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The Effect of Smoke from Plastics on Digital Communications Equipment

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Abstract

Smoke from plastics can cause immediate problems in electrical equipment in the form of shorting and increased leakage currents, as well as long-term corrosion (metal loss). The short-term problems can be especially serious for critical control instrumentation such as that found in nuclear reactors or telecommunications systems. The U.S. Nuclear Regulatory Commission and Sandia National Laboratories are sponsoring a program to determine the modes and probabilities of digital equipment failure during exposure to smoke and up to 24 hours after the exposure. Early tests on computer systems have shown that the most common immediate problems are temporary and are likely to be caused by increased leakage currents. High-voltage circuits are especially vulnerable since the charged particles in smoke are drawn to those surfaces. To study failure probabilities, smoke exposure tests with real-time measurements will be carried out to determine how the electrical properties of the environment are affected by smoke concentration and content. Digital communication cable will be included in the tests because temporary shorts that cannot be detected through dc measurements may cause interruptions in communications between computers. The reaction of the equipment to changed electrical properties of the environment will be modeled. Equipment that can be used for testing and modeling is being solicited.

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1 INTRODUCTION

1.1 Purpose of this Program

Nuclear power plants are replacing analog instrumentation and control (I&C) equipment with digital I&C equipment; however, there is concern about how these new control systems will be affected by abnormal or severe environments, such as smoke from an electrical fire.[1] In 1994, the U.S. Nuclear Regulatory Commission (USNRC) initiated a program at Sandia National Laboratories (SNL) to determine the impact of smoke on advanced instrumentation and digital safety systems and to determine if smoke can cause failures in reactor safety systems. From

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a plant-risk perspective, short-term damage modes are most significant. Smoke is expected to cause immediate failures by circuit bridging and an increase in contact resistance, but corrosion is expected to cause long-term failures. In addition to determining possible failure modes, the USNRC is interested in threshold levels for failure and the behavior of the failed equipment.

1.2 Background on Smoke Exposure Testing

When this program started, there were little data on how smoke affected active electronics. Smoke damage in other industries, such as telecommunications, was serious enough to merit detailed analysis of smoke corrosivity and equipment recovery. However, except for the full-scale tests by Jacobus[2] on relays, power supplies, and switches, no reports have been found in the public literature that measure the performance of electronics in smoke. Since nuclear power plants require continuous control and feedback from the reactor, the ability to salvage equipment after a fire is not adequate. Rather, the continuous safe operation of the systems during and after a fire must be considered. Hence, it is necessary to be able to determine the real-time effects of smoke on an active digital system.

Smoke tests to determine the relative corrosivity of different materials have been developed by the military and telecommunications industry. The early studies by the Navy concentrated on the effects of smoke on structural elements in ships.[3] Because of smoke corrosivity, the Navy also created standards for testing the smoke from various cable materials to measure its acidity. Cables that produced less acid were used in ships. Since many of the acidic gases are produced by halogenated compounds (i.e., chlorine and bromine), the Navy has been limiting the use of these materials on ships. Recently, the telecommunications industry and insurance companies have been most active in the development of test methods. Most of these methods measure acidity of gases or metal loss. The acidity of the gases is assumed to be directly related to corrosive metal loss. Some of the standards developed for smoke corrosivity testing are ASTM D5485; IEC 754-1, 1994-01; DIN 53436; and CNET(ISO/DIS 11907 part 2).

Degradation of electronics due to smoke can be similar to degradation from air pollution. Polluted air contains many of the same ionic contaminants as smoke (i.e., chlorides and sulfates); however, the deposition rate from air pollution is much slower than from a fire.[4] Ionic contaminants increase leakage currents by providing an alternative current path. In the presence of ionic contaminants, electrically biased conductors develop metallic dendridic growths that increase leakage currents. The role of ionic contaminants has been studied by those involved in studying reliability of electronics. One way to determine the effect of these contaminants is to measure the surface insulation resistance using an interdigitated comb pattern, as on IPC-B-24.[5] This method is also being used for some smoke corrosivity testing.[6] Higher levels of contamination lead to higher leakage currents.

