially risky from a life safety and/or product liability standpoint for low-volume production (1000 per year). The good news is that a one-in-a-million problem is not likely to happen. The bad news is that the product may not have the financial backing to insure against reasonably expected failures, poor design, supplier component variation, unanticipated shipping issues or customer misuse, etc. A product can have a problem that occurs only in one out of every ten thousand households. With over 133 million households in the USA alone in 2014, it is reasonable to expect at least 13,300 homes to experience an unlikely event as defined in Chap. 1.

The other end of the spectrum that is typically much more difficult to deal with is when hundreds of thousands or millions of "identical" products have been produced within a five-year period or so. The more individual the parts and processes from which the final product exists and the more varied its environment, the more complex any potential product forensic investigation will be.

Any product that startles someone by smelling hot, smelling like smoke or arcs and sparks presents a serious issue for those financially and emotionally responsible for its existence. It is not necessary for a unit to erupt into flames, destroy property, and potentially take innocent lives to create a product nightmare. Just the fear of this due to an overlooked new product introduction failure generating smoke or sparks in a home or in shipment can be disastrous if the issue is not dealt with quickly and rationally.

As with all things in life, it is very difficult, if not impossible, to prove something cannot possibly happen. It is much easier to prove something can happen. It is important to note that a level (voltage, current, power, or energy) below which a product fire cannot exist is never claimed. The bench experiments presented in Chap. 14 can be cited to prove levels and conditions at which a fire can exist but not a level at which a fire cannot exist. The experiments in Chap. 14 are designed to demonstrate how little voltage, power, and energy are actually necessary to allow an event to occur.

The author has been intrigued with electronics since he first watched the slowly building glow of tubes in his Hammarlund shortwave amateur radio receiver in the early 1960s. He was awestruck at the conversations he heard magically coming from around the world. Electronics technology was at that time beginning its rapid rise that has touched virtually every aspect of humanity. As with any advance in knowledge, boundaries are always being tested. We always want more for less and that translates into more discrete conductive material in smaller areas. This also translates into higher energy densities. One limiting factor of increasing energy densities is that of the all-too-well-known event that is the focus of this book.

The information that follows is either referenced, is demonstrated through experimentation, or has been learned through many years of new product designs, development, and production cycles.

To the excited, curious and fearless engineer a word about change. In the exciting worlds of research, new product design, and development, embrace change and embrace the associated risks. However, once you "pull the trigger" for a new high-volume product, restrain your urge to make it better when time is too late for adequate testing. It is entirely possible to make a seemingly minor change to eliminate a problem with very minor consequences, while creating a much less likely problem, however with horrible consequences.

Fort Wayne, IN, USA James E. Small

Acknowledgements

A great deal of the information presented in this book was made possible due to my exceptionally good fortune to work closely with so many talented people over the years and especially the following three gentlemen. Richard Vicars, the General Manager of Kodiak, Fire & Safety Consulting (now Jensen Hughes) forensic engineering facility in Fort Wayne, IN, Terry Munson, the founder and CEO of Forsite Inc., in Kokomo IN, and Dan Churchword, the President and founder of Kodiak Enterprises, Inc.

High-volume production and reliability idiosyncrasies continue to be discovered through my good fortune to have worked with Richard Vicars countless hours in a mutually driven and relentless quest to understand that which we knew "could not possibly happen."

Most contamination-related information presented in this book has been gleaned over the past 25 years through Terry Munson and his amazing team's generous use of his facility plus his personal insight to help quench my curiosity.

Dan Churchward has pushed my artificially imposed "possibility boundaries" through his gifts in the field of forensics and for knowing the really hard questions that can be asked during litigation. His participation in the creation of and his passion for NFPA 921, Guide for Fire and Explosion Investigation, in concert with his excellence in general, have been and continue to be a powerful force in my life.

Dan has also provided a great deal of his personal time in making this book pertinent and valuable for the forensic community.

I also want to thank Dr. Vyto Babrauskas, author of the *IGNITION HANDBOOK*, and hundreds of technical papers dealing with fire science for reviewing a draft manuscript of this book. Vyto has provided me with invaluable editorial comments, especially regarding his revelations about Paschen's law.

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Last but not least, I want to thank my amazing wife Margo, for her encouragement in completing this book and for her countless hours of exceptionally patient, detailed proofreading, and graphics assistance.

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About the Author

James E. Small is an electrical engineer retired from United Technologies Hamilton Sundstrand Aerospace Division in CT. James has held senior engineering positions at United Technologies Electronic Controls, Honeywell's North America Homes Division in Golden Valley, MN, and their Life Safety Division in CT. He was also the director of Research and Development at Emerson's Weigand Appliance Controls Division in AL. Since 2006, he has devoted his insatiable curiosity to solving mysterious electronic control-related product issues working with his colleagues primarily at Kodiak Fire and Safety Consulting (now Jensen Hughes) in their Fort Wayne, IN, facility as a consulting engineer and expert witness. He has also provided recent in-house consulting during the new product development phase for several Fortune 500 companies prior to their release of new electronic control-related products.

He is experienced in all aspects of electronic design from concept through production. He holds nine US patents, all related to the design of electronic appliance controls. As the director of Emerson Electric's R&D, Weigand Appliance Controls Division, he drove breakthrough designs of electronic controls and unique infrared heating components for present-day smooth glass cooktop residential ranges. As the director of Honeywell's North America Homes Engineering Organization within their Automation and Controls Solutions (ACS) business unit, he was deeply involved in revolutionary electronic control concepts, designs, and manufacturing innovations. During this time, Honeywell's ACS business unit was awarded Minnesota's prestigious annual "Tekne" Award for three of his organization's new products based on customer ease of use and ease of manufacturing. Jim has taught Six Sigma/Lean courses extensively through Purdue University's Technical Assistance Program/Manufacturing Extension Partnership (TAP/MEP) and has taught Masters Level Statistics as Adjunct Faculty at Indiana Wesleyan University. Jim holds a BSEE from Purdue University and an MBA from Indiana Wesleyan University. James began his own consulting business in Fort Wayne, Indiana, early 2006. More information regarding James can be found at lowwattagefires.com and he can be reached at jesmall65@gmail.com.

Introduction

The phrase "electronic controls" conjures up different images for different people. Many believe a control is "electronic" if we interact with it by the use of a digital display such as a 7-segment LED (light-emitting diode) or a LCD (liquid crystal display). Electronic controls in the context of this book will refer to any electronic assembly that includes components such as a printed circuit board, resistors, and capacitors that controls another appliance, such as a washing machine.

We are virtually surrounded by "electronic controls" in today's way of life. We can go to sleep watching TV and are kept comfortable by a heating and cooling system. Some even set the firmness of their mattress by the press of a button. We are kept safe by a security system, and smoke detectors as we sleep. The TV, heating and cooling system, air mattress pump, security system and smoke detectors each have their own electronic control.

Each morning before we awake, the heating and cooling thermostat automatically makes our house the perfect temperature. We awake due to a preset alarm and delight in a warm shower. A sonic toothbrush and an electric razor may also be called upon prior to our morning toast, microwaved egg burrito, and perfectly brewed coffee. The thermostat, morning alarm, water heater, sonic toothbrush, electric razor, toaster, microwave, and coffee maker each have their own unique electronic control.

While drinking our coffee, we click an electronic control to remotely start our car so that it will be nice and toasty or cooled down (the temperature is controlled by another electronic control) before we get in. We then use another "key fob" electronic control to unlock the car before we are on our way. So each morning, we have used at least 10 electronic controls before we even get out on the road!

The list of electronic controls in our life is a very long list indeed, and each of these electronic controls is unique. Four electronic controls are depicted in Figs. 1, 2, 3, 4, 5, and 6. When many electronic controlled products in our daily life function properly, we tend to take them for granted and forget they are even there. Unlike thirty or forty years ago, consumers today have a more "throwaway mentality." Feeding this throwaway mentality is the belief and experience that whatever

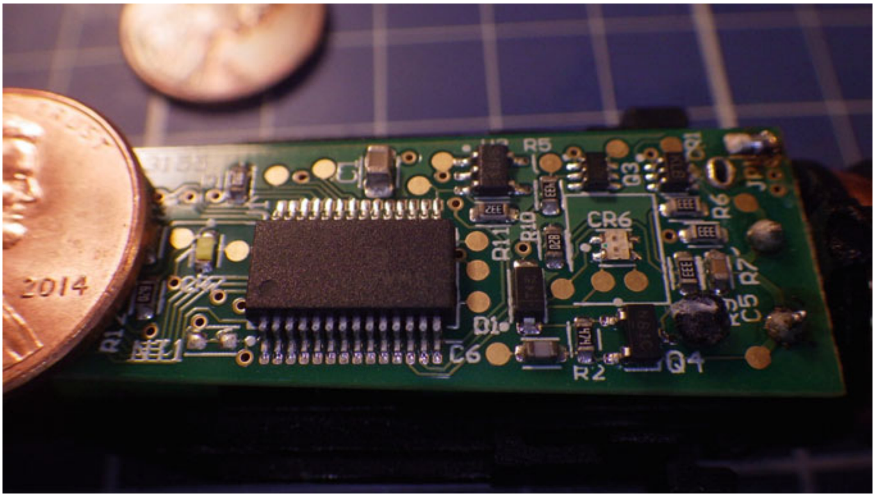

Fig. 1 Lower portion of an ultrasonic toothbrush electronic control

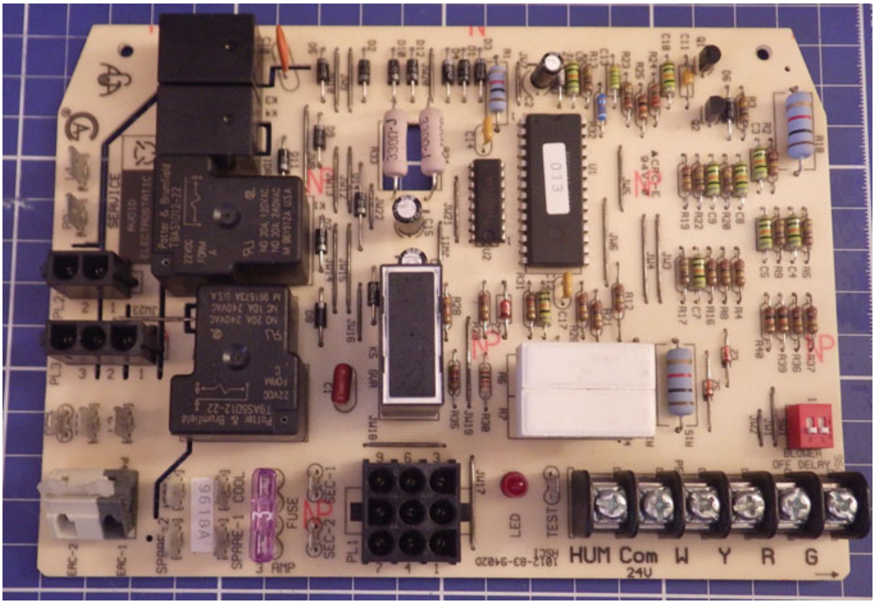

Fig. 2 A residential furnace electronic control

we buy today will be replaced in 6 months to 3 years with something better and perhaps less expensive.

Prior to our product development cycle becoming 6 months to 3 years, it would have been thought absurd and totally unacceptable for electronic products to fail

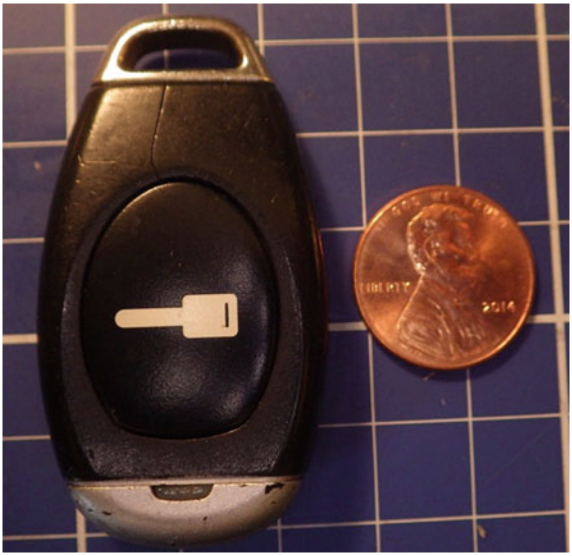

Fig. 3 An electronic control designed to start a vehicle remotely

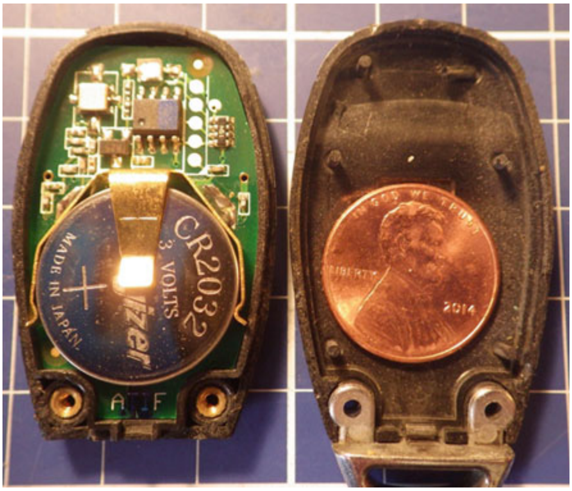

Fig. 4 Contents of the control depicted in Fig. 3 of an electronic control made to start a vehicle remotely

or need replacement after only 3 years. For this reason, a great deal of time and thought was spent on engineering to make certain known failure modes over a 20+ year time frame were minimized, safe and any life safety issues for the homeowner were all but eliminated. In comparison, today's low expectations for product longevity have promoted more inexpensive products and quick-to-market design and manufacturing processes with an increased propensity for the chance of things that can go wrong, to go wrong.

