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CIRCUIT BRIDGING OF DIGITAL EQUIPMENT CAUSED BY SMOKE FROM A CABLE FIRE*

Tina J. Tanaka
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-0747
(505) 844-2981

Dennis J. Anderson
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-0746
(505) 845-9837

ABSTRACT

Advanced reactor systems are likely to use protection systems with digital electronics that ideally should be resistant to environmental hazards, including smoke from possible cable fires. Previous smoke tests have shown that digital safety systems can fail even at relatively low levels of smoke density and that short-term failures are likely to be caused by circuit bridging. Experiments were performed to examine these failures, with a focus on component packaging and protection schemes. Circuit bridging, which causes increased leakage currents and arcs, was gauged by measuring leakage currents among the leads of component packages. The resistance among circuit leads typically varies over a wide range, depending on the nature of the circuitry between the pins, bias conditions, circuit board material, etc. Resistance between leads can be as low as 20 kΩ and still be good, depending on the component. For these tests, we chose a printed circuit board and components that normally have an interlead resistance above 10^{12} Ω, but if the circuit is exposed to smoke, circuit bridging causes the resistance to fall below 10^3 Ω. Plated-through-hole (PTH) and surface-mounted (SMT) packages were exposed to a series of different smoke environments using a mixture of environmentally qualified cables for fuel. Conformal coatings and enclosures were tested as circuit protection methods. High fuel levels, high humidity, and high flaming burns were the conditions most likely to cause circuit bridging. The inexpensive conformal coating that was tested—an acrylic spray—reduced leakage currents, but enclosure in a chassis with a fan did not. PTH packages were more resistant to smoke-induced circuit bridging than SMT packages. Active components failed most often in tests where the leakage currents were high, but failure did not always accompany high leakage currents

I. INTRODUCTION

Nuclear power plants are starting to convert to digital instrumentation and control equipment.[1] Existing instrumentation and control (I&C) technology at nuclear power plants is aging and analog replacement tends to be obsolete. The added functions available in digital I&C are motivating utilities to adopt some of this digital I&C technology into nuclear power plants. While these technologies have several advantages and, in fact, have been in widespread use in the non-nuclear industry for several years, a concern with their use in safety-related systems in nuclear power plants is the lack of experience with this equipment in such environments.

However, to ensure that the digital technology is implemented safely in nuclear power plants, existing qualification standards and applicable regulatory guides are being reviewed. This review will possibly produce recommendations for modification and enhancement of present regulatory guidelines to accommodate the use of new technology. Qualification requirements for digital instrumentation and control equipment are currently being considered for different environments that may be encountered in a nuclear power plant, and one of these

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environments is smoke. Thus, in 1994, the USNRC started a program to determine the impact of smoke on digital instrumentation and control systems.[2] The USNRC is also sponsoring work by Oak Ridge National Laboratory (ORNL) on environmental qualification for digital equipment that includes electromagnetic interference, high temperature, and high humidity.[3] This paper presents the results of smoke exposure tests at Sandia National Laboratories on digital equipment and components.[+]

A. Digital Equipment Smoke Exposures

In order to determine the modes by which smoke will degrade electronics, several experiments were conducted at SNL on active circuit boards and digital systems. In cooperation with ORNL, tests on three multiplexer boards were conducted at relatively high levels of smoke density using three different cable materials as fuel. A multiplexer board, which was connected to a personal computer through a serial connection, failed–albeit temporarily (time-out error)–in one case while the polyvinyl chloride fuel was burning. The board continued to function after the main computer program was restarted. Error diagnostics indicated that the serial communication had been interrupted.

To study the reaction of a "typical" digital system, ORNL developed an experimental digital safety channel.[3] The ORNL safety channel was exposed to a series of eight exposures at three smoke levels. For this networked system, the severity of errors (e.g. time-outs, buffer overruns) generally increased as the density of the smoke increased. In addition, communication errors were observed at all levels of smoke density, ranging from network retransmissions at low smoke densities to serial-like time-out errors at higher smoke densities. Another general observation was that once the various units had been exposed to smoke, the baseline tests were no longer error free. This behavior underscores the potential difficulty of thoroughly ridding a previously exposed board of all residual smoke particulates through cleaning and may point to the need to replace all exposed circuit boards after a fire as a matter of policy.