All of this research was focused on long-term damage from a fire. An important parameter for the damage is the ionic contamination deposited on surfaces. Given that all work in the past has been based on postfire analysis, surface deposition is the only quantitative measure of smoke exposure available. These analyses do not address the increased leakage currents that may occur during a fire, which can lead to temporary malfunction of a circuit.

1.3 Previous Smoke Exposure Testing at SNL

To date, the smoke exposure testing at SNL has concentrated on the reaction of electronics during and immediately after a fire. Cable insulation was burned since it is a common fuel in nuclear power plants and is likely to cause more damage than other common materials. The first tests were carried out with the cooperation of Oak Ridge National Laboratory (ORNL) and their USNRC-sponsored program on advanced I&C qualification and exposed active digital systems.[7] These systems included a computer network linked by fiber optics (FDDI). The smoke caused temporary interruptions and retransmission of data. Since these interruptions were temporary and immediate, metal loss was not a likely failure mode. Digital systems that were tested did not contain electromechanical switches, so the temporary failures could not be due to soot coating the contacts. Therefore we assumed that a likely cause of failure was temporary shorts caused by increased leakage currents.

Leakage currents were studied in more detail when empty component packages were biased with 5 Vdc and the currents measured during a smoke exposure. Humidity, fuel levels, fuel mixture, suppression by CO_2, and burning mode (smoldering vs. flaming) were varied to determine which fire conditions affected the leakage currents the most. The tests showed that smoke immediately reduces insulation resistance, but that the resistance may recover if the smoke is vented. The major results found from all of these tests were that:

- Smoke increases leakage currents across biased contacts and causes shorts.
- Shorted electrical signals cause digital systems to receive faulty data and upset systems.
- The upsets cause intermittent failure of the system.
- High smoke density, high humidity, and flaming fires cause more failures than less smoke, low humidity, and smoldering fires.
- Conformal coatings and chip packages with large lead spacing can improve smoke tolerance.

1.4 Focus of Paper

The research reported here has focused on the impact of smoke on active circuits, rather than recovery of electronic equipment. It addresses the need of nuclear power plants to continuously monitor and control a reactor and to determine the immediate effects of smoke on equipment. All of the exposures in our experiments included real-time monitoring to determine what happens as circuits are exposed to smoke. This paper compares various smoke failure modes and describes a program to obtain information or important electrical properties of smoke that will be used to predict the failure of electronic equipment.

2 SMOKE EXPOSURE METHODS

Because there are no electronic qualification test standards for smoke, the method of exposure has been based on the draft smoke corrosivity standard for the radiant heat method proposed by ASTM E05.21.70. This method tests different materials and is a static smoke exposure—all

Table 1: Cable materials burned for smoke exposures.

Cable name	Insulation	Jacket
Rockbestos Firewall III	FRXLPE[a]	CSPE[b]
Anaconda Flameguard 1 kv	EPR[c]	CSPE
Brand Rex XLPE	XLPE[d]	CSPE
Okonite Okolon	EPR	CSPE
Kerite HTK	unknown	unknown
Rockbestos Coax (le)	unknown	unknown
Raychem	XLPE	XLPE
Dekoron Dekorad	EPDM[e]	CSPE
BIW	EPR	CSPE
Kerite FR	unknown	unknown

[a] Fire-resistant cross-linked polyethylene
[b] Chlorosulfonated polyethylene
[c] Ethylene propylene rubber
[d] Cross-linked polyethylene
[e] Ethylene propylene diene monomer

of the smoke that is created is contained within an enclosure rather than being pumped through the exposure chamber as in dynamic smoke exposures.

The set of tests reported here studied the effects of three possible failure modes on a functional circuit board: (1) circuit bridging, (2) corrosion of contacts, and (3) induction of stray capacitance. Stray capacitance can be induced by adding conductive surfaces near high-frequency circuits, and hence is related to circuit bridging. These failures were studied on functional boards containing circuits sensitive to these failure modes. The components on the boards were those commonly used in modern electrical circuits. The boards contained high-voltage (to study circuit bridging), high-current (to study corrosion), high-frequency (to study stray capacitance), and high-speed digital circuits. Circuit performance was measured continuously on bare and conformally coated boards during the smoke exposure and for 24 hours after the start of the exposure. The boards were also subjected to a range of smoke levels to try to determine failure thresholds.

