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Circuit Bridging of Components by Smoke

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Sandia National Laboratories
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U.S. Nuclear Regulatory Commission

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Abstract

Smoke can adversely affect digital electronics; in the short term, it can lead to circuit bridging and in the long term to corrosion of metal parts. This report is a summary of the work to date and component-level tests by Sandia National Laboratories for the Nuclear Regulatory Commission to determine the impact of smoke on digital instrumentation and control equipment. The component tests focused on short-term effects such as circuit bridging in typical components and the factors that