The conclusion from both the ORNL and SNL tests was that smoke could cause interruptions in the communications of digital equipment systems. These interruptions could take place both during the smoke exposure and after the equipment was cleaned. In a nuclear power plant, interruptions in communications may be serious because of the need to constantly monitor plant conditions, especially during a fire.

B. Surface Insulation Resistance as a Predictor of Electrical Equipment Failure

Ionic particles damage electronics by causing electrical leakage, arcing, and corrosion. Recently, new methods have been developed to analyze potential equipment failure caused by ionic particulates in smog.[4] Smoke contains ionic particles[2] and may cause problems similar to those of smog, but more quickly because of the higher concentration. The resistance of surface insulation or surface conductivity can be used to measure electrical leakage. Higher surface insulation resistance indicates less leakage and hence a longer anticipated mean-time-to-failure. Surface insulation resistance is measured with an interdigitated comb pattern on standard printed circuit boards (e. g., the Institute for Interconnecting and Packaging Electronic Circuits board, IPC-B-24)[5] and comb patterns are now being used to measure surface insulation in studies of smoke corrosivity.[6]

II. EXPERIMENTAL METHOD

A series of 27 tests exposed electronic circuit boards with active and inactive components to smoke using differing conditions, including fuel amount, fire burn temperature, humidity level, and fuel mixture. The smoke environment was also changed by adding galvanized metal above the circuit boards (a potential hazard[7]) and using CO_2 for fire suppression. Two types of measurements were made on individual components: (1) resistance measurements to determine how smoke affects circuit bridging and (2) pass/fail measurements to determine whether components survived the smoke exposure.

A. Resistance Measurements

Typical digital component packages that included both PTH and SMT technologies were exposed to smoke and monitored to determine how individual components are affected by smoke. The SMT packages have a higher lead density and are preferred for reducing the size of digital equipment. The component packages listed in Table 1

[+] The USNRC has funded one other limited test program on smoke at SNL: analog equipment was exposed to smoke from a full-scale fire to determine what types of equipment would be affected by smoke. [M. J. Jacobus, Screening Tests of Representative Nuclear Power Plant Components Exposed to Secondary Environments Created by Fires, Sandia National Laboratories, NUREG/CR-4596, SAND86-0394 (1986).]

Table 1. Component packages for resistance measurements

Label from Figure 2	Component Package	Body Material	PTH/ SMT	Lead Spacing (inches)	Lead Separation (inches)
U1	Leadless chip carrier	Ceramic	SMT	0.04	0.017
U2	Dual-in-line package (DIP)	Ceramic	PTH	0.10	0.045
U3	Flat pack	Ceramic	SMT	0.05	0.025
U4	Transistor outline can	Metal	PTH	0.08	0.036
U5	Dual-in-line (DIP)	Plastic	PTH	0.10	0.040
U6	Small-outline integrated chip	Plastic	SMT	0.05	0.025
U7	Leaded chip carrier	Plastic	SMT	0.04	0.026

were mounted on a printed circuit board with traces that connected every other lead of the empty (ceramic and metal) packages. Table 1 also contains the center-to-center lead spacing and minimum lead separation of the components tested, as shown in Figure 1.

All components were mounted on printed circuit boards as shown in Figure 1. The ceramic and metal chip packages were empty, but the plastic-bodied packages contained active circuits. For the plastic packages, only adjacent leads that were independent of one another in the circuit were included in the resistance measurements.

Figure 2 shows a typical wiring diagram used for testing empty component packages. The leakage current between leads was measured by biasing every other lead with 5 Vdc. For the 8-pin transistor outline can, the odd-numbered pins were grounded while the even-numbered pins were connected to 5 Vdc. The total current flowing between the even- and odd- numbered pins was measured with a multirange ammeter. The lead-to-lead resistance, R, was calculated from the measured current using Ohm's law ($R = V/I - 510\ \Omega$ where V is 5 V and I is the measured current). The resistance rather than the current was plotted in the results because it is more independent of the applied voltage.