In all the smoke exposure tests, the fuel is placed in quartz combustion chambers located underneath an exposure chamber and is heated and ignited in this chamber. The smoke rises up stainless steel chimneys to the exposure chamber containing the device under test. Two smoke exposure chambers were built—one that is the same size as the draft standard, and a larger one that could hold an entire computer. The smaller chamber is shown in Figure 1. The standard exposure time is 1 hour. The radiant heat lamps that heat the fuel are on for only 15 minutes. The smoke is vented after the 1-hour exposure, and the electronics continue to be monitored for 24 hours after the exposure starts.

There are a large number of nuclear-qualified cables that are used throughout nuclear power plants. The cable materials that were burned are listed in Table 1. Rather than burning any one material individually, a mixture of the materials was burned because it would be more representative of the fires that may be encountered in a plant. The fuel was analyzed by Schwarzkopf Microanalytic Laboratory (Woodside, NY). The burned fuel yielded 23% ash, 1% bromide, 12.6% chloride, and 0.49% fluoride. The heat yield was 10370 Btu/lb (2.4×10^7 J/kg).

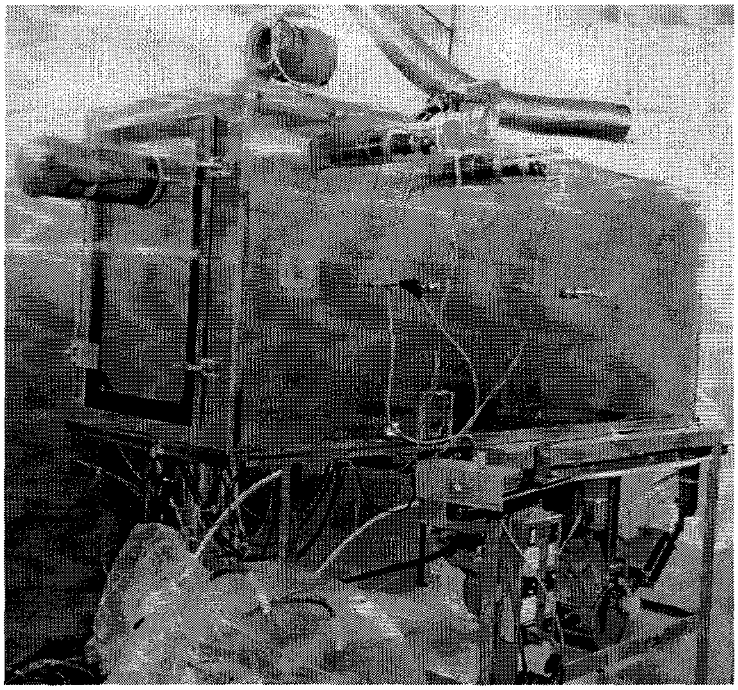

Figure 1: Smoke exposure chamber(124 × 470 × 39.5 cm).

3 RECENT RESULTS

Recent results include the functional circuit tests, comparison of chip technology, and the comparison of conformal coatings. The comparisons of functional circuit tests and chip technology were reported in NUREG/CR-6543.[8] The comparisons of conformal coatings have been completed and will be included in a results and insights report due in 1998.

3.1 Comparison of Electronic Failure Modes

The functional circuit board tests consisted of 12 tests that compared the effect of smoke on different types of circuits. These circuits, listed in Table 2, were designed by the Low Residue Soldering Task Force at SNL to investigate different soldering manufacturing practices. Each circuit was designed to be vulnerable to a particular failure mechanism.[9] The components of this circuit board include both plated-through hole (PTH) and surface-mounted (SMT) components. In general, SMT components are smaller and easier to install because there is no need to drill holes in printed circuit boards to install them. Thus, more and more digital systems are expected to contain SMT components. When reasonable, two identical circuits were built on the functional circuit board, one containing only SMT components and one containing only PTH components. The components of the two circuits had the same nominal value. Figure 2 shows the functional circuit board.