Fig. 5 An electronic control designed to lock and unlock a vehicle remotely

Fig. 6 Contents of the control depicted in Fig. 5 of an electronic control that will lock and unlock a vehicle remotely

In this book, many of those things that can go wrong are discussed from the perspective of both the design and manufacturing functions and clarified for the responsible forensic team. It is the intent of this book to make known many pitfalls of this fast-paced new risk-laden product introduction environment and help minimize the number of electronic control fires and other menacing events of today.

Chapter 3 provides a detailed list of many “things that can go wrong.” It is my hope that a design team would take this list to heart and make certain any new electronic control they introduce will not be subject to any of its many possible downfalls.

The astute forensic team who did not evolve through the design, manufacturing, and field service worlds of electronic controls will find this book particularly enlightening and extremely valuable in his or her role as an expert witness.

New, and extremely valuable, empirical data are provided and discussed at length in the later chapters of this book. These data become a very powerful tool in the hands of a skilled attorney and expert witness.

The design and manufacturing teams will find lists of “things that can go wrong” and do go wrong so often today. Having this information early in the product development cycle can remove a great deal of stress from the lives of those responsible for today’s many new product introductions.

How to quickly uncover and fix many unwelcome problems due to shortened product life span is the focus of “Electronic Control Fires,” the first ever monograph on this topic.

Chapter 1
The Event Defined

A. The Dreaded Event

An engineer is summoned due to the infamous and dreaded event. This is the politically correct term for someone made a very serious mistake… attorneys will be involved… heads will roll… and fortunes may be lost. In the context of this book the short definition of an event is a smoke and/or fire occurrence when and/or where it is not expected and should not happen. Event is an excellent albeit vague term. When you first hear of the event it will be called a product recall, a fire, smoke, popping, sizzling, arson, explosion etc. These are all dangerous and nearly always inaccurate and misleading descriptions. Hence, it is best described as the "event" until the investigation reaches its completion.

B. Investigating the Flame, Cause and Effect

A more detailed and therefore useful definition, especially for a forensic investigation of an event and what must be present to allow it is as follows.

From a very fundamental aspect, hydrogen, carbon and oxygen must all be present at the same time in appropriate amounts in the presence of an adequate energy source for an observable period of time. This adequate energy source is simply very quickly vibrating atoms encroaching on the hydrogen and carbon molecules, enabling them to escape their intended and more happy place in a solid material such as a plastic housing or a printed circuit board. These quickly vibrating atoms cause the hydrogen and carbon molecules to fly from their happy home (**Pyrolysis**). In the presence of adequate oxygen (**Oxidation**) this can initiate the infamous event. If adequate energy is present and hydrogen, carbon and oxygen are available the remarkable blue flame will appear (**Chemiluminescence**). If there is adequate oxygen to feed this blue flame there will be no smoke or soot (unconsumed carbon particles) but possibly a lot of material consumed, AKA missing material, e.g., a hole. If the available oxygen becomes inadequate to oxidize all of

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the carbon an unhappy yellow flame or hue somewhere between blue and red will appear. This consists of relatively big chunks of carbon atoms clumped together and glowing (**Incandescence**).

The visible color indicates the temperature at which the chunks of carbon are glowing. The hottest (most energetic) part of the flame is blue. The coolest part of the flame (least energy) is red. Recall our friend ROY G. BIV (Red–Orange–Yellow–Green–Blue–Indigo–Violet). This visual color experience is not to be confused with the preceding phase of chemiluminescence that produces colors based on the chemicals involved, how tightly their outer shell electrons are held, and therefore the amount i.e. color of energy released.

C. Importance of "Amounts" as It Relates to an Event

The amount of energy available in any design or forensic investigation is key to understanding what could or could not have happened.

Heating a 6-inch (15.24 cm) square piece of aluminum to 350 °F will store a specific amount of energy. A 6-inch (15.24 cm) square piece of aluminum *foil* heated to 350 °F will store X_1 joules of energy. A 6-inch (15.24 cm) square piece of aluminum *3 inches thick* (7.62 cm) heated to 350 °F will store X_2 joules of energy. Experience teaches one that grabbing the *thin sheet* of aluminum foil with one's bare fingers will not cause a painful experience. However, grabbing the *thick block* of aluminum with one's bare fingers will cause a significantly painful experience.

This illustration of "amounts" of energy is carried over to the arena of the potential for and seriousness of an event.

Chapter 2
Facts Regarding Typical Events

An electronic control is sometimes accused of causing a fire if evidence exists of the product failing due to overheating. If a plastic housing or a printed circuit board, mostly intact with a localized area of black soot or other obvious visible damage, is found the first piece of the map that can ultimately lead to the root cause of the event is at hand and available. In the end perseverance through uncovering clues will lead to an understanding of why the event occurred and how to prevent it from occurring again. In many instances the “how” to prevent it from occurring again with a practical solution will be the most challenging task.

In the case of the event clue being a localized area of visible damage it is a matter of determining how too much energy was forced through too small of an area for too long of a time. The first question to answer is what is unique about this event? Was it an unexpected increase in the amount of energy delivered for a given period of time? Or… was it an unexpected decrease in the expected material’s thermal characteristics through which this energy flowed?

In order to provide legal evidence that an event was caused by a specific hypothesis a competent ignition source and a demonstrated first fuel, as defined by NFPA 921: Guide for Fire and Explosion Investigations, must be satisfactorily explained.

When determining if a control is guilty or innocent of causing a fire note the following language from NFPA 921, “Fire cause factors: The determination of the cause of a fire requires the identification of those factors that were necessary for the fire to have occurred. Those factors include the presence of a competent ignition source, the type and form of the first fuel, and the circumstances such as failures or such as human actions that allowed the factors to come together and start the fire.”

Forensics involving electronic control investigations would be greatly advanced if there was an accepted metric such as W-Sec, W, Volts or even Amps below which a control could not combust. Some within the forensics community believe that if you don’t have 240VAC or 120VAC available to an electronic control it cannot be the cause of an event. This notion may contribute to the very large

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number of fire investigations that result in “cause unknown”. As demonstrated in Chap. 14, a power level of $\leq$3 W can ignite (visible flame) a PCB as well as a DC voltage of 0.59 V. It is also true that a 6000 K arc can be generated from as little as 1 A [1].

A. **Self-ignition of Electronics Assemblies**

Not knowing the failure modes of electronics assemblies and their propensity for self-ignition can be a very unnerving and potentially very costly business decision.

The following allows a hitherto difficult “self ignition analysis” of any electronics assembly to be accomplished within a reasonable amount of time. The best-case scenario is obviously to deploy the following during the concept, design and initial production stages. A relatively easy “Self Ignition Analysis” can be performed after the basics as presented are understood.

Following is a primarily empirical elaboration of classical physics applied to today’s materials and manufacturing processes.

The answer to the question (W-Sec, Watts, Volts or Amps below which a control cannot combust) is full of qualifying conditions. The short answers are as follows and are based upon results of bench experiments detailed in Chap. 14 of this book. The “below which” is not above and most likely below the values of each experiment. In order to determine and present the “lowest levels” one would have to complete a well thought out DOE (Design Of Experiments) or a similar statistically structured method. This will be left up to any interested party who would like to know the statistical boundary “below which” combustion will not happen.

B. **Quantity of Fuel**

Just because an arc or a spark is found possible and even probable during FMEA (Failure Mode Effects Analysis) testing, it does not mean that this product can or cannot cause a fire.

C. **PCB Conductor Spacing**

The subject of minimum PCB conductor spacing is not an easy one. From a design engineer’s perspective there is a very long list of criteria that the physical copper layout and minimum spacing must obey to function properly. From a manufacturing engineer’s perspective minimum spacing is based on the limits of the manufacturing equipment and known process limits. From a forensic engineer’s perspective it may simply be the UL spacing required where 120 VAC or 240 VAC is found within the control.

Minimum spacing will certainly depend on the maximum voltage anticipated given reasonably expected failure modes. Minimum conductor spacing must be specified such that arcing through air or contaminant accumulated over years will not occur.

In practice, the value historically relied upon for an electronic control has been a variant of 340 V [2] as suggested by Paschen’s law. The reality is that hot plasma arcs can occur well below 100 V for narrowing conductor gaps of 1 μm or less. The interested reader is encouraged to consider Vytenis Babrauskas's Ph.D. paper, "Arc Breakdown In Air Over Very Small Gap Distances", Interscience Communications Ltd. From Proceedings of Interflam 2013.

Just because a product is designed and specified such that it *should never* see voltage levels over the level at which an arc can occur, does not mean that an arc could not have ignited the PCB or its plastic housing. If evidence points towards an unlikely arcing event, it is prudent to look for failure modes that could open inductive current carrying paths in the damaged vicinity. Since an inductance will rapidly produce a very high opposing voltage to minimize the rate at which its current changes, it is entirely feasible that an inductive separation arc occurred.

Modeling the peak voltage and energy level due to a PCB conductor separating especially between 0 and 5 μm is not trivial as explained in the ECE234/434 handout available on-line from the University of Rochester [3]. Energy estimates for separation arcs can be made by taking half of the open circuit voltage, times half of the closed circuit current, times the duration of the arc. Energy contained in the arc is therefore:

$$E_{arc} = \frac{1}{2} V_{oc} \times I_{cc} \times D_{arc}$$

One other general statement regarding the potential PCB damage from arcing is that for a DC waveform and an AC waveform having equal RMS (Root Mean Square) values, the alternating current is normally less damaging than the direct current because it may not always reignite its arc after its current passes the zero crossing twice each cycle.

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Chapter 3
Localized Events

Typical Areas of Localized Events

A. **Near the AC Power Input Wiring**

MOVs (Metal Oxide Varistors) are often placed across AC power lines feeding a control. If there is inadequate current limiting into the MOV and the actual/fault maximum required MOV power dissipation is unknown, the MOV is susceptible to a very rapid explosive event that may result in a sustained fire if there is adequate fuel and oxygen in the immediate area. Every MOV has a maximum joule rating that must be clearly understood if it is to be safely designed into a circuit. Experiment #2 as described in Chap. 14, demonstrates that 3.9 J is adequate to generate smoke within 1 s. Therefore, if an MOV is correctly expected to absorb 3.9 J or more and fails, this point of failure is capable of creating smoke.

B. **Near Control Input/Output Lines**

Due to inductive voltage spikes from relay or contactor coils, or fault conditions such as a locked rotor for an AC motor, unanticipated currents from locked rotors may heat up copper PCB paths to the point of separating them from the laminate. The wildly swaying serpent-like trace will sometimes fuse open leaving an energized wire free to energize an area causing a shock and/or fire hazard.

C. **Near Antenna Connections**

Due to unintended high voltage contact such as lightning strikes or from other nearby sources; external connections such as antenna feeds are very susceptible to transferring energy into a control, thus resulting in an event.

D. **Lightning Strikes**

If a control is designed and manufactured properly for typically anticipated lightning strikes, a control will only experience an event at its incoming power

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connection if this path does not meet code. UL rated wall outlets and wiring within the structure will arc over limiting the energy available at the control to safe limits.

Typical Reasons for Localized Events

A. **Copper Trace Finished Dimensions**

Confusion regarding copper trace finished dimensions or over and under etching during the PCB (printed circuit board) etching process frequently exists. Traces can easily be underspecified and therefore overheat to the point of ignition. An underspecified copper trace can overheat, delaminate and curl up away from the laminate to contact another conductor with disastrous consequences. This can be difficult to reproduce since the delamination and curling of the trace may not always contact the same conductor each time.

B. **Small Surface Areas with Little or No Copper**

The thermal resistance from the surface of a PCB, with no copper plating, to ambient air is

$$\theta_{SA} = \frac{155\,\frac{in^2K}{W}}{Surface\ Area}$$

Therefore the smaller the surface area, the larger the thermal resistance to any escaping heat [1]. Copper properly adhered to a PCB laminate will quickly pass energy from the laminate into the surrounding air as long as the copper is exposed to cooler air. Thicker laminate is harder to ignite than thinner laminate. Copper surface area exposed to cool air quickly transfers energy to its surroundings. Therefore, maximizing copper surface area with an abundant supply of cooler air makes an event less likely. Maximizing laminate thickness also makes an event less likely.

C. **Non-plated Holes**

Peppering a thin laminate full of holes with little or no copper provides a great place for oxygen to combine with any hydrogen and carbon released from the PCB material during the early stages of an event. A non-plated hole through the PCB can aid combustion by providing a chimney effect as demonstrated in Experiment #10 of Chap. 14, Fig. 14.59.

D. **Isolating Small PCB Sections by Use of Punched Slots and/or Holes**

PCB slots designed into a PCB between 120VAC and 240VAC power inputs are occasionally candidates for events. This is true especially if the copper pads are minimum size due to typical published spacing constraints. The condition of rapid heat build up is magnified if the incoming power leads are not properly wetted and soldered. This results in inadequate heat sinking of the leads themselves. The present evolving industry requirement for use of lead-free solder aggravates this issue since the lead-free process is more difficult.

E. **PCB Connector Ampacity is Often Vaguely Specified and Not Understood**

Incoming power wire is frequently the primary source for drawing heat from the immediate PCB connections. An unintended reduction in the incoming wire gauge may cause unnoticed dramatic risks for an event in this area of the control. The "critical to heat sinking" specified wire gauge might be fine when the product is shipped but four weeks later in the field be inadequate to provide the heat sinking required to prevent an event. For example, an effective gauge reduction can happen through corrosion of wire due to inadequately heated fluxes during the tinning process. This, like many other root causes, can be difficult to determine after the event has occurred in this PCB location. If all logical causes are ruled out during a forensic product investigation with an exemplar and the subject unit, it will be necessary to investigate the production line.

F. **Manufacturing "Supposed To Be" Versus "Actual"**

No matter how qualified the manufacturing facility is it is never adequate to simply discuss the manufacturing process/s with those directly responsible. It is critical to walk the process and see what is actually being done. It is always informative to look closely at each process while it is being performed unannounced to the person doing the work. It is frequently informative to look closely into the "non-existent" scrap containers conveniently located out of view. Another very telling location for forensic analysis within the manufacturing facility is in the supply cabinets for problematic chemicals, materials, etc.