In each test bare and coated circuit boards were exposed to smoke. The coated printed circuit boards were

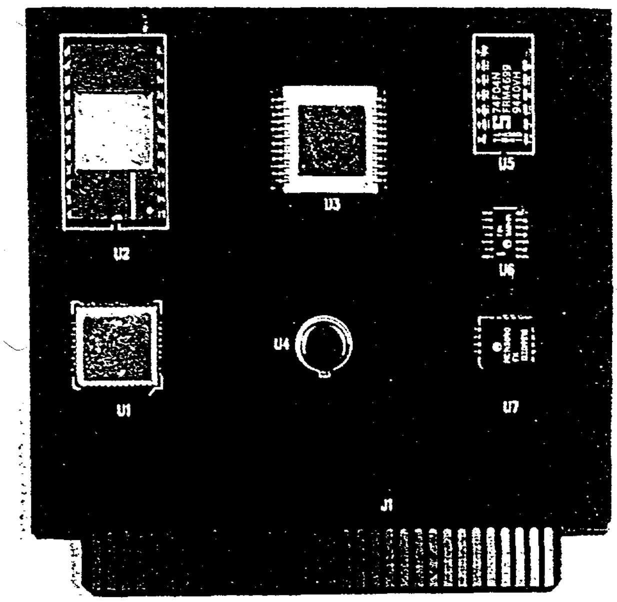

Figure 1. Printed circuit board for circuit bridging measurements of different component packages.

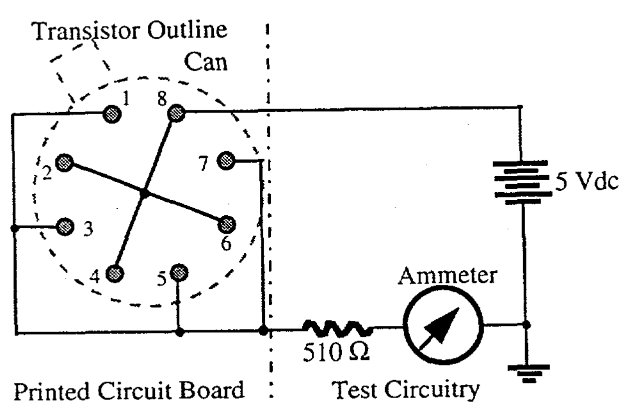

Figure 2. Wiring diagram for transistor outline can. In the event the component shorted, current-limiting resistors (510 Ω in this case) were included in the circuit to prevent overdriving the ammeter.

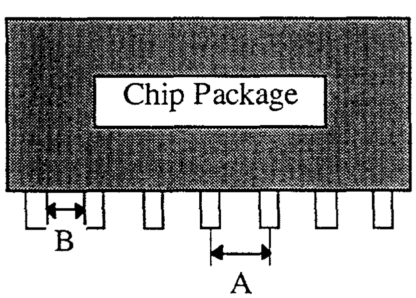

Figure 3. Center-to-center lead spacing (A) and minimum lead separation (B).

sprayed with an acrylic conformal coating (Fine-L-Kote™ AR 2103 by Tech Spray Inc). Uncoated printed circuit boards were placed inside an IBM personal computer chassis. The chassis contained a fan, but no other working electronics. In addition to these test boards, an identical bare printed circuit board was placed in the environmental chamber, outside of the smoke exposure chamber, to serve as a control. In all, four component-mounted boards were measured for each test: (1) bare, in smoke; (2) coated, in smoke; (3) bare, in the chassis; and (4) bare, unexposed to smoke (the control). Surface insulation resistance measurements were also made using IPC-B-24 interdigitated comb boards. These results have already been reported in NUREG/CR-6476.[2]

B. Pass/Fail Component Measurements

Two other types of components were included in the smoke exposure during the circuit bridging tests: 16K memory chips and optical isolators (Table 2). The memory chips had two types of bodies: ceramic and plastic. The plastic-bodied chips were DIP chips that are commercially available, while the ceramic-bodied chips, which were hermetically sealed, were manufactured by SNL. During the test the memory chips were biased with 5 Vdc, but they were not active. These memory chips were tested before and after the smoke exposure.