The failures observed during the smoke exposures for the circuits were:

- High voltage, low current—increase in conduction around both PTH and SMT circuits, resulting in reduced resistance measurement

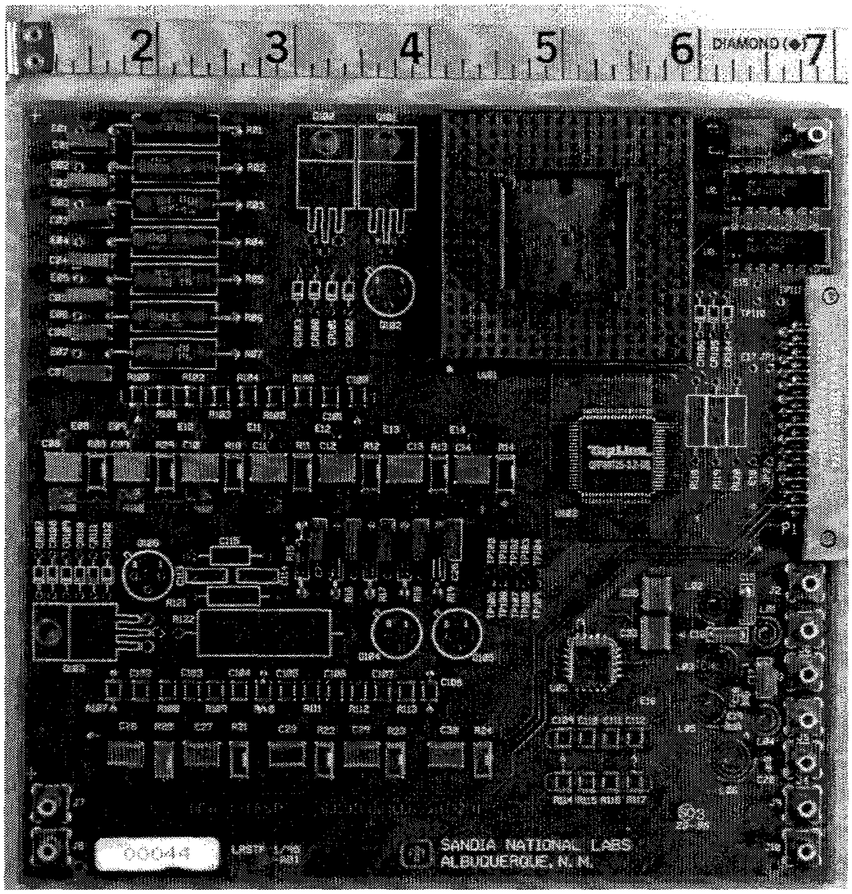

Figure 2: The functional circuit boards allowed testing for different smoke failure modes.

Table 2: Functional circuits tested and their likely failures.

Circuit	Sensitivity	Package
High voltage low current	Alternative current leakage paths	PTH/SMT
High current low voltage	Increased resistance in solder joints	PTH/SMT
High-frequency transmission line	Coupling between transmission lines	N/A
Low-pass filter(200 MHz)	Increased inductance or capacitance	PTH/SMT
High-speed digital	Increased pulse rise, fall, or delay times	PTH/SMT