G. **Flux From a Soldering or Rework Process**

Flux from an improper soldering or rework process can leave conductive moisture absorbing residue under a relay allowing the relay to chatter and therefore initiate a thermal event as described in this chapter. It is easy to over-flux plated through-holes, resulting in moisture absorbing, conductive and corrosive flux residue under the electrically functional relay. Casualties of this mistake are depicted in Figs. 3.1 and 3.2.

H. **No-Clean Flux Residues (Courtesy of Foresite, Inc.)**

If improperly applied, no-clean liquid fluxes on selective and robotic soldering processes can leave clear flux residues with WOA (weak organic acids), such as succinic, adipic, glutaric acids, to name a few, where the residues can actually become corrosive. This is a typical complex issue due to the precarious nature of the pallet design. The pallet is a custom-made boat like device, required to carry the PCB assembly through the intricate soldering and cleaning processes. It must isolate through-hole leads while at the same time preventing final flux levels from becoming corrosive. If no-clean liquid fluxes have been applied properly the

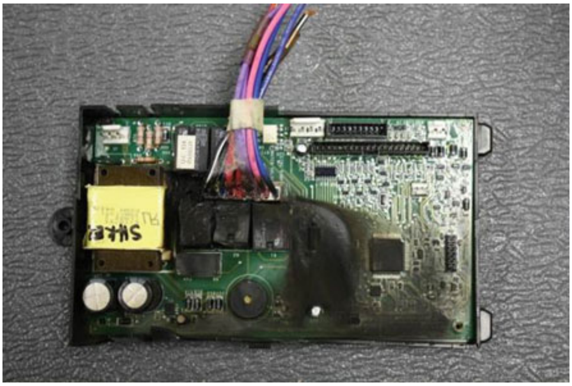

Fig. 3.1 Damage resulting from over-fluxing under a through-hole leaded relay. Photo is courtesy of Foresite, Inc.

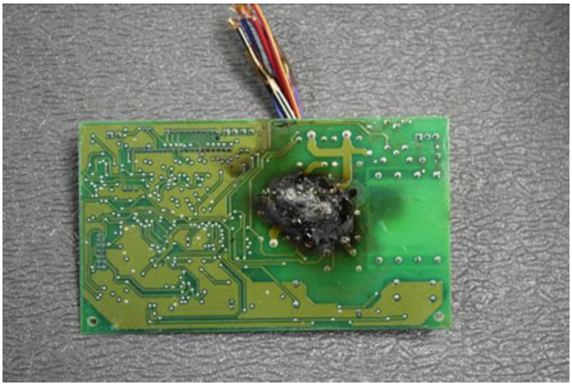

Fig. 3.2 Bottom side of damaged PCB depicted in Fig. 3.1. Photo is courtesy of Foresite, Inc.

amount of flux residue, when extracted by a C3* and Ion Chromatography System, will have WOA at 150 µg/in^2 or less. Areas of flux that cause dendrites to form are typically at WOA residue levels of 175–350 µg/in^2. Figure 3.3 depicts dendritic growth that has formed under a conformal coating.

*Foresite C3—Critical Cleanliness Control®.

As of this publication, it is the only tester on the market that indicates whether a specific, critical area of a PCBA is clean.

Localized Small Explosive Events

A. **Moisture Under Coating**

Events that appear to be explosive within the confines of a control are frequently caused by contaminants combined with moisture under a coating or absorbed into a porous material. These events tend to appear in warm humid areas after months of

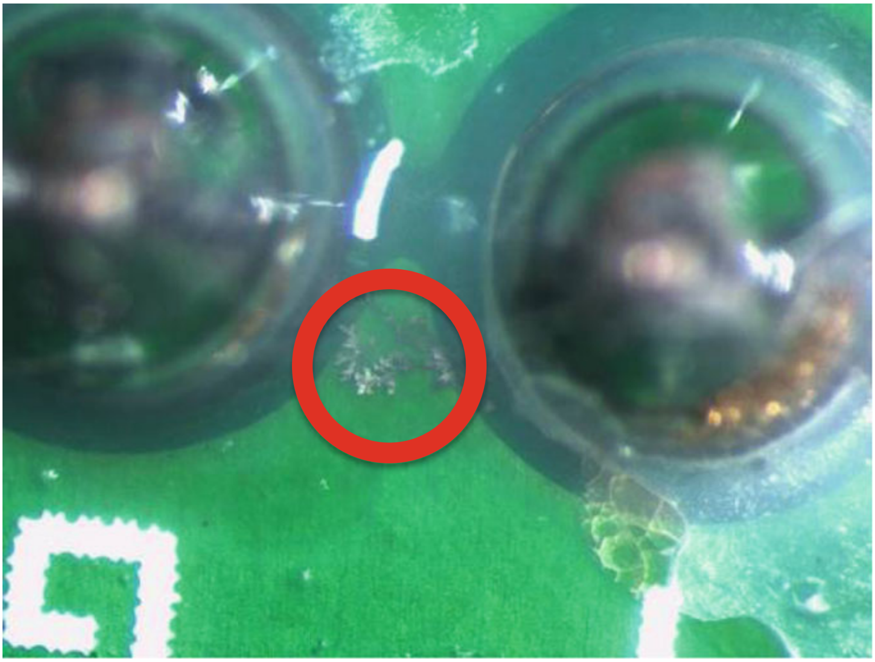

Fig. 3.3 Dendritic growth under a conformal coating. Photo is courtesy of Foresite, Inc.

use. The higher the voltage and the lower the line frequency, e.g., DC versus 240VAC-50 Hz versus 120VAC-60 Hz, the more vulnerable the product is to conductive contaminants [2, 3].

B. **Chattering Relay**

Another common example involves a solder connection to a power relay's output connection. If the relay contacts start chattering (vibrating at 60 Hz or less) for any reason, the heat generated by the chattering contacts is now added to the current/heat path. A marginal copper trace or solder fillet at either of these leads can melt. As the solder fillet melts and separates from the relay pin an extremely violent separation arc can be produced. This separation arc can easily cause an event as defined in Chap. 1 of this book.

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1. "Texas Instruments Application Report, SNVA419C, Thermal Design By Insight, Not Hindsight April", Last modified April, 2013, http://www.ti.com.cn/cn/lit/an/snva419c/snva419c.pdf AN-2020

2. S.W. Chaikin, J. Janney, EM. Church, and C.W. McClelland, "Silver Migration and Printed Wiring," Indust. Eng. Chem., vol. 51, p. 299, 1959.
3. Bumiller, E and Hillman, Hillman, Dr. Craig, "Review of Models for Time-to- Failure Due to Metallic Migration Mechanisms", Last accessed June, 2016, http://www.dfrsolutions.com/uploads/white-papers/Time-to-Failure_Metallic_Migration.pdf

Chapter 4
Who Is At Fault

If you are fortunate a FMEA (Failure Mode Effects Analysis) will be available from the design organization. It will be very helpful to review it. It is entirely possible that you are witness to an anticipated failure mode. If this is the case your quest may indeed be over.

From the product owner's perspective, questions to be answered are:

Did the product event occur within its published specifications?
Did the product event occur within its advertised environment?

If the product failed within its published specifications and its advertised environment, either marketing's requirements to the developing organization are incorrect or the developer misled the marketing organization.

If it occurred outside of the intended environment it is now the forensic engineer's responsibly to explain the details. Depending on the circumstances it may be required to communicate how and why it failed to someone with absolutely no technical knowledge or you may be afforded the luxury of simply convincing another equally knowledgeable engineer of your conclusions.

If it occurred within the intended environment and cannot be reproduced with a functional control of the same vintage and background (exemplar), it will be necessary to determine what is unique about the unit that experienced the event.

If the "Product Champion" owns the design and the manufacturing organizations, it may be possible to get documentation detailing the design at the system and schematic level along with any changes made to the product. In a few rare cases you will be able to get both a design and a manufacturing FMEA (Failure Mode Effect Analysis). In this author's experience it is rare to find properly documented and controlled manufacturing processes. It is also extremely rare to find documented and controlled risk mitigation plans for areas of the appliance control that cannot be automatically tested. Frequently risk mitigation is ignored since components are automatically inserted. Automatic insertion processes start and stop and are therefore prone to errors, granted to a much lower degree than manual insertion, but

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errors can occur. Automatic insertion equipment also occasionally misses components and therefore requires a person to intervene with a mistake prone manual component placement.

From an engineering perspective, there are two very intense investigations that will immediately ensue after a forensic engineer determines the product is at fault for an event… design versus manufacturing.

Design Versus Manufacturing Problem

The following is this author's personal definition of the two possible culprits and may or may not comply with any legal definitions. The designer specifies product failures based on agreed upon tolerances of all components and manufacturing processes deployed. If all worst case conditions are considered agreed upon and an event occurs, it is the designer's responsibility. If a component supplier or manufacturing facility does not meet the agreed upon tolerance specifications, and this results in the event, the fault lies with the supplier or manufacturer.

- It is worthwhile to mention that a lot of today's technology, now in the field for the past 5–10 years, met a process validation protocol used for much older technology and testing conditions. The advent of recent environmental legislation has required dramatic changes in both manufacturing materials and processes. This requires an urgent response and a thorough understanding of anything unanticipated regarding production and/or field issues prior to them becoming an unnecessary manufacturing crisis, or worse yet, a serious field recall issue. No unanticipated production anomaly or early field issue should ever be allowed in the "do nothing further" category. Everything should be thoroughly understood and resolved from a liability perspective.

Chapter 5
High Current PCB Connections

Current levels in the range of 3–18 A passing through PCB inserted connectors, copper pads and traces are not uncommon. When a hole is burned through a PCB at a high current connection such as this, it is due to one of five reasons. Note: Experiment #9b of Chap. 14 demonstrates that 4.7 W for 31 s (145.7 J) is adequate burn a hole through CEM-1 (94V-0). Experiment #6 of Chap. 14 demonstrates that 4.44 W for 52 s (230.88 J) is adequate to burn a hole through FR-4 (94V-0).

(1) The male to female connection became excessively resistive and got hot enough for a long enough period of time to ignite the PCB laminate.
(2) The connection from the connector to the PCB trace became excessively resistive and got hot enough for a long enough period of time to ignite the PCB laminate.
(3) The solder fillet attaching the connector to the PCB melted *due to surrounding I^2R heating* and ignited the PCB.
(4) The solder fillet melted due to I^2R heating (*due to its thermal resistance)* and ignited the PCB.
(5) The solder fillet melted due to I^2R heating from the male to female connection. As the solder fillet melted and fell out of the hole, arcing between the connector pin and the lead's pad occurred. These arcs are hot plasma and typically in the neighborhood of 6000 K. Ignition and vaporization of surrounding material is nearly always present. Any fuel close to this arcing event is frequently ignited and will burn as long as the supply of energy, oxygen, hydrogen and carbon are present.

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How to Determine if Excessive I^2R Heating Is Within a Connector, a Nearby Solder Connection, or a Trace

It is not always obvious if the connector assembly attached to the PCB, the PCB lead to hole/pad geometries, or the high current PCB traces is the root cause of an event.

In order to determine the root cause of this common scenario it is essential to use an IR (infrared) camera in order to see temperatures in three dimensions as a function of time. It is difficult to see the directional flow of energy (heat) since very slight differences change and move very quickly through all three dimensions and time. It is imperative to have your camera set up properly and understand what you are recording. It is also imperative to carefully paint all surfaces flat black, for consistent emissivity, while not altering the original thermal characteristics to get meaningful results.

What will be found:

(1) A properly soldered connection will or will not allow this event.
(2) A marginal and or abused connector will or will not allow this event.

From a post event standpoint, assuming the preceding evaluation demonstrated that the solder fillet melted and allowed arcing to occur, it is essential to determine if the solder fillet melting was due to heat generated within the connector assembly or the PCB.

One way to determine this is by using exemplars for the following tests:

(1) Hold a carefully regulated soldering tip to the ***connector pins solder fillet*** hot spot (as indicated in an IR Camera evaluation) until the solder fillet melts and separates.
(2) Hold the same heated soldering iron tip to the ***junction of the male and female connectors*** until the solder fillet melts, separates and begins arcing.
(3) Carefully cut loose the connector assembly, with an isopropyl rinsed contamination free tool. Closely examine all inside and outside surfaces of the connector body assembly and the proximal PCB area for any resemblance to the unit(s) recovered from the original event. Looking closely enough will reveal a visible heat deformation signature telling you how the subject unit's original event failed and therefore its cause.

Chapter 6
Liquid, Moisture and Electronics

Many are surprised to hear that water near an electrical appliance may cause an event. After all, water is used to put out fires, isn't it? Water has an amazing ability to absorb large amounts of energy and therefore lower heat, resulting in slowing or extinguishing fires. This being said, water is very insidious when it comes in contact with electrical energy in its ability to conduct electrical currents and to form unwanted electrically conductive paths that can cause events.

Typical water is full of electrically conductive material. This material (ionic) is notorious for laying down unwanted conductive bridges that can fuse and reform multiple times per sec, creating havoc. It does not take a deep puddle of water to allow this issue. Studies demonstrate that a liquid depth of 20 molecules* will allow the electromigration of conductive material [1].

Copper ions in the presence of water (pure or otherwise) will break from their metallic bonds and flow into their lowest energy state as directed by an engulfing electric field. Tiny copper particles will be violently tossed about in a liquid as they attempt to align themselves with the imposed electric field before it reverses. The stronger the field and the more often it reverses, the more chaotic their motion. For an applied DC voltage the copper movement is not nearly as chaotic. For a DC voltage applied across a typical PCB copper spacing of 0.010 inches a conductive bridge can form easily in less than one sec. Depending on the available current this unintended connection may be blown apart and reform many times within a few sec or months. The time frame depends on how often this process is allowed to repeat itself. Repeated applications of fluid will support this process until no more copper or other conductive material is available to add to this unintended current path. Typically in the early stages of the process the mobilizing fluid is entirely vaporized due to I^2R heating. Once the fluid is gone there is no longer a transport mechanism to further build this bridge.