Table 2. Pass/Fail Components

Component type	Technology	Package
Optical isolator	LED	Plastic DIP
16K Memory	CMOS[a]	Plastic DIP
16K Memory	CMOS	Ceramic DIP

[a] Complementary metal-oxide semiconductor

The optical isolators were 6N138 high-gain optocouplers that were housed in plastic DIP packages. During the smoke exposures, a simple switching test was performed on the optical isolators: a 5-V square-wave pulse was input to the optical isolator, which then output a similar pulse. The output pulse rise, fall, and delay times relative to the input pulse were measured by a digitizing oscilloscope. None of these pass/fail components was protected by a coating or enclosure.

C. Smoke Environment

Smoke was produced by burning cable insulation in the chamber shown in Figure 4. The components to be exposed were placed in the Lexan chamber shown in the upper half of Figure 4, while the smoke was generated below and rose into the chamber. The chamber was located within an environmental chamber that controlled

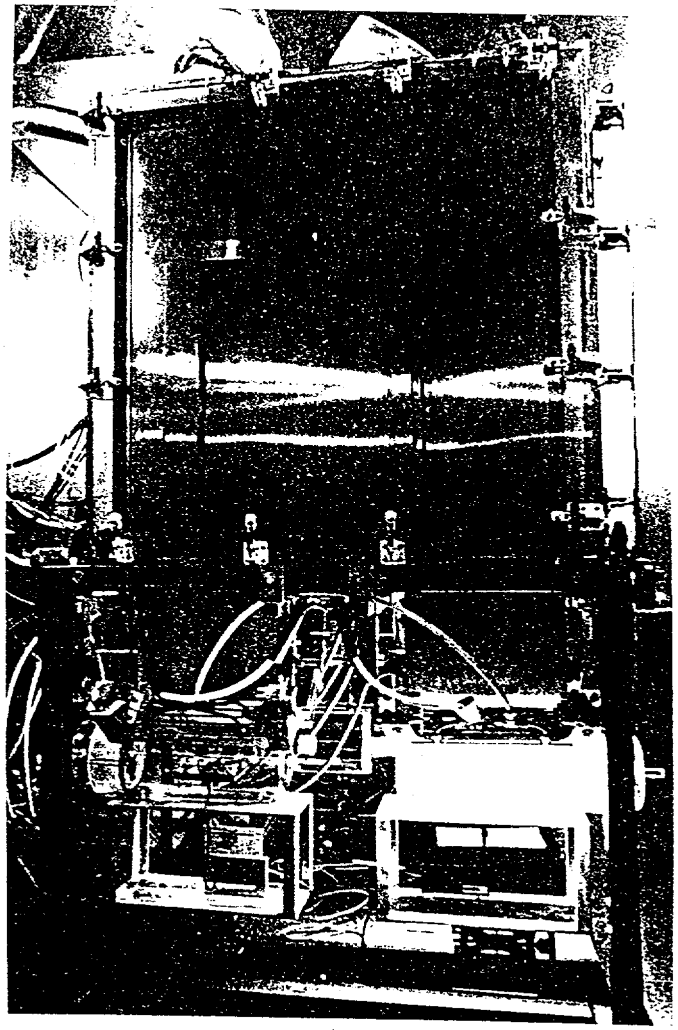

Figure 4. Smoke exposure chamber.

the temperature and humidity before and after the smoke exposure. No temperature or humidity control was used during the smoke exposure because the smoke would have badly corroded the environmental chamber.

The components were tested under different smoke environments so that the effects on circuit bridging could be compared. Each condition that was varied had only two states; for example, fuel levels were either high (100 g of cable insulation fuel per m^3 of air volume in the test chamber) or low (3 g of fuel per m^3 of air volume). Relative humidity levels were either high (75%) or low (< 20%.) Burn temperatures and conditions were either high (50 kW/m^2 irradiance and flaming) or low (25 kW/m^2 irradiance and smoldering.) In some cases, the smoke environment was changed by including PVC in the fuel, using CO_2 for fire suppression after the fire extinguished, or including galvanized metal in the smoke exposure chamber. PVC smoke contains high levels of hydrochloric acid that is expected to be highly corrosive. The CO_2 was added because it may cool equipment suddenly and hence cause lead or component bodies to crack. Galvanized metal was placed above the circuit boards because hydrochloric acid may combine with zinc in the galvanized material to form a thick liquid of zinc chloride and water that can drip on electronics.[7] The fuel consisted of a mixture of commonly used cables as determined from Table 3.4 of EPRI TR-103841[8] on environmentally qualified cables. The amount of electrical insulation from each cable was proportional to the number of plants given for each of the 10 cable types listed in the table.