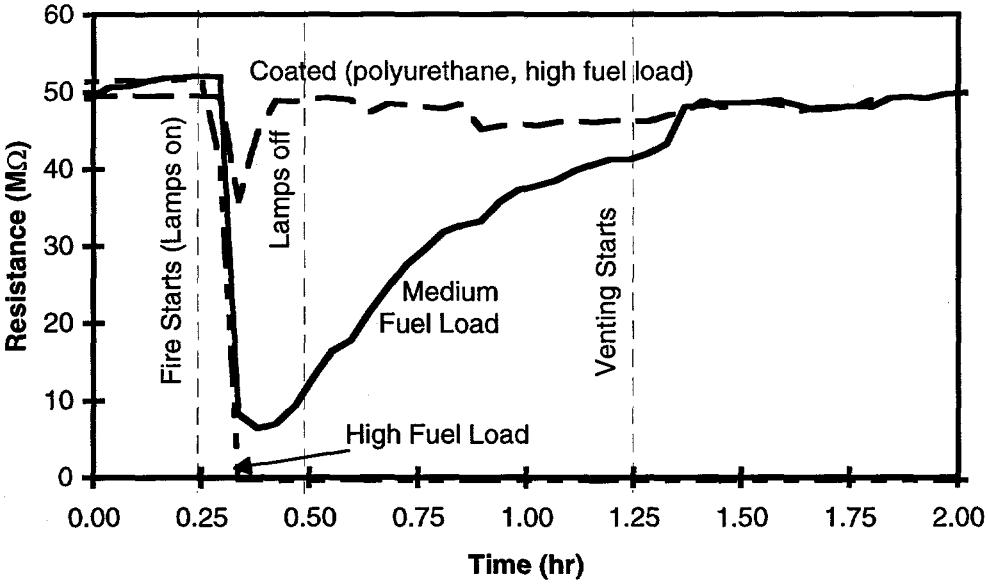

Figure 3: Increased conduction (reduced resistance) is caused by smoke particles in the air and surface deposition for the high-voltage, low-current circuit.

- High current, low voltage—increase in resistance for SMT circuit only
- High-frequency transmission line—increase in coupling while smoke in chamber
- Low-pass filter—very little change from smoke
- High-speed digital—pulse stopped either immediately or after a few hours of exposure, but restarted.

To illustrate the effect of smoke on these circuits, Figures 3–5 plot the response of the circuits to smoke. In general, the circuits that responded the most to the smoke were the high-voltage, low-current circuits. These circuits had a high potential, 300 Vdc, across a high impedance circuit of 50 MΩ. The measured resistance of the high-voltage low-current circuit depended on the smoke density. Figure 3 shows how a high-voltage, low-current circuit reacts to different amounts of smoke. For medium smoke density (25 g of fuel per m^3), the measured resistance falls; but as the smoke clears by deposition and venting, the resistance returns to normal. The circuits tested with a high fuel load (50 g of fuel per m^3) did not recover after venting. The surface deposition was high enough that the current must have passed through the soot on the surface. The resistance of the coated high-voltage, low-current circuit did not decrease as much as either of the other circuits. A conformal coating might protect such a circuit.

The high-current, low-voltage circuit was a low-resistance circuit that was sensitive to loss of conductivity due to the corrosive action of the smoke. Figure 4 shows the reaction of the high-current, low-voltage PTH and SMT circuits to smoke (high fuel load, 50 g of fuel per m^3). The resistance of the SMT circuit increases during the smoke exposure and does not return to normal after the tests. The PTH circuit seems to be unaffected. The conductive traces or solder joints of the SMT circuit are probably attacked by smoke. Smaller amounts of smoke showed similar but less reaction. The corrosive and permanent effect of smoke is shown here by a change in resistance. The change is small—only 2%, even for large fuel loads.

The transmission line coupling increased at 50 MHz, as shown in Figure 5. This means that the signal transmitted by one line was picked up on a parallel line. This effect is high while the

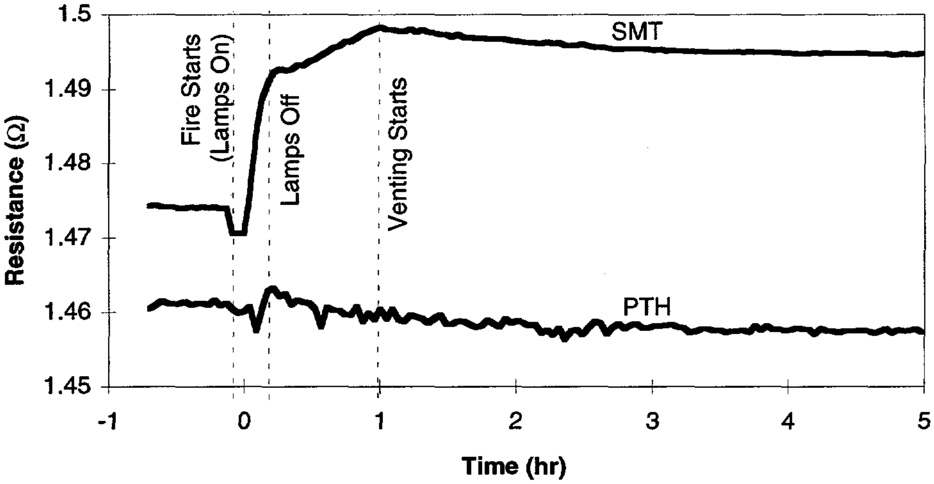

Figure 4: Smoke causes slight increases in resistance of the high-current low-voltage circuit.