Moisture that bridges two electrical conductors such as a 120 VAC or 240 VAC terminal can very slowly (months), or quickly (min), build extremely hot and frequently explosive incidents along its path. Ionic contaminants such as the ever so

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prevalent sulfur and chlorine in today's environment will greatly enhance the copper transportation-land bridge calamity as previously described. Ionic contaminants in sufficient amounts will allow events to occur in very insidious ways, sometimes taking years to reveal themselves.

*For a visual perspective of this thickness, imagine you find a pencil lying on the street next to a 43-story building. The thickness of the pencil is comparable the depth of the 20 molecule deep water, and the height of a 1 oz copper PCB trace is comparable to the height of the 43-story building.

Reference

1. Bumiller, E and Hillman, Hillman, Dr. Craig, "Review of Models for Time-to-Failure Due to Metallic Migration Mechanisms", Last accessed June, 2016, http://www.dfrsolutions.com/uploads/white-papers/Time-to-Failure_Metallic_Migration.pdf.

Chapter 7
The Ugly Process

Standard plastic material molded over two 120 VAC or 240 VAC pins will in all likelihood contain some level of mobile conductive material in the form of sulfur and/or chloride [1]. If these tiny ionic particles (bridge builders) are not capable of moving close enough to touch and then separate, there is no problem and therefore no event. This Ugly Process is also referred to as “Wet Tracking”.

If a fluid is present to allow movement of these ionic particles, a carbonized chain whose links consist of carbonized arcs can form along the electric field lines. This chain will conduct current and then separate somewhere along its length. Watching this insidious process under a microscope in real time is very much like watching a jagged marching chain of tiny exploding robots. The parade of exploding arcs dims and then intensifies repeatedly. Once the many domes of moisture have vaporized the March stops.

This “ugly process” is easily duplicated in the lab. Visual artifacts are typically evident and also easily reproduced in the lab as detailed in the following.

The connector used to create these contamination related visual artifacts are depicted in Figs. 7.1 and 7.2. Figure 7.2 Depicts the AC power line cord metal to metal measurements and the surface prior to sanding it down for purposes of expediting visual artifacts due to a heavily contaminated 120 VAC interface connection. Special processing to expedite the creation of the visual artifacts is depicted in Fig. 7.3. Salt water is indicative of many other ionic contaminants and was therefore used for this process. One drop of a saturated salt solution was placed on the sanded surface of the 120 VAC connector as depicted in Fig. 7.4. Figures 7.5, 7.6 and 7.7 depict the results of shorting out the 120 VAC by the liquid/contaminant and its vaporization through the boiling process. The parade of exploding arcs dims and then intensifies repeatedly and is very difficult to capture with a limited number of snap shots. However one shot of the “…exploding arcs…” is depicted in Fig. 7.5. Indisputable visual evidence of the “jagged marching chain of tiny exploding robots” is depicted in Figs. 7.6 and 7.7.

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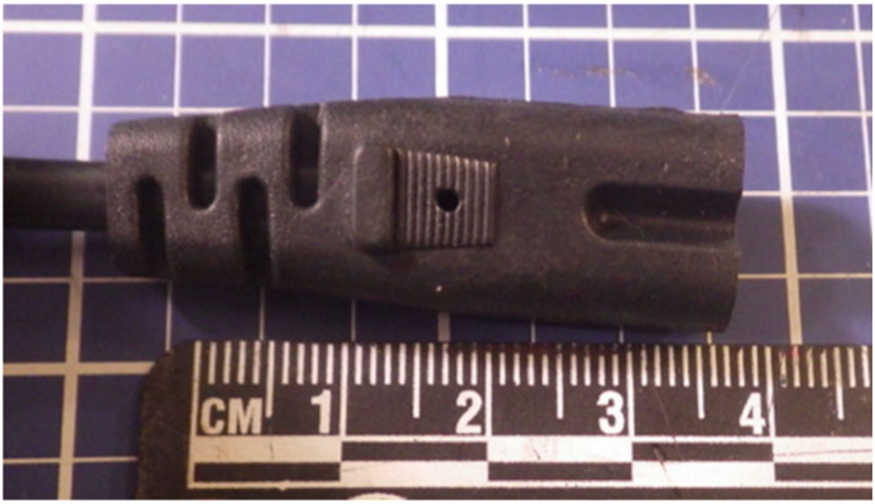

Fig. 7.1 The 120 VAC power cable-connector used to attach appliances, TVs, audio equipment, test equipment, etc. it will be used to create typical visual artifacts of contamination caused events

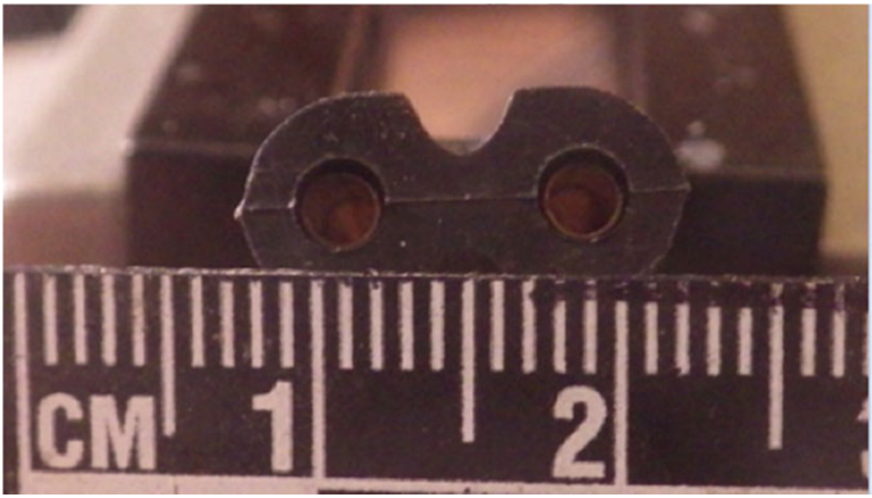

Fig. 7.2 Metal to metal distance between the connections is $\sim$5 mm

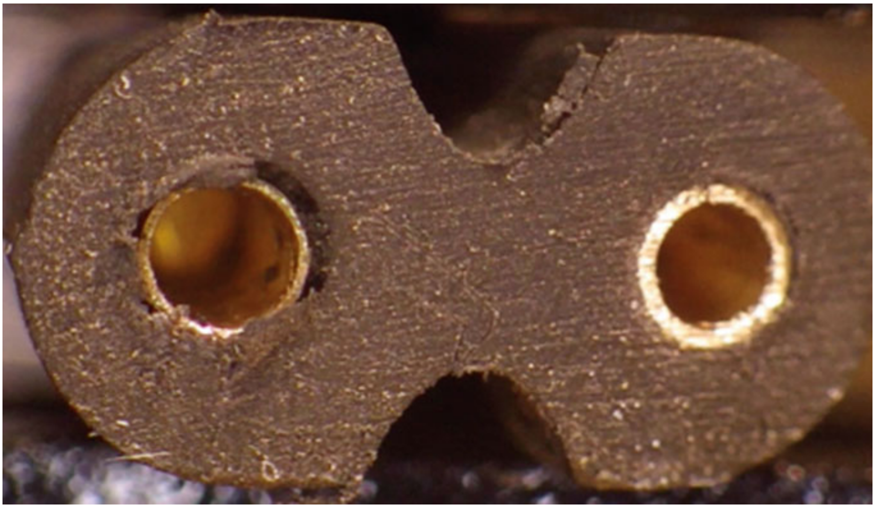

Fig. 7.3 Typical 120 VAC power cable-connector sanded down to expose the AC pins in order to expedite the "ugly process"

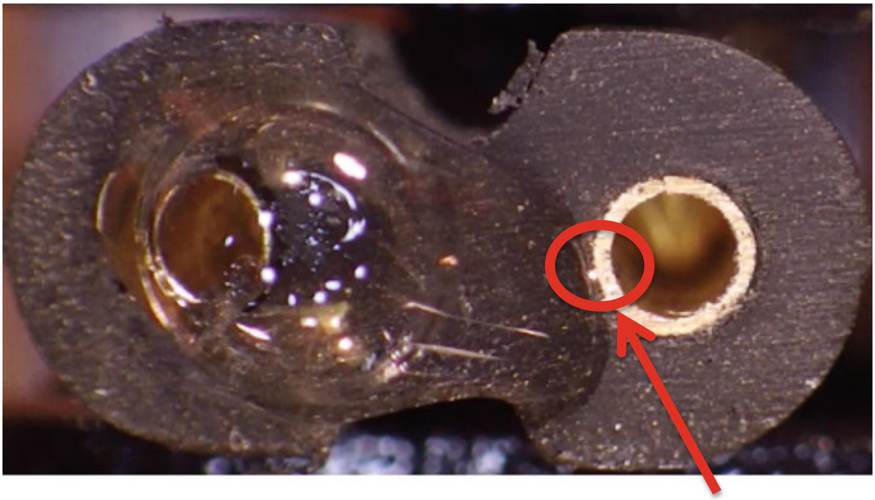

Fig. 7.4 One drop of liquid (saturated salt solution) is placed on connector. As the drop moves towards the opposite polarity connection an electrical arc is formed

For additional information regarding this "ugly process" and PCB related contamination issues see "Low Voltage The Incompetent Ignition Source Dispelling The Myth" [1].

Fig. 7.5 The arc depicted in the previous photo quickly passed current through the liquid to boil it away leaving a new and much wider arc boundary as enclosed by the *red curve*. (The "jagged marching chain of tiny exploding robots")

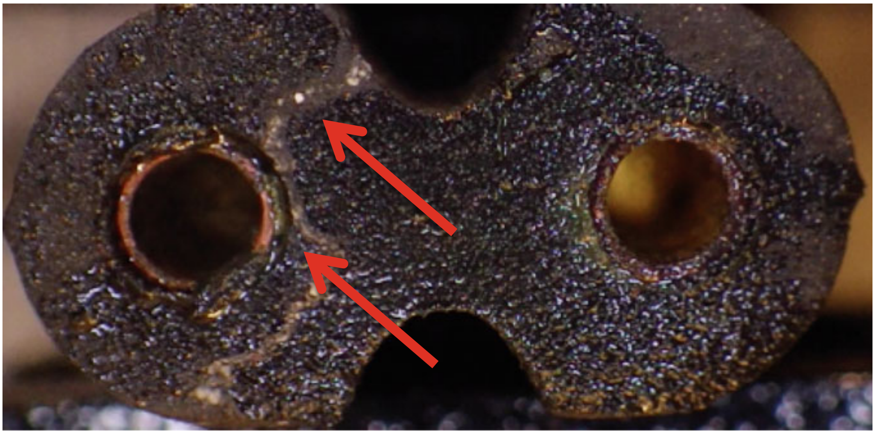

Fig. 7.6 To expedite this photographic record, additional saturated salt solution was dropped onto the surface. A new arc boundary forms at the liquid boundaries to the left, as indicated by the *red line*. The "jagged marching chain of tiny exploding robots" created this trough. *Note* "The exploding robots" are difficult to capture in one frame but are visually apparent in real time videos

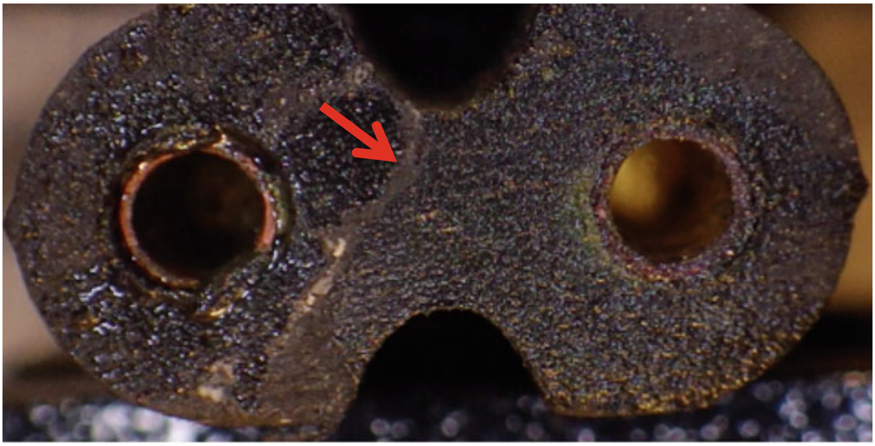

Fig. 7.7 Looking closely will reveal an arc boundary shift from *left* to *right* for the upper half of the previous boundary. This is a typical artifact for contamination-initiated events. Close examination will reveal that this is actually dendritic growth that completes itself each half cycle, is then scrambled and continually rebuilt

Manifestations of the Ugly Process

Two common scenarios:

1. The microscopic explosions persist for a few seconds and then the March is over. A conductive bridge has formed between negatively and positively charged surfaces. A plume of smoke rises out of the trail and is wisped away. A circuit breaker *does not trip* and the event immediately begins or is delayed until conditions are once again right.
2. A circuit *breaker trips* and disconnects power from the appliance. Someone assumes the appliance was not working because the circuit breaker tripped. The circuit breaker is reset. The appliance works fine but gives off a burnt odor.

Depending upon the level of carbonization due to arcing, the type and concentration of ionic contaminants along the trail and condensing moisture in the area, a very serious event may occur.

The seriousness of this event depends primarily on three factors:

1. The flame retardant properties of nearby components
2. Availability of oxygen
3. Transient response of the circuit breaker

Depending on the time allowing these copper atoms to travel, a conductive bridge may form and then be blown apart by its inability to handle the current flowing through it. This bridge will reconnect until it is capable of tolerating the current to create a visible event. This can occur within both DC and AC fields.

Under favorable conditions it requires less than one sec to form a conductive bridge. Therefore, the longer the time between polarity reversals, the faster the bridge will be formed that can result in a noticeable event.