The components were exposed to smoke for 1 hour, and then the smoke exposure chamber was vented. Component function was monitored for a total of 24 hours after the beginning of the smoke exposure.

III. RESULTS

A. Resistance Measurements

As smoke was introduced into the exposure chamber, the resistance among the leads decreased rapidly. Figure 5 presents a semilog plot of resistance (R) vs. time for the transistor outline can for test 18. The four traces represent the four conditions of the test. All of the transistor outline cans reacted strongly to the smoke environment, exhibiting a large decrease in resistance during the first hour of this test. The bare and chassis-enclosed transistor outline cans decreased in resistance and remained low in this high-fuel, high-humidity, flaming exposure. The coated transistor outline can did not perform significantly better than the bare can. The acrylic coating is an inexpensive, all-purpose coating, but is not recommended for protection against chemicals, thermal shock, or moisture. The resistance of the chassis-enclosed transistor outline can decreased and then increased slightly after the first 8 hours. Many of the components reacted in this manner, the resistance dropping during the smoke exposure, then recovering after 1 or 2 hours of venting. This behavior was more evident in low fuel tests.

B. Pass/Fail Results

Table 3 compares the results of the pass/fail components for the 27 tests. The optical isolators operated continuously during the smoke exposure tests except in 4 tests, where the output signal stopped entirely. Likewise,