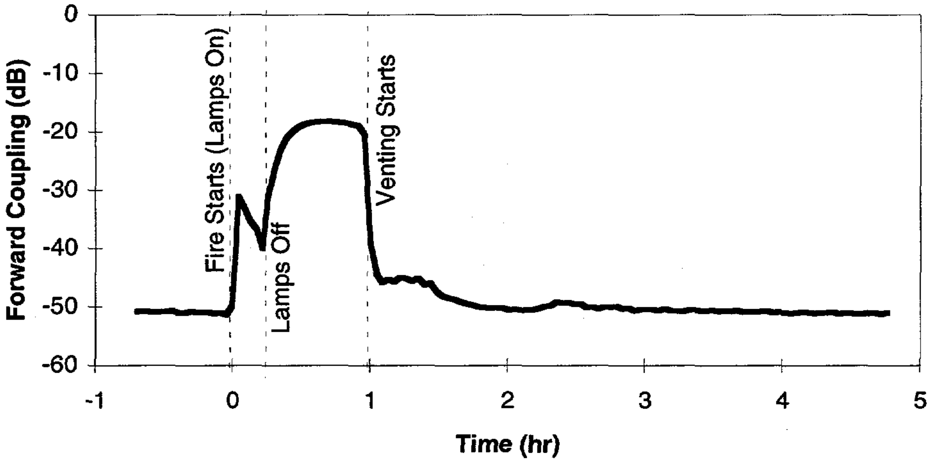

Figure 5: Smoke in the air increases transmission line coupling at 50 MHz.

smoke is in the chamber, but diminishes once the smoke is vented. The smoke seems to act like a conductive layer between the two transmission lines.

3.2 Coating Tests

Conformal coatings can substantially increase the smoke tolerance of circuits. There are more than 75 conformal coatings on the market. In general, there are five types: polyurethane, epoxy, silicone, acrylic, and parylene. One coating from each of the five types was selected and applied by Specialty Coating, Inc. (Indianapolis, IN) to protect the functional boards. These coatings are listed in Table 3. The smoke exposure tests showed that all the circuits performed much better with a conformal coating, although there were minor differences in the performance of the different coatings.

The best circuit to demonstrate differences in coatings is the high-voltage, low-current circuit, because it is the most sensitive to smoke. The coatings were expected to provide quite a bit of protection, so a very high fuel level was used (200 g/m^3). Twelve boards remained uncoated, while each of the five conformal coatings was applied to four boards (total of 20 coated boards).

Table 3: Coatings tested.

Coating Types	Brand	Product	Thickness (mm)	Application Method	Ave. Resistance[a] (MΩ)
Acrylic	Humiseal	1B-31	0.064	Dipped	45.6
Epoxy	Envibar	UV1244	0.064	Dipped	33.4
Parylene	Union Carbide	Type C	0.019	Vacuum Deposition	48.0
Polyurethane	Conap	CE-1155	0.064	Dipped	44.2
Silicone	Dow	3-1765	0.13	Dipped	29.6
Uncoated	N/A[b]	N/A	N/A	N/A	7.3

[a] The results are shown for the SMT circuit

[b] N/A=not applicable

These results are shown in Table 3 for the SMT circuit. The average resistance for the circuit is shown during the burning phase of the test. Parylene was the best coating material, followed by acrylic and polyurethane. The epoxy and silicone coatings were an improvement over the uncoated boards, but did not protect as well as the other three coatings. These results only show differences among the particular coatings tested, and do not imply differences among classes of coatings.