Liquid, Moisture on a Coated PCB

Solder mask and/or conformal coatings are frequently used over AC power inputs and outputs of a PCB to minimize the risk of conductive contaminants bridging a high-energy source. What is not often realized is that conformal coatings will trap conductive material (solder balls, chloride, sulfur, etc.) and simply make it more difficult for moisture to reach this trapped conductive material. Thus begins the unwanted conductive path scenarios as previously detailed. The problem with water puddling on a conformal coating is that the H_2O will pass through the barrier (leaving its ionic content behind) and then provide a transportation mechanism for the ionic content laying in wait below the surface. The presence of moisture under the coating now makes the bridge building, carbon forming and arcing process occur in a *pressurized environment*. Possible 6000 K arcs in combination with the trapped expanding gases can now make for an especially ugly and violent event. In this scenario the coating made the problem worse. It is frequently prudent to specify that no conformal coating be applied over line voltage PCB trace areas.

Getting a product such as an electronic appliance control into the revenue stream from conception requires a major orchestration of tasks. Given the high volume and rush to market it is imperative that the owner/maker of the product thoroughly understands and mitigates any risks due the high potential cost of an event. A risk mitigation plan must be auditable, audited and survive inevitable organizational transitions.

Reference

1. Vicars, Richard J., Terry Munson, Small, James E., "Low Voltage The Incompetent Ignition Source - Dispelling The Myth", 2010, Sarasota, Fla. National Association of Fire Investigators 2010.

Chapter 8
Liability Related Electronic Control Deficiencies

(1) Connector requirement and specifications are misunderstood:

   (a) Connectors are often chosen for a new design due to their success in a previous similar design without adequate FMEA (Failure Mode Effects Analysis). It is often the case that more of the available connections within a connector are used in a new application, without realizing the current rating of each conductor may be adversely affected.

(2) Fault condition copper heat rise is underestimated:

   (a) Published, suggested highline VAC used by many component manufacturers is sometimes too low. Newly developed neighborhoods will frequently show higher than expected "high" limits for VAC.
   (b) Confusion between the design engineer and the PCB supplier is not unusual and can lead to traces that are 1/2 oz when they were intended to be 1 oz finished copper.

(3) The fault current and energy from a 24 VAC, 40 VA Class 2 transformer is underestimated [1]:

   (a) Many don't realize that this transformer can output greater than 6 A for over 60 s during a short-circuit condition. Note: Experiment #9b of Chap. 14, Fig. 14.53 depicts a flame that peaked after 5.9 A at 0.78 V was present for 20 s.

(4) Critical component cleanliness specifications are ignored and/or not monitored:

   (a) Some components may be specified to a cleanliness level as received, and then unwittingly contaminated. For example, wiping a plastic housing with an antistatic wipe may fix one problem but allow contaminants (chlorides in the antistatic wipe) to slowly run over nearby previously uncontaminated components. These unanticipated contaminants can result in an event as explained in the "Ugly Process".

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DOI 10.1007/978-3-319-52845-8_8

(5) UL flammability ratings are misunderstood:

   (a) UL 94 V-0 allows a flame to persist for a specified amount of time. Not realizing a flame is allowed, a nylon connector body without a 94 V-0 rating, may be vulnerable to igniting and causing a major event.

(6) Proper precautions are not taken to limit incoming power during a major control malfunction where charring and flames are present:

   (a) Cutting off external power quickly is critical to preventing a major loss.
   (b) It is important to understand that a flame across a blown fuse will conduct current thereby feeding a control fire.

(7) Importance of wire gage attached to the control from external sources is not realized or communicated:

   (a) It is critical to know if externally attached wires are acting as heat sinks by virtue of their gage. This is a typical organizational issue, i.e., "*not my* fault our board ignited because *they* changed *their* wire gage PCB connector ampacity".

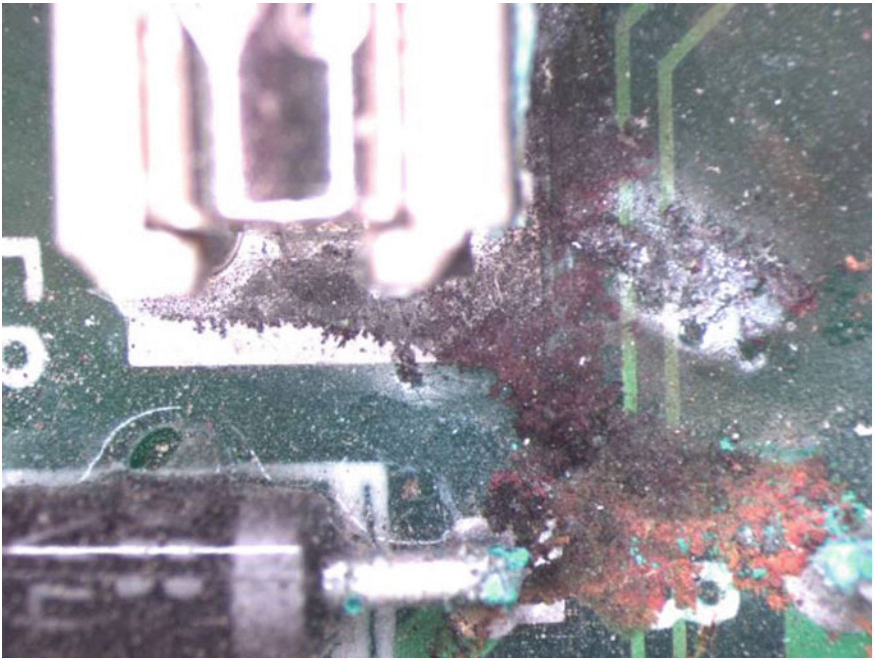

Fig. 8.1 Photo of contaminant combined with moisture under a coating depicts a short circuit that can precipitate an event. *Photo* is courtesy of Foresite, Inc.

(8) Control cleanliness requirements are not understood:

(a) Events that appear to be explosive within the confines of a control are frequently caused by contaminants combined with moisture under a coating on a nonporous material or absorbed into a porous material. These events tend to appear in warm humid areas after months of use. See Fig. 8.1.

(b) Dendrites are not normally discussed when VAC is considered. For line frequencies of 60 Hz and below it is important to consider the possibility of contamination related issues. Since dendritic growth requires time to initiate and to grow it may well be the case that 50 Hz is more prone to contaminants than 60 Hz since more time is available between phase reversals [2, 3].

(c) Reasonably dry geographical areas will allow sulfur crystallization as depicted in Fig. 8.2. Unlike dendritic growth this crystallization, also known as "Creep Corrosion" is formed by galvanic action and can form on PCBs prior to being powered.

(d) Inter-layer laminate contamination fills in voids due to improperly processed glass weave by the PCB supplier. This contaminant filled void can act as a high power internal short-circuit.

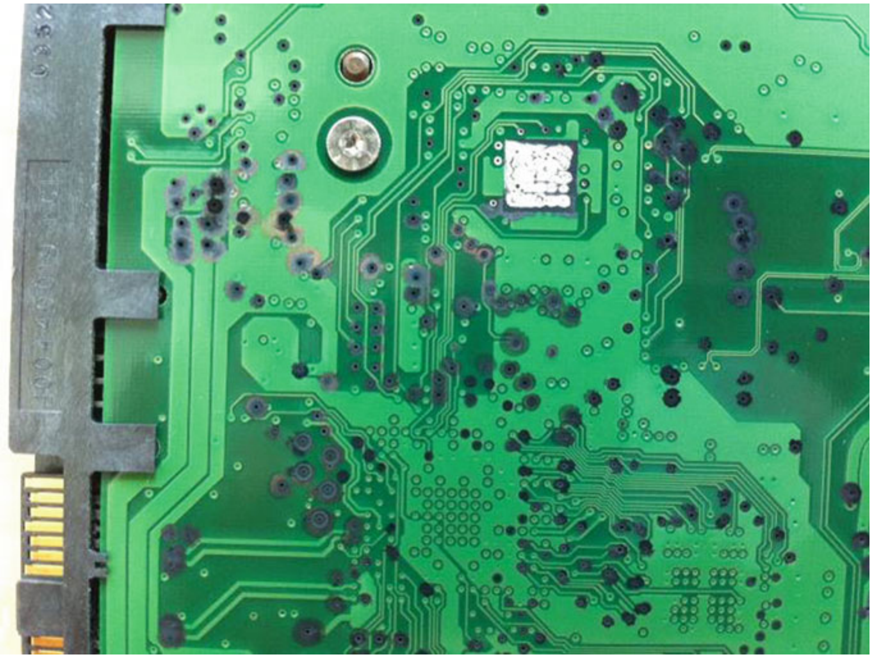

Fig. 8.2 The many very evident black appearing blotches are creep corrosion sites formed during a warm dry 30 °C with 45% RH over a 3 month period. *Photo* is courtesy of Foresite, Inc.

(9) Power relay switching contact's lead-to-hole ratios and pad geometries are marginal:

   (a) Power relay suppliers typically specify maximum current ratings based upon use of particular optimized pad geometry. Many designs do not use the specified pad.

(10) Power relay worst case analysis is not done or incorrectly done:

   (a) Contacts can chatter, i.e., vibrate at a 60 Hz or lower rate.
   (b) Heat generated by the chattering contacts is now added to the current/heat path. A marginal copper trace or solder fillet at either of these leads can melt. As the solder fillet melts and separates from the relay pin an extremely intense separation arc can be produced.

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Chapter 9
Localized Event Explained—Charred Hole

Visual Artifact

A charred hole is found at a high current (High $\geq$ 1 A) connector location.

Evaluation

In order to entirely burn away PCB base material a very intense arcing environment for $\sim$1 min is required. For a 1.574 mm thick FR4 laminate this can occur with 39 J for 9 s to ignite and 47 J to sustain a flame for 11 s. This flame is capable of carbonizing the material that can fall out and leave a hole. For a 1.574 mm thick CEM-1 laminate this can occur with 27 J for 6 s to ignite and 157 J to sustain a flame for 35 s that is capable of carbonizing the material that can fall out an leave a hole. See experiments #5, #9a and #9b of Chap. 14 for comparative details.

Cause

This arcing event happened in one of two ways:

(1) The solder fillet melted, fell out due to I^2R heating and arcing began.
(2) The solder fillet was never present. The current connecting lead was an unintended, marginal press-fit with the PCB connecting copper. The arcing event began when power was initially applied to the control while the control was required to supply current through the connection. A separation arc began when the marginal connection path exceeded the material's melting point and the solder fell away.

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DOI 10.1007/978-3-319-52845-8_9

Time to Failure

Time to failure depends on:

(1) How marginal the unwanted press-fit connection was.
(2) The power per unit time the "press-fit" was required to support.
(3) The rate that energy transfers out of the hottest spot compared to the rate that energy flows into this location.

All of this being said the time to failure is typically minutes or days at most from the product's initial power up.

Problem Resolution

Business entity requiring attention:

Where the fault lies has many different levels and sub-levels from a business entity perspective. From a very high level the cause will be found in one of the following three:

(1) The control was improperly specified for its actual application and designed as specified.
(2) The control design entity created a product that allowed the failure due to accepted contractual manufacturing quality levels.
(3) The control assembly entity allowed the failure by not keeping one or more of the process variations within contractual limits.

Chapter 10
Localized Event Explained-Partially Charred Surface

Visual Artifact

A partially charred surface area is found.

Evaluation

In order to burn away PCB surface material several things must be present:

(1) A moist environment for several min at a time.
(2) Repeated moist environment episodes in the presence of voltage and current.
(3) An external supply of energy for a 1.574 mm thick FR4 laminate in the neighborhood of 39 J for 9 s to ignite and 47 J to sustain a flame for 11 s that is capable of carbonizing the material. For a 1.574 mm thick CEM-1 laminate this can occur with 27 J for 6 s to ignite and 157 J to sustain a flame for 35 s that is capable of carbonizing the material. See experiments #5, #9a and #9b of Chap. 14 for comparative details.

Cause

This material charring is due to surface arcing of unintended conductive paths formed between opposite polarities. The most typical path is caused by water on the PCB surface as thin as 20 molecules [1], spanning between two conductors.

The liquid allows arcing in one of two ways. Depending upon the amount and type of conductive material available, the thickness of the liquid layer, the amount of voltage, available current and the exposed copper within the wet area, one of two dominant processes will transpire.

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(1) The liquid spill forms one bubble enclosing opposite polarities.
For 240 VAC or 120 VAC (50–60) HZ systems where an ample supply of liquid has *formed quickly*, such as a liquid being spilled onto the subject area, the following sequence of events will transpire:

(a) The liquid forms one bubble enclosing opposite polarities. Current flows through the liquid raising its temperature to boil. If the current flow is inadequate to open an inline fuse or circuit, the volume of liquid will decrease rapidly and typically go from one bubble to two smaller connected bubbles. As the two smaller bubbles decrease in volume due to vaporization their inner edges pull apart resulting in a separation arc.
(b) This arc carbonizes the PCB surface that in effect leaves a conductive "stepping stone" for this process to continue more easily. Whenever adequate voltage, current and moisture are present across this subject area the process will repeat until one of the carbonized spots ignites the PCB. On a CEM-1 it will resemble a 4th of July sparkler.
(c) Or… the carbonized spots will form a continuous conductive path without ignition if conditions don't allow. This continuous conductive path will result in a length of material missing from FR-4 laminate or a slot missing from CEM-1 material. In order for this event to ignite material other than the immediate PCB material it is necessary for the arc or flame to contact a plastic housing or plastic connector body as an additional source of fuel. NFPA 921, "Guide for Fire and Explosion Investigations" requires proof of a competent ignition source and a second fuel to declare the device responsible for a fire.

It is important to understand that a 94 V-0 flame rating for materials such as plastics and PCB laminates does not mean they won't burn.

(2) The moisture forms a thin layer enclosing opposite polarities.
For 240 VAC (50–60) HZ down to 5 VDC systems where an ample supply of liquid *does not form quickly*, such as dew point condensation, the following sequence of events will transpire:

(a) (Assume a high chloride and/or sulfide ion content is present and phosphorus is not). With a lot of water, exposed copper and a small concentration of chloride ($\geq$5.0 micrograms/square inch) the copper molecules will break away from the PCB and quickly align themselves with the engulfing electric field. As water evaporates the copper molecules will form dendritic paths in conjunction with any ionic content available such as chloride and/or sulfide. These conductive paths will coat the PCB surface after the water has evaporated. As the water evaporates and deposits this tiny layer of conductive material, tiny visible separation arcs will appear forming conductive paths of ionic material plus carbonized PCB material. Each time enough moisture is present the process will reinitiate and strengthen itself. Each time the separation arcs become larger due to the increased current carrying capability of the dendritic path.