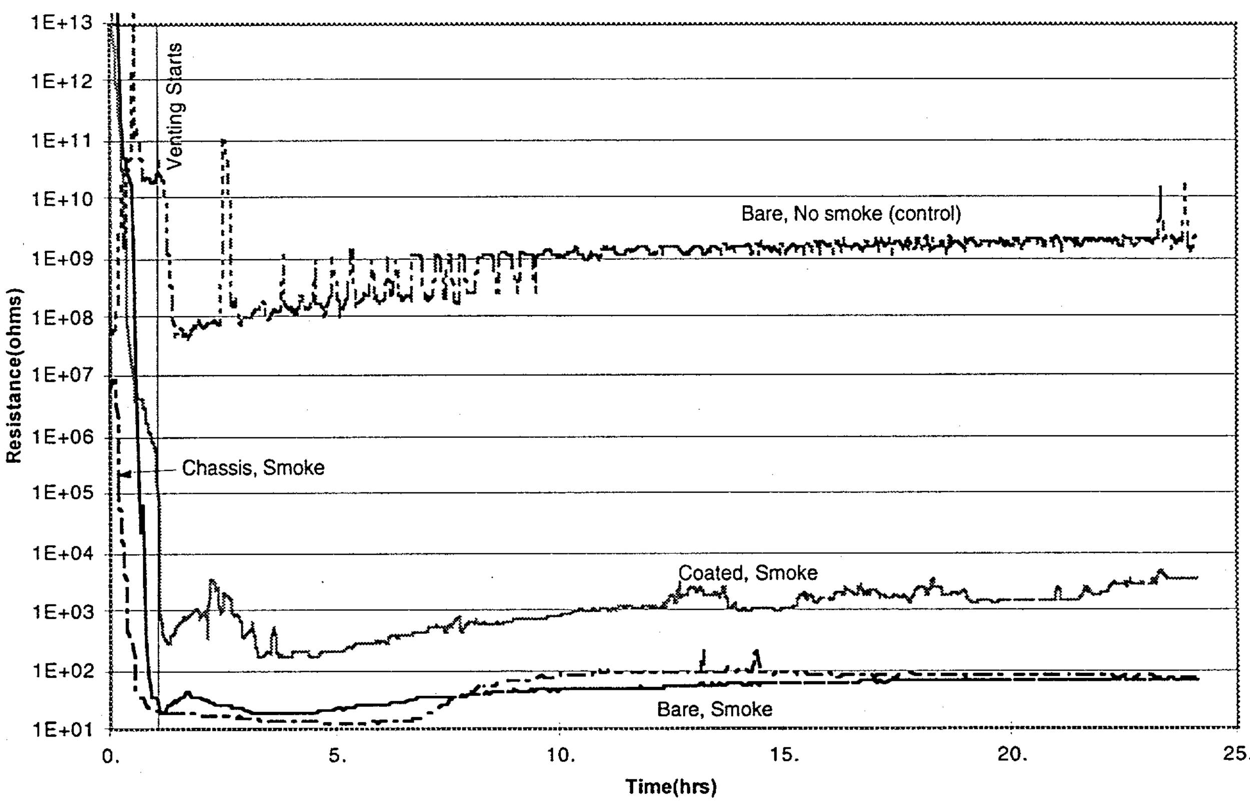

Figure 5. Transistor outline can: resistance vs. time (Test 18)

Table 3. Comparison of resistance with optical isolator and memory chip failure

Minimum Plastic DIP resistance	Number of tests	Ceramic Memory chip Failures	Plastic Memory chip failures	Optical Isolator Failures
$>10^6\ \Omega$	17	0	0	1
$<10^6\ \Omega$	10	1	6	3

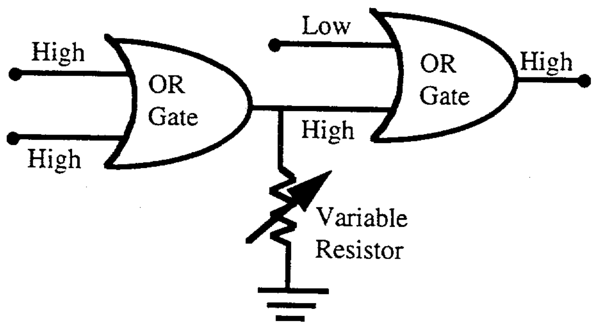

Figure 6. Wiring diagram for shunt resistance test. This test determines the critical value of the shunt resistance that would cause errors in this simple OR gate circuit.

the ceramic memory chips survived most of the smoke exposures and the plastic-bodied memory chips had 6 failures out of 27 tests. Since all these were DIP packages, their pass/fail records can be compared with results from measuring the resistance of the plastic DIP itself. When the resistance between leads of the plastic DIP was higher than $10^6\ \Omega$, only 1 optical isolator and no memory chips failed during the 17 tests. When the interlead resistance was less than $10^6\ \Omega$, many more failures occurred, but failures did not occur in every test. The resistance correlates strongly with failure, but is not a perfect predictor. The plastic memory chips were especially susceptible to failure when the resistance was low. The conditions that create low resistance ($< 10^6\ \Omega$) include high humidity, high fuel load, and a flaming fire. High humidity is also expected to be able to penetrate the bodies of the plastic chips, causing corrosion in the wires that bond the chip to the package.

C. Logic Family Comparisons

Smoke deposition causes shunt conductance among leads that can cause logic circuits to fail. Failure can occur when the shunt resistance pulls a low logic level high, or a high logic level low. Logic circuits typically have four to five different voltages. Transistor-to-transistor logic (TTL) circuits, for example, have a supply voltage, high logic level, low logic level, and ground. Smoke deposition causes shunt conductance between these levels that can lead to failure. The value of shunt conductance that causes failure depends upon the voltages being shunted and the particular logic family. Logic families include TTL, complementary metal-oxide semiconductor (CMOS), and emitter-coupled logic (ECL).[9] Among these logic types, there is a tradeoff between speed (requiring high drive current to charge and discharge circuit capacitance) and low power consumption.