3.3 Measurements of Electrical Properties

Since smoke causes the most drastic changes in the high-voltage, low-current circuit, in the next set of tests we are concentrating on measuring how smoke changes those electrical properties that most affect this circuit. Two such parameters are conductivity and dielectric permittivity of the air. To measure these properties, parallel plates biased with different dc voltages are placed in the smoke. Leakage currents between the parallel plates indicate a change in conductivity. For ac circuits, a change in dielectric permittivity is measured using a network analyzer, which can measure this value over a range of frequencies. Other electrical measurements include the resistance across a printed circuit board surface that is oriented in either a vertical or a horizontal direction.

The objective of these new tests is to correlate the change in electric properties to smoke density and content. Once the electrical properties are known, the effect on any particular electronic equipment may be predicted using an electronics model such as the SPICE program, with resistors between adjacent contacts to model the smoke. The advantage of this type of analysis is that the results can be generalized to other pieces of equipment and a failure rate can be predicted for a given smoke density.

Two indicators will be used to determine smoke density: opacity and mass density. Opacity will be measured with a laser beam and the mass density will be measured by filtering a known volume of the air. The content will be determined by the type of fuel to be burned. Up until now the SNL team has burned only cable materials. Other fuels, such as wood and aviation fuel, will be used in these tests. Wood and aviation fuel have been used in other fire and smoke tests and can provide a comparison of test methods.

In addition to these basic measurements, some digital communications signals will be tested, including serial, ethernet (10-baseT), and parallel signals. A printed circuit board has been developed to serve as a smoke target that allows these signals to be transmitted from one connector to another through the smoke test chamber. The communication lines will be monitored by software that measures bit-error rate.

To check the failure possibilities of these connections, the data lines were shorted to ground with a variable resistor to determine what level of shorting was required to cause an interruption of the signal. All of the communications lines were good current sources; the serial line required 170 Ω to cause shorting, the parallel 50 Ω, and the ethernet only 20 Ω. The lower the resistance required to cause an interruption, the more smoke tolerant the signal.

4 Future Work

Other tests that are planned include the exposure of memory chips to smoke. Two types of memory chips are planned for testing: electrically programmable read-only memories (EPROMs) and static random-access memories (SRAMs). EPROMs are used to store programs and data for long-term use and are typically preprogrammed before use in the field. SRAMs are typically used for high-speed data caches in computers. Both of these memory chips are built using complementary metal oxide semiconductor (CMOS) technology, which reduces the amount of power consumed when they perform a function. Low-power consumption is an advantage for reducing size and increasing speed in electronics, but we predict that it will also increase vulnerability to smoke.

A goal of the program measuring the electrical properties of smoke is to be able to model failure for general electrical equipment. In order to determine whether the failure of this equipment can be modeled accurately, we are soliciting proposals of different equipment to be used in testing the model. The plan is to model the equipment using SPICE, including resistive connections that are not part of the normal circuit to simulate smoke. Once the critical resistance for failure is obtained for the equipment, it will be exposed to smoke at the concentration that is expected to cause failure. Suggestions for equipment should be forwarded to the authors.

5 CONCLUSIONS

Smoke exposure testing is not a well-developed field in terms of an environmental qualification test for equipment. The program described here has supported some of the first tests on how digital equipment will react to smoke in real time. Smoke causes intermittent failures of digital communications. These failures are probably caused by circuit bridging; the charged smoke particles act as a bridge for electrical current. Conductivity is increased by both the airborne smoke and by soot deposits. Smoke can also cause a breakdown in solder joints, a long-term effect, and the smoke in the air causes increased coupling between transmission lines.

The SNL has begun a program to determine how to include smoke in risk assessments. This program will measure the electrical characteristics of smoke, such as conductivity, as a function of smoke density and fuel. In addition to these direct current measurements, SNL will expose connectors carrying digital signals. These communications are expected to be more sensitive to momentary shorts than the direct current measurements; however, they may be a better measure of the smoke tolerance of digital equipment. Bit error rates will be recorded for those measurements.

Another area of interest is connectors because they are not conformally coated and may be the most vulnerable region of a digital system. To date, the SNL tests have protected the connectors used for the component and functional board smoke exposures.

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