All else being equal, a DC voltage will ignite before an AC 50 Hz RMS equivalent. The AC 50 Hz equivalent will ignite before an AC 60 Hz equivalent. The typical process for 240 VAC is rather violent visually since the dendritic paths are formed and then repeatedly torn apart by the rapid VAC reversals. It is important to know that this process may take years to raise its ugly head.

The time to failure and the magnitude of the event depends primarily on three variables:

(1) The amount of liquids present
(2) How often they are present
(3) The amount of and type of ionic contamination.

Anything over 6-micrograms/square inch of chloride and/or sulfide will greatly accelerate the time to failure. Phosphorus that has recently been used as a flame retardant in both plastics and PCB materials in place of bromine will delay and possibly minimize the degree of damage caused by the final eruption of material.

Time to Failure

Time to failure is within minutes to hours of the applied liquid. This is typically due to an unintended easy access path for a spilled drink by an unsuspecting bystander to vulnerable areas of the electronic control's PCB. Time to failure for spilled drinks tend to be random in time but not so random in locations.

Time to failure is often tied to factory and product modifications in the field. A more sinister time to failure is often tied to a field service bulletin supposedly not related to the subject electronic control. Service technicians working near a subject control can unwittingly splash liquids or otherwise abuse a control that mysteriously exhibits indications of a splashed liquid.

Problem Resolution

Where the fault lies has many different levels and sub-levels from a business entity perspective. From a very high level the cause will be found in one of the following three:

(1) The control was improperly specified for its actual application and designed as specified.
(2) The control design entity created a product that allowed the failure due to accepted contractual manufacturing quality levels.
(3) The control assembly entity allowed the failure by not keeping one or more of their process variations within contractual limits.

Reference

1. Bumiller, E and Hillman, Hillman, Dr. Craig, “Review of Models for Time-to-Failure Due to Metallic Migration Mechanisms”, Last accessed June, 2016, http://www.dfrsolutions.com/uploads/white-papers/Time-to-Failure_Metallic_Migration.pdf

Chapter 11
Localized Event Explained-Scorched FR-4 with no Missing Weave

Visual Artifact

A fiberglass laminate substrate is found with no missing weave. The epoxy layers are gone and a single layer of weave similar to a window screen remains intact.

Evaluation

Given an entire glass weave laminate is remaining with no evidence of an arc-thru event.

Three Possibilities

1. The PCB ignited and consumed itself. All of the bench experiments (Chap. 14) indicate that if the subject PCB is UL, 94-V0 rated it is not capable of consuming itself. None of the experiments indicated greater than two thirds of the test PCB was self-consumed. Also note that in the bench experiments, non-UL 94-V0 materials are capable of totally consuming themselves. These experiments are not included in this text.
2. The PCB ignited and burned long enough to ignite something in its surroundings, that in turn consumed it, leaving the glass weave. This possibility requires a second fuel that can be ignited from the first.
3. The PCB was not the source of ignition but the victim of another substantial fire.

J.E. Small, *Electronic Control Fires*, SpringerBriefs in Fire,
DOI 10.1007/978-3-319-52845-8_11

Cause

Even with the control's external power source remaining intact, testing in Chap. 14 shows that it is not possible to consume itself without a nearby externally ignited fuel source. If no additional fuel can be ignited by the subject control, the subject control was the victim of a substantial fire beginning elsewhere.

Time to Failure

If the second of three possibilities is factual, the time to failure for this scenario is usually random.

Problem Resolution

Where the fault lies has many different levels and sub-levels from a business entity perspective. From a very high level the cause will be found in one of the following three:

1. The control was improperly specified for its actual application and designed as specified.
2. The control design entity created a product that allowed the failure due to accepted contractual manufacturing quality levels.
3. The control assembly entity allowed the failure by not keeping one or more of the process variations within contractual limits.

Chapter 12
Localized Event Explained-Scorched FR-4 with Missing Weave

Visual Artifact

A scorched laminate weave is found with missing material.

Evaluation

In order to entirely burn away PCB base material a very intense arcing environment is required.

If the missing material did not originally include high current solder connections the cause will be from one of the following scenarios:

1. Ionic contamination under a surface coating became moist enough to allow dendritic growth that fused open and reformed multiple times until arcing ignited nearby materials.
2. Ionic contamination introduced by an externally applied liquid, such as condensation flowing over chloride contaminated plastics, allowed dendritic growth that fused open and reformed multiple times until arcing ignited nearby materials.
3. Unintended "splashing" of ionic liquids onto this area due to inadequately trained field service personnel.
4. A foreign object such as a paper clip, insect, etc., bridged a gap and allowed arcing to occur.
5. A flame or arcing event was close enough to this area long enough to ignite it.

J.E. Small, *Electronic Control Fires*, SpringerBriefs in Fire,
DOI 10.1007/978-3-319-52845-8_12

Time to Failure

It is typically months to years from the product's power up.

If a valid UL 94-V0 PCB control is found with only copper traces and various metallic components remaining. The only rational explanation is that it was consumed by a separate nearby substantial fuel source with plenty of airflow. If there was truly no possible substantial second fuel; then something such as a propane or butane torch or other nefarious device was temporarily involved.

Problem Resolution

Where the fault lies has many different levels and sub-levels from a business entity perspective. From a very high level the cause will be found in one of the following three:

1. The control was improperly specified for its actual application and designed as specified.
2. The control design entity created a product that allowed the failure due to accepted contractual manufacturing quality levels.
3. The control assembly entity allowed the failure by not keeping one or more of the process variations within contractual limits.

Chapter 13
PCB Smoke and Fire Damage for Power Levels Below 5 Watts

Low voltage control fires:

The first obvious question is what exactly is low voltage?

Where Do We Start?

Using Texas Instruments "Typical PCB Thermal Resistance Values": 1000 °C will be generated within 0.032 thick FR4 laminate for each W of power flowing through a 1 cm^2 area [1]. 1000 °C is well above the temperature required to ignite a PCB.

The thicker the copper the more easily heat will transfer away from any attached heat source [1]. The thermal resistance of a copper plane to lateral heat transfer is

$$\theta_{Cu} = \frac{\frac{1}{\lambda_{Cu}} \times Length}{Width \times Length}$$

where $\lambda_{Cu} = 4\ \mathrm{W/cm\ K}$, Length and Width are in centimeters, and copper Thickness = 0.0035 cm multiplied by the copper weight in ounces (0.5 oz. typical, 14.17 g) [1].

The most easily ignited PCB laminate area is one that has the least amount of copper and the most surface area per volume of material.

For anyone who has struggled to start a camp-fire nothing within the following experiments should be surprising. If you want to keep newspaper from burning, don't separate the pages or wad them up. This will decrease the oxygen to surface area; thereby inhibiting flame. Just as this is true, four layers of tightly woven fiberglass epoxied together into a typical 1.574 mm thick sandwich is difficult to ignite, but not impossible.

J.E. Small, *Electronic Control Fires*, SpringerBriefs in Fire,
DOI 10.1007/978-3-319-52845-8_13

The following experiments have not demonstrated an obvious difference between FR4 and CEM-1 regarding their ability to flame. One plausible explanation is that the amount of flame-retardants used in the production of both is an equalizer. Production electronic control fire related field problems have gone away when the more expensive FR4 was replaced with CEM-1 material. CEM-1 is softer and less prone to fracturing around high-current rigid metal posts.

The definitions and values in “Table 1. Typical Thermal Resistance Values” from Texas Instruments Application Report: SNVA419C—April 2010—Revised April 2013 are suggested for those interested in a practical quantifiable approach to a sanity check for the experiments that follow.

θ_{CU} is 71.4 °C/W for the following conditions: Length is 1 cm, width is 1 cm, 1 oz copper thickness is 0.0035 cm, thermal conductivity of copper is 4 W/(cm °C)
θ_{FR4} is 13.9 °C/W for the following conditions: 1 cm^2, FR-4 thickness is 0.032 cm (12.6 mil), thermal conductivity of FR-4 (λ_{FR4}) is 0.0023 W/(cm °C)
θ_{VIA} is 261 °C/W for a thermal resistance of a typical 12 mil via
θ_{SA} is 1000 °C/W thermal resistance from the surface of a 1 cm square of the PCB to the ambient air due to natural convection
Another critical factor is the time that this 1000 °C exists. The joule is a convenient unit of energy because it includes time. More specifically, one joule is 1 Amp × 1 V × 1 s.

Reference

1. “Texas Instruments Application Report, SNVA419C, Thermal Design By Insight, Not Hindsight April”, Last modified April, 2013, http://www.ti.com.cn/cn/lit/an/snva419c/snva419c.pdf AN-2020

Chapter 14
Bench Experiments

Mark Twain said "There are three kinds of lies: lies, damned lies and statistics." Nothing will be inferred from the following and the reader is therefore encouraged to bask in the delight of the available data and any statistical inference he or she may find.

For Each Experiment Conducted

Tests were run in a 21 °C environment at 52% relative humidity with a barometric pressure of 760 Torr. Each test coupon was cut to ~ 1 cm^2.

To equalize moisture content between samples each PCB section tested was baked in an oven at 350 °F for one hour, and then lowered to 150 °F for twelve hours prior to running the tests.

Each test coupon's measured width, height, thickness and weight are included with the test results. This will allow a "sanity check" using the stated through plane conductivity of 0.29 W/m-K, [1] 0.343 W/m-K [2] and an in-plane thermal conductivity of 0.1 W/m-K [1], 1.059 W/m-K [2] for FR-4, and/or the Texas Instrument's °C/W numbers previously stated.

Voltage and current measurements were taken by meters that were each checked against a calibrated Fluke 8646A 6-½ digit precision multi-meter. The depicted voltage and current meters tracked the Fluke within ±0.003 units between 0.000 and 24.000 V and 0.000–10.000 Amps.

Voltage sense lines are 33 gage (1.542 mm diameter) nichrome wire welded to either side of the sample material at the entrance and exit of the 28 gage (0.305 mm diameter) nichrome current carrying wire as depicted in Fig. 14.1.

J.E. Small, *Electronic Control Fires*, SpringerBriefs in Fire,
DOI 10.1007/978-3-319-52845-8_14

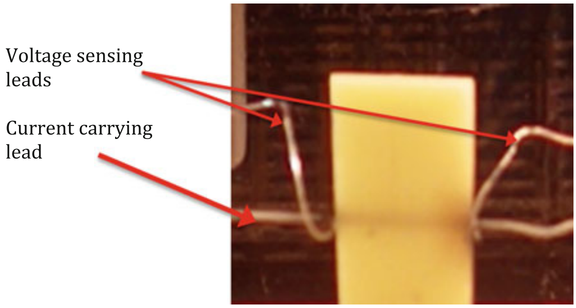


Fig. 14.1 Typical 1 cm^2 PCB test coupon construction

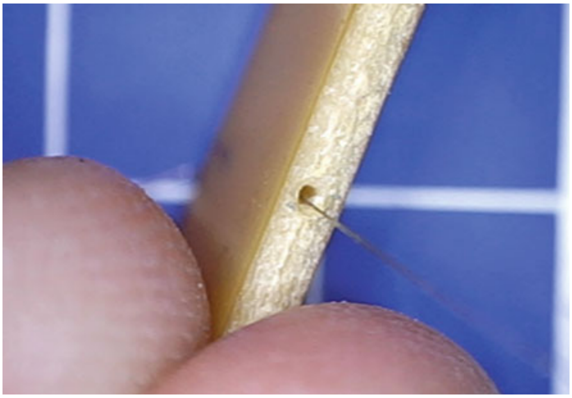


Fig. 14.2 A current carrying wire inserted into the hole drilled into each coupon

Sample Construction

Figure 14.2 depicts the current carrying conductor after it has been run through the drilled hole approximately parallel to its thickness. The two voltage sensing leads are welded to this conductor as close as possible to the entry and exit sides of the hole.

Sources of Variation

The thickness width and length of each sample are measured to 1/1000 of an inch (0.0254 mm) with dimensions provided for each sample tested.

The positioning of the hole drilled parallel to the sample's surface will vary in how close it is to the midpoint of the material's thickness. The $\sim$0.019 in. (0.483 mm) diameter hole will typically be larger at the drill bit's exit than its entrance. Therefore, the mode of heat transfer from the hot wire to the laminate will vary along the holes' length and from sample to sample.

Samples in comparable tests are adjacent cut-outs from a common laminate and therefore make the laminate chemistry itself a non-variable for purposes of these experiments.

Experiment #1

Purpose:

Document the visible effects of an increasing step power level from 0.0 to 3.6 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

$(0.145 \times 0.846 \times 1.496)$ cm
0.338 g
1.266 cm^2
0.184 cm^3
1.842 g/cm^3.

Increasing power levels were applied by manually adjusting the current from a bench lab supply until a voltage current product was approximately 0.5 W greater than the previous step (Figs. 14.3, 14.4, 14.5, 14.6, 14.7, 14.8 and 14.9).

Fig. 14.3 Result of 0.8 W being applied for 2 min from power up

Fig. 14.4 Result of 1.3 W being applied for 1 min after the preceding 0.8 W level for 2 min

Fig. 14.5 Result of 1.8 W being applied for 1 min after the preceding 1.3 W level (elapsed time from power up is 4 min)

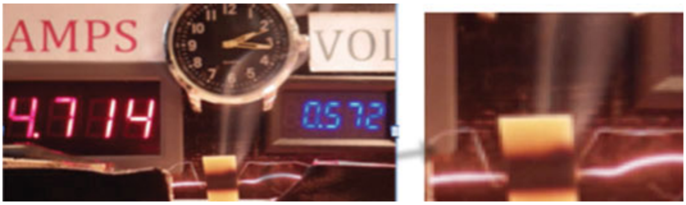


Fig. 14.6 Result of 2.3 W being applied for 1 min after the preceding 1.8 W level (elapsed time from power up is 5 min)

Fig. 14.7 Result of 2.7 W being applied for 1 min after the preceding 2.3 W level (elapsed time from power up is 6 min)

Fig. 14.8 Result of 3.2 W being applied for 1 min after the preceding 2.7 W level (elapsed time from power up is 7 min)

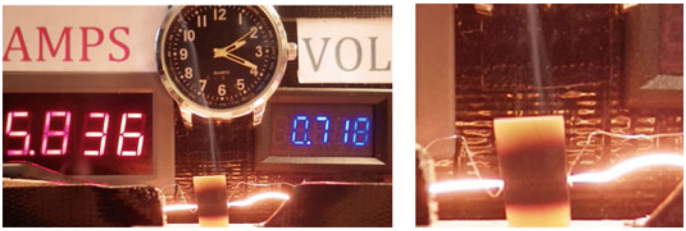


Fig. 14.9 Result of 3.6 W being applied for 1 min after the preceding 3.2 W level (elapsed time from power up is 8 min)

Experiment #2

Purpose:

Document the visible effects of applying a single step power level from 0.0 to 3.7 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

$(0.147 \times 0.708 \times 1.394)$ cm
0.314 g
0.987 cm^2
0.145 cm^3
2.164 g/cm^3.

The step in power level from 0.0 to 3.7 W is applied by adjusting the power level prior to the experiment and not after power is applied. Four frames from a video recording are presented to illustrate the key effects of power and time on the test sample (Figs. 14.10, 14.11, 14.12 and 14.13).

Fig. 14.10 Elapsed time from zero power ~1 s, 3.72 W. Wisp of smoke with no visible charring (real time captured in video is 12:34:10)

Fig. 14.11 Elapsed time from zero power is 20 s, 3.75 W. Increasing smoke with increased charring (real time captured in video is 12:34:30)

Fig. 14.12 Elapsed time from zero power is 50 s, 3.78 W. Smoke has diminished (real time captured in video is 12:35:00)

Fig. 14.13 Elapsed time from zero power is 1 min 20 s, 3.79 W. Smoke is no longer visible (real time captured in video is 12:35:30)

Experiment #3

Purpose:

Document the visible effects of an increasing step power level from 0.0 to 3.9 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

(0.147 $\times$ 0.731 $\times$ 1.521) cm
0.309 g
1.112 cm^2
0.163 cm^3
1.891 g/cm^3.

The step in power level from 0.0 to 3.9 is applied by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment (Figs. 14.14, 14.15, 14.16 and 14.17).

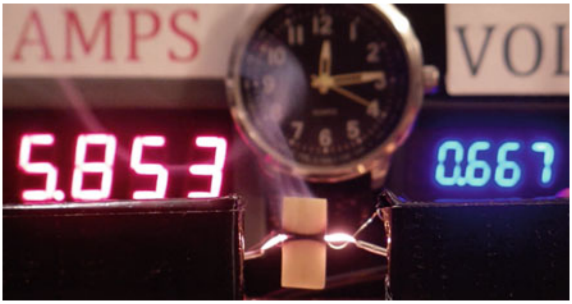


Fig. 14.14 Elapsed time from zero power ~1 s, 3.90 W. Smoke with visible charring (real time captured in video is 12:14:20)

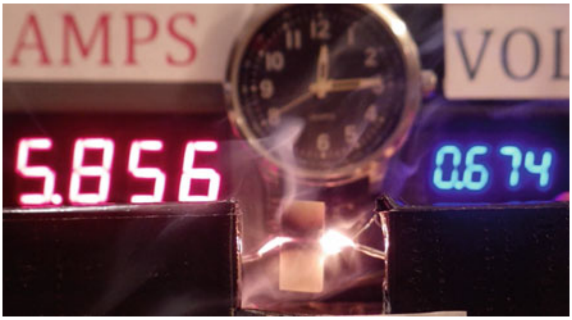


Fig. 14.15 Elapsed time from zero power is 20 s, 3.94 W. Flame with increased charring (real time captured in video is 12:14:40)

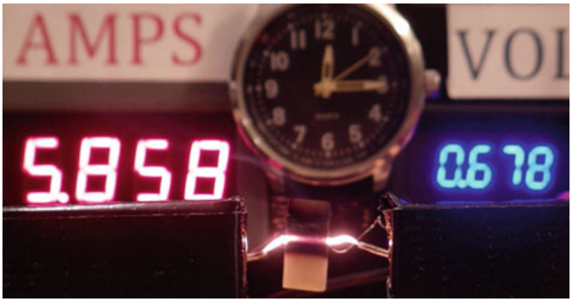


Fig. 14.16 Elapsed time from zero power is 50 s, 3.97 W. Smoke has diminished slightly (real time captured in video is 12:15:10)

Fig. 14.17 Elapsed time from zero power is 1 min 20 s, 4.00 W. Smoke has stopped (real time captured in video is 12:15:40)

Experiment #4

Purpose:

Determine the visible effects of applying a single step power level from 0.0 to 4.1 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

(0.145 × 0.742 × 1.521) cm
0.314 g
1.129 cm^2
0.164 cm^3
1.919 g/cm^3.

The step in power level from 0.0 to 4.1 is applied by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment. Four frames from a video recording are presented to illustrate the effects of power and time on the test sample (Figs. 14.18, 14.19, 14.20 and 14.21).

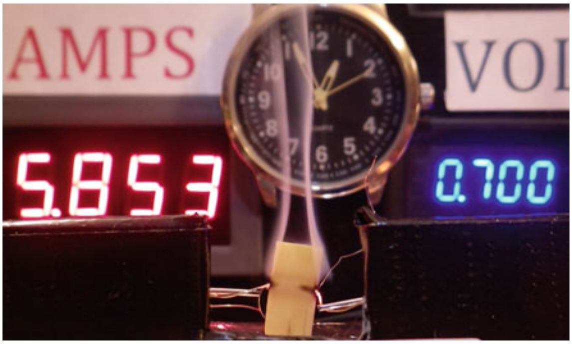


Fig. 14.18 Elapsed time from zero power ~1 s, 4.09 W. Smoke with visible charring (real time captured in video is 12:56:10)

Fig. 14.19 Elapsed time from zero power is 20 s, 4.12 W. Increasing smoke with increased charring (real time captured in video is 12:56:30)

Fig. 14.20 Elapsed time from zero power is 50 s, 4.15 W. Smoke has slightly diminished with increasing char (real time captured in video is 12:57:00)

Fig. 14.21 Elapsed time from zero power is 1 min 20 s, 4.18 W. Smoke has stopped (real time captured in video is 12:57:30)

Experiment #5

Purpose:

Determine the visible effects of applying a single step power level from 0.0 to 4.3 W on a commonly used PCB laminate within an electronic appliance control. This experiment indicates that 38.7 J is adequate energy to ignite a 1.574 mm thick $\sim$1 cm^2 section of FR4 (4.3 W $\times$ 9 s).

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

$(0.145 \times 0.818 \times 1.468)$ cm
0.329 g
1.201 cm^2
0.174 cm^3
1.890 g/cm^3.

The step in power level from 0.0 to 4.3 W is applied by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment. Five frames from a video recording are presented to illustrate the effects of power and time on the test sample (Figs. 14.22, 14.23, 14.24, 14.25 and 14.26).

Fig. 14.22 Elapsed time from zero power ∼1 s, 4.28 W. Smoke with charring at wire entrance and exit locations (real time captured in video is 01:16:10)

Fig. 14.23 Elapsed time from zero power is 9 s, 4.30 W. Flames burst from openings (real time captured in video is 01:16:18)

Fig. 14.24 Elapsed time from zero power is 20 s, 4.33 W. Flame extinguishes (real time captured in video is 01:16:29)

Fig. 14.25 Elapsed time from zero power is 50 s, 4.36 W. Smoke and flame have stopped (real time captured in video is 01:17:00)

Fig. 14.26 Elapsed time from zero power is 1 min 10 s, 4.99 W. No additional smoke or flame (real time captured in video is 01:17:31)

Experiment #6

Purpose:

Determine the visible effects of applying a single step power level from 0.0 to 4.4 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Epoxy resins with glass weave laminates
Material is 94 V-0 stamped
Section is cut from laminate as sold to the bare laminate market.

Actual sample dimensions:

(0.145 × 0.808 × 1.511) cm
0.335 cm
1.221 cm^2
0.177 cm^3
1.892 g/cm^3.

The step in power level from 0.0 to 4.4 W is applied by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment. Five frames from a video recording are presented to illustrate the effects of power and time on the test sample (Figs. 14.27, 14.28, 14.29, 14.30 and 14.31).

Fig. 14.27 Elapsed time from zero power ~1 s, 4.39 W. Smoke with visible charring (real time captured in video is 01:28:40)

Fig. 14.28 Elapsed time from zero power is 22 s, 4.46 W. Flame (real time captured in video is 01:29:00)

Fig. 14.29 Elapsed time from zero power is 23 s, 4.45 W. Flame increases dramatically within 1 s of this step (real time captured in video is 01:29:01)

Fig. 14.30 Elapsed time from zero power is 32 s, 4.45 W. Flame is decreasing (real time captured in video is 01:29:10)

Fig. 14.31 Elapsed time from zero power is 52 s, 4.44 W. Flame is gone (real time captured in video is 01:29:30)

Experiment #7

Purpose:

Determine the visible effects of increasing power levels below 5 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Cellulose paper core with one woven glass fabric surface
Material is 94 V-0 stamped
Section is cut from bare PCB designed for a residential microwave oven.

Actual sample dimensions:

(0155 × 0.820 × 1.463) cm
0.224 g before experiment, 0.135 g after experiment
1.200 cm^2
0.186 cm^3
1.205 g/cm^3.

Power is stepped gradually from 0.00 to 0.89 W in 9 s and remains for nearly 4 min. At that time the power is gradually raised to a peak of 2.92 W. At that point the sample ignites (Figs. 14.32, 14.33, 14.34, 14.35, 14.36, 14.37, 14.38 and 14.39).

Fig. 14.32 Elapsed time from zero power ~1 s, 0.25 W. No visible smoke or charring (real time captured in video is 08:53:09)

Fig. 14.33 Elapsed time from zero power is 3 s, 0.61 W. No visible smoke or charring (real time captured in video is 08:53:11)

Fig. 14.34 Elapsed time from zero power is 4 s, 1.82 W. No visible smoke or charring (real time captured in video is 08:53:13)

Fig. 14.35 Elapsed time from zero power is 6 s, 0.89 W. No visible smoke or charring (real time captured in video is 08:53:15)

Fig. 14.36 Elapsed time from zero power is 3 min 58 s, 1.82 W. Visible smoke and charring (real time captured in video is 08:57:07)

Fig. 14.37 Elapsed time from zero power is 4 min 14 s, 2.92 W. Initial flame (real time captured in video is 08:57:23)

Fig. 14.38 Elapsed time from zero power ~4 min 25 s, 2.92 W. Flame continues (real time captured in video is 08:57:34)

Fig. 14.39 Elapsed time from zero power is 4 min 36 s, 2.83 W. Smoke continues after flame stops (real time captured in video is 08:57:45)

Experiment #8

Purpose:

Determine the visible effects of applying a single step power level from 0.0 to 4.1 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Cellulose paper core with one woven glass fabric surface
Material is 94 V-0 stamped
Section is cut from bare PCB designed for a residential microwave oven.

Actual sample dimensions:

(0.145 × 0.808 × 1.511) cm
0.335 cm
1.221 cm^2
0.177 cm^3
1.892 g/cm^3.

The step-in power level from 0.0 to 4.1 W is applied by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment (Figs. 14.40, 14.41, 14.42 and 14.43).

Fig. 14.40 Elapsed time from zero power ∼1 s, 4.1 W. No visible smoke or charring (real time captured in video is 01:46:42)

Fig. 14.41 Elapsed time from zero power is 28 s, 4.1 W. Initial flame (real time captured in video is 01:47:10)

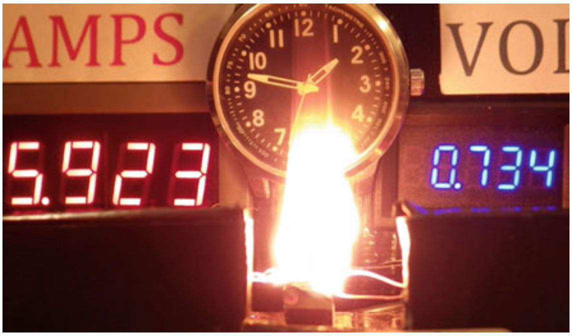


Fig. 14.42 Elapsed time from zero power is 41 s, 4.1 W. Flame peaks (real time captured in video is 01:47:33)

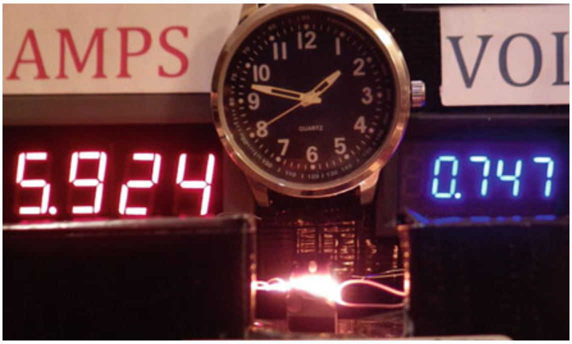


Fig. 14.43 Elapsed time from zero power is 58 s, 4.1 W. Smoke & flame are gone (real time captured in video is 01:47:40)

Experiment #9a

Purpose:

Determine the visible effects of applying a single step power level from 0.0 to 4.1 W on a commonly used PCB laminate within an electronic appliance control. This experiment indicates that 27.3 J is an adequate energy to ignite a 1.574 mm thick $\sim$1 cm^2 piece of CEM-1 (4.5 W $\times$ 6 s).

Material evaluated:

Cellulose paper core with one woven glass fabric surface
Material is 94 V-0 stamped
Section is cut from bare PCB designed for a residential microwave oven.

Actual sample dimensions:

(0.145 × 0.808 × 1.511) cm
0.335 g
1.221 cm^2
0.177 cm^3
1.892 g/cm^3
Sample identifier-F2355.

The step-in power level from 0.0 to 4.4 W is accomplished by adjusting the current and voltage as required prior to power up and then simply turning the current supply on without further adjustment (Figs. 14.44, 14.45, 14.46, 14.47 and 14.48).

Fig. 14.44 Elapsed time from zero power ~1 s, 4.4 W. Charring is instant (real time captured in video is 02:06:20)

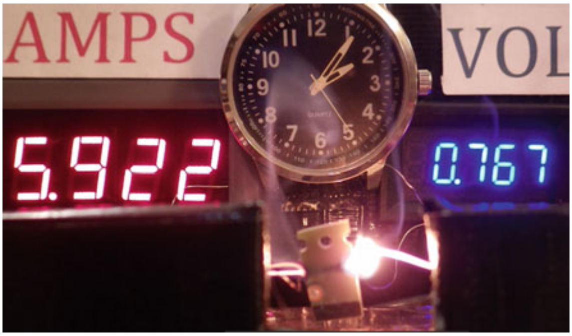
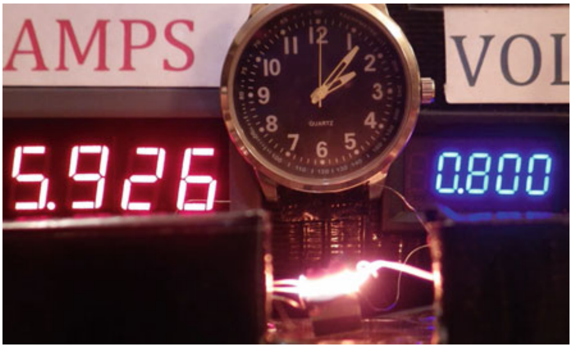


Fig. 14.45 Elapsed time from zero power is 6 s, 4.5 W. Smoke and flame (real time captured in video is 02:06:25)

Fig. 14.46 Elapsed time from zero power is 17 s, 4.6 W. Flame intensifies (real time captured in video is 02:06:36)

Fig. 14.47 Elapsed time from zero power is 31 s, 4.7 W. Engulfing flame (real time captured in video is 02:06:50)

Fig. 14.48 Elapsed time from zero power is 41 s, 4.7 W. Smoke & flame are gone (real time captured in video is 02:07:00)



Experiment #9b

In addition to video snapshots reviewed in experiment #9A the following six snapshots capture key transitions of the experiment. Recall-one single step in the power level from 0.0 to 4.5 W are accomplished by adjusting the current until the voltage current product is as depicted (Figs. 14.49, 14.50, 14.51, 14.52, 14.53 and 14.54).

Fig. 14.49 Applied 4.3 W at 02:06:18. No visible combustion at power up

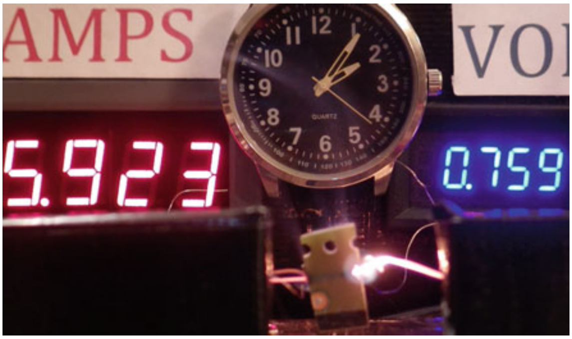


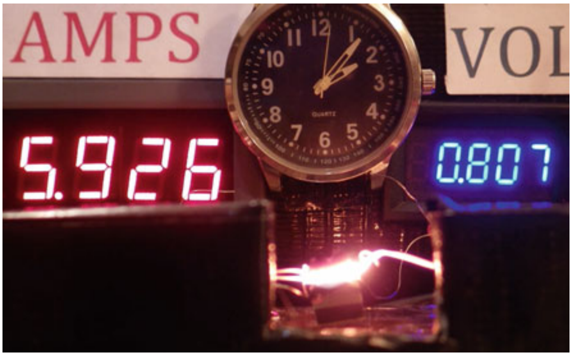
Fig. 14.50 First visible combustion occurred at elapsed time of 4 s, Power is 4.5 W. *Note* The power level change is not forced but is due to a decrease in resistance of the current carrying wire

Fig. 14.51 The flame that began in the previous snapshot grew quickly into the flame depicted here over 8 s. Power is 4.5 W at 02:06:30. Elapsed time from zero power is 12 s

Fig. 14.52 The flame grows continually over 15 s into the flame as depicted to the right. Power is 4.6 W at 02:06:45. Elapsed time from zero power is 15 s

Fig. 14.53 The flame grows and peaks as depicted to the right. Power is 4.6 W at 02:06:50. Elapsed time from zero power is 20 s. Observation: Flame peaks and begins to decline

Fig. 14.54 The flame gradually declines from the peak flame depicted in the previous snapshot to the final self-extinguished state depicted here. Power is 4.7 W at 02:07:01. Elapsed time from zero power is 31 s



Experiment #10

Purpose:

Determine the visible effects of applying a single-step power level from 0.0 to 4.1 W on a commonly used PCB laminate within an electronic appliance control.

Material evaluated:

Cellulose paper core with one woven glass fabric surface
Material is 94 V-0 stamped
Section is cut from bare PCB designed for a residential microwave oven.

Actual sample dimensions:

$(0.157 \times 0.818 \times 1.458)$ cm
0.193 g
1.193 cm^2
0.187 cm^3
1.031 g/cm^3.

Multiple steps in the power level from 0.0 to 3.8 W are accomplished by adjusting the current until the voltage current product is as depicted (Figs. 14.55, 14.56, 14.57, 14.58, 14.59, 14.60, 14.61 and 14.62).

Fig. 14.55 Elapsed time from zero power ~1 s, 0.03 W. No visible smoke or charring (real time captured in video is 10:03:06)

Fig. 14.56 Elapsed time from zero power is 6 s, 0.94 W. No visible smoke or charring (real time captured in video is 10:03:12)

Fig. 14.57 Elapsed time from zero power is 18 s, 0.95 W. Light smoke appears with very light charring (real time captured in video is 10:03:24)

Fig. 14.58 Elapsed time from zero power is 1 min 9 s, 0.97 W. Smoke intensifies with visible charring (real time captured in video is 10:04:15)

Fig. 14.59 Elapsed time from zero power is 2 min 9 s. <u>Stepped up</u> to 1.8 W. Intense smoke (real time captured in video is 10:05:15)

Fig. 14.60 Elapsed time from zero power is 2 min 29 s, 1.8 W. Intense smoke declines (real time captured in video is 10:05:35)

Fig. 14.61 Elapsed time from zero power is 2 min 55 s, Stepped up to 2.5 W smoke nearly gone (real time captured in video is 10:06:01)

Fig. 14.62 Elapsed time from zero power is 3 min 57 s, Stepped up to 3.8 W (real time captured in video is 10:07:03)

References

1. Azar, K: Graebner J. E. (1996). "Experimental Determination of Thermal Conductivity of Printed Wiring Boards". Proceedings of the Twelfth IEEE SEMI-THERM Symposium: 169–182. doi:10.1109/STHERM.1996.545107.
2. Sarvar, F.: N. J. Poole: P. A. Witting (1990). "PCB glass-fibre laminates: Thermal conductivity measurements and their effect on simulation". Journal of Electronic Materials 19 (12): 1345–1350. doi:10.1007/bf02662823.

Chapter 15
Summary of Experiments

For FR4 94 V-0	• The least amount of energy required to ignite a solid ~1 cm^2 for the experiments presented was 38.52 J **(4.28 W for 9 s)**	• The amount of energy required to sustain this flame and carbonize ~2/3 of a solid ~1 cm^2 for the experiments presented was 47.08 J (4.28 W for 11 s)
For CEM-1 94 V-0	• The least amount of energy required to ignite a nonsolid ~1 cm^2 for the experiments presented was 27 J **(4.5 W for 6 s)**	• The amount of energy required to sustain this flame and carbonize ~2/3 of a solid ~1 cm^2 for the experiments presented was 157.5 J (4.5 W for 35 s)
For CEM-1 94 V-0	• The lowest wattage level for ignition was at **2.92 W (4.8 A × 0.6 V)**	
Experiment #1 94 V-0 FR4	No visible smoke after **0.8 W for 2 min (2.6A × 0.3 V)**	• Step up to 1.3 W for 1 min (3.3A × 0.39 V) • Visible smoke after 1.3 W for 1 min
Experiment #2 94 V-0 FR4	Visible smoke within 1 s of applied power at **3.7 W (5.8A × 0.6 V)**	• ~40% of the material was charred and stopped smoking after 1 min 20 s

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Experiment #3 94 V-0 FR4	**3.9 W (5.8A × 0.6 V)** • Visible smoke within 1 s of applied power	• Flamed after 20 s • Flamed for 30 s and then self-extinguished
Experiment #4 94 V-0 FR4	**4.1 W (5.8A × 0.7 V)** • Did not flame • Visible smoke within 1 s of applied power • Smoke peaked at 20 s	• Combustible material was depleted after 1 min 20 s and then self-extinguished
Experiment #5 94 V-0 FR4	**4.3 W (5.8A × 0.7 V)** • Visible smoke and charring evident within 1 s of applied power	• Flamed after 9 s • Flamed for 11 s and then self-extinguished
Experiment #6 94 V-0 FR4	**4.4 W (5.9A × 0.7 V)** • Visible smoke and charring evident within 1 s of applied power	• Flamed after 22 s • Flamed for 30 s and then self-extinguished
Experiment #7 94 V-0 CEM-1	• Power is stepped gradually from **0.00 to 0.89 W in 9 s** and remains at this level for 4 min and 14 s	• The power is then gradually raised to a peak of 2.92 W when it ignites and burns for 22 s • 0.89 W (1.5A × 0.1 V) • 2.92 W (4.8A × 0.6 V
Experiment #8 94 V-0 CEM-1	**4.1 W (5.9A × 0.69 V)** • Visible smoke and charring is not evident within 1 s of applied power	• Flamed for 30 s and then it self-extinguished • 01:46:42 start • 01:47:10 first flame • 01:47:23 peak • 01:47:40 self-extinguished
Experiment #9A, B 94 V-0 CEM-1	**4.4 W (5.9A × 0.7 V)** • Visible smoke and charring evident within 1 s of applied power • Flamed after 6 s and continued for 35 s until it self-extinguished	• This experiment indicates that 27.3 J can ignite a 1.574 mm thick ~1 cm^2 piece of CEM1. (4.5 W × 6 s) • 02:06:20 start • 02:06:25 first flame • 02:06:50 peaked • 02:07:00 self-extinguished

Experiment #10 94 V-0 CEM-1			
Watts	Current × Volts	Hr:Min:Sec	Observation
0.03	0.41 × 0.079	10:03:06	Nothing apparent visually
0.94	2.82 × 0.332	10:03:12	Nothing apparent visually
0.94	2.82 × 0.338	10:03:24	Smoke appears
0.97	2.81 × 0.343	10:04:15	Smoke and charring continue
1.77	3.79 × 0.469	10:05:15	Intense smoke and charring
1.78	3.80 × 0.470	10:05:35	Smoke and charring stopped

Did not flame.

- Visible smoke for 2 min 10 s.
- Intense smoke for the last 20 s at which time it smoked for 2 min 20 s and then self-extinguished.

Appendix

btu and joules

The following is for interested practitioners who may not use btu or joules in their daily conversations.

KITCHEN MATCHES, PEANUTS AND LIGHT BULBS

Using btu when working with current and voltage is not convenient, to say the least.

However, most are more familiar with btu than joules.

How big would a 1.0 btu kitchen match be?

Assumptions:

Made from Eastern Pine having a heat value of 15,000,000 btu/cord.

It measures 1.6 in. × 0.1 in. × 0.1 in.

One cord = 221,184 in.^{3}

Plugging these values into the following equation will reveal that a 1 btu match will be a stick 0.1 in. × 0.1 in. and 1.6 in. long.

$$\begin{aligned} 1.0\left(\frac{\text{btu}}{\text{match}}\right) &= \left[15{,}000{,}000\left(\frac{\text{btu}}{\text{cord}}\right)\right] \\ &\times \left[1.6\ \text{in.} \times 0.1\ \text{in.} \times 0.1\ \text{in.}\left(\frac{\text{in.}^3}{\text{match}}\right)\right] \\ &\times \left[\frac{1}{221{,}184}\left(\frac{\text{cord}}{\text{in.}^3}\right)\right] \end{aligned}$$

Therefore, a 1.6 in. kitchen match, with no phosphorus = 1.0 btu = 1055 J.

This is equivalent to about 18 s of a working 60 W bulb.

We are surrounded by items not normally thought of as combustible.

A dry roasted peanut jar label discloses the fact that one peanut contains 170 kcal/39 peanuts. That is about 4.3 kcal/peanut. A 1.0 btu kitchen match and a 17 btu peanut are depicted in Figs. A.1 and A.2.

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Fig. A.1 A 17 btu peanut and the marked length for a 1.0 btu match

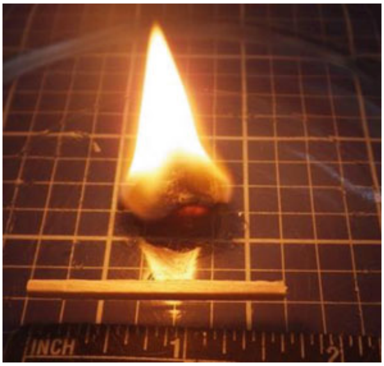

Fig. A.2 The ignited peanut contains 17 btu of energy and the match stick, 1.0 btu

One dry roasted peanut = 17 btu = 17,991 J.
This is about 100 s of 3 working 60 W bulbs.
The mighty peanut!