The value of shunt resistance that leads to failure was measured in logic circuits by placing a variable resistor between the various voltage levels and decreasing the resistance until the state changed. Figure 6 shows a logic circuit for determining the shunt resistance between high logic levels and ground that causes the high level to be pulled down. Table 4 lists the maximum shunt resistance (most vulnerable path) among all voltage levels that causes failure in each logic type; this shunt resistance varies appreciably among the logic types. Lower shunt resistance (i.e., greater smoke immunity) is tolerated in higher speed logic families that supply high output currents; these families can sustain more shunt loading before failure.

D. Comparison of Chip Packages and Protection Systems

Since high fuel load, high humidity, and a flaming fire are the most difficult conditions for maintaining high resistance among leads, the results of the tests performed with these conditions were investigated further. For many components, smoke exposures with these conditions resulted in interlead resistance below the recording levels considered reliable ($<10^3\ \Omega$). The amount of time required to reach a resistance level less than $10^3\ \Omega$ was averaged for four tests, all of which had high fuel load, high humidity, and a flaming fire. Figure 7 shows comparisons among the seven chip packages and two protection methods.

Packages with the larger lead spacing tended to last longer (shorted later) than the closely spaced lead packages. Comparisons of the bare chip packages show that the transistor outline can takes the longest to short, while the small-outline integrated chip package shorted sooner. The spacing between leads for these packages can be compared in Table 1. Both the lead spacing and separation of the transistor outline can are larger than those of the small-outline integrated chip. In general, SMT packages were more closely spaced than PTH packages, and PTH packages were better able to maintain a high resistance.

Table 4. Failure resistance for different logic families

Logic Family	Supply Voltage (Vdc)	Output High Current (mA)	Output Low Current (mA)	Shunt Resistance at Failure (Ω)
TTL				
Low-power Schottky (LS)	+5.0	–0.4	8.0	100
Advanced Schottky (FAST)	+5.0	–1.0	20.0	31
CMOS				
Metal-gate (MG)				
	+5.0	–0.88	0.88	1220
	+10.0	–2.25	2.25	605
	+15.0	–8.8	8.8	490
High-speed silicon gate (HC)				
	+2.0	–0.02	0.02	130
	+4.5	–4.0	4.0	68
	+6.0	–5.2	5.2	56
Advanced (FACT)				
	+3.0	–12	12	30
	+4.5	–24	24	30
	+6.0	–24	24	25
ECL				
100K	-5.2	50	22	121
10H	-5.2	22	22	64

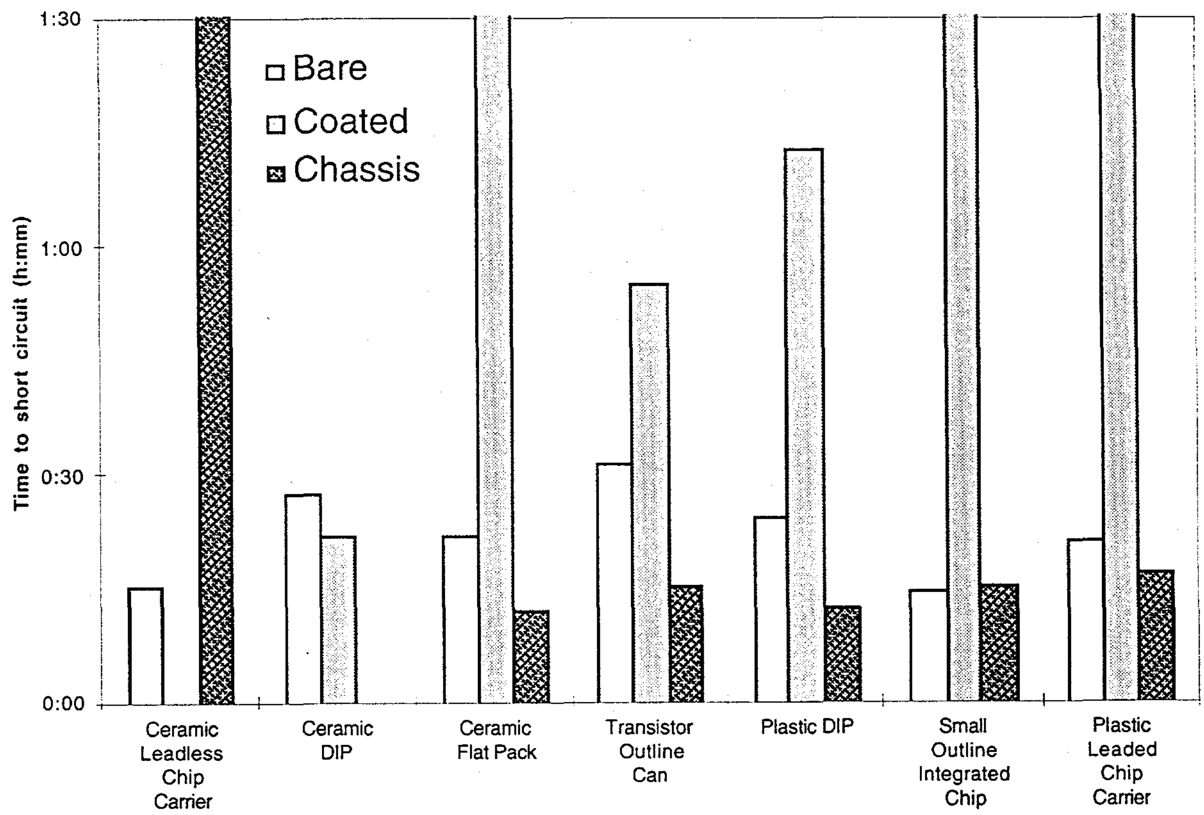

Figure 7. Time to shorting for different components. Columns that extend off of the graph indicate components that did not reach $10^3\,\Omega$ by the end of the test.

Figure 7 also compares different protective treatments. The coated ceramic leadless chip carrier and the chassis-enclosed ceramic DIP were not included because the instrumentation wires to these components broke. In general, the coated chip packages took longer to short than either the bare or chassis-enclosed packages. The chassis-enclosed packages shorted in less or equal time than the bare packages, except for the ceramic leadless chip carrier. The acrylic coating improved leakage resistance somewhat and hence performance. Bare components exposed directly to the smoke performed the same or better than bare components inside a fan-ventilated chassis.

IV. CONCLUSIONS

Digital equipment requires delivery of short pulses of current at specified time intervals in a particular order. Voltages must be maintained to preserve digital states, and extraneous pulses or stray currents may cause errors and failures. When resistance among component leads decreases below critical values, stray pulses or currents may appear from neighboring power sources. The results of these tests showed that resistance among circuit leads was lowest during the actual smoke exposure and recovered to somewhat higher levels if only a small amount of fuel was burned. However, for high fuel amounts, the interlead resistance dropped and remained low ($10^3\ \Omega$). Smoke and humidity reduce the resistance among leads and promote failure of digital equipment. Failures of this type are likely to occur concurrently with a fire because resistance is lowest during smoke production. The equipment may recover later, depending on environmental conditions, but this recovery time may be longer than is permissible for protection systems.

The conditions that produce the worst circuit bridging failures are high humidity, large amounts of smoke, and flaming fires. Failures can be reduced by controlling the transport of smoke, reducing the humidity, and ventilating the area as quickly as possible after a fire. Physical protection of circuitry by conformal coatings may be helpful, as indicated by the results for the boards that were coated with an acrylic spray. Enclosures with ventilation fans do not provide significant protection. Components with smaller spacing between leads, such as typical surface-mounted chip packages, were more easily affected by smoke than plated-through-hole packages, which have larger interlead spacing. Components that have higher output drive current are more resistant to smoke.

V. FUTURE WORK

Future work on the impact of smoke on digital electronics will concentrate on effects on functional circuits. Tests are planned to expose different types of circuits (using both SMT and PTH packages) and coatings to smoke. Individual circuits will react differently to smoke; thus it is important to determine how various types of circuits will react.

Conformal coatings have shown promise in reducing the loss of resistance. Five main coating types exist: acrylic, polyurethane, epoxy, parylene, and silicone. Future experiments will test which coatings are the most protective without otherwise harming circuits.

Smoke exposures are difficult to reproduce and standards for testing are not established at this time. Nonetheless the results of this work will define adequate safety from a sound technical basis for digital I&C by suggesting technologies that can best resist smoke-induced failures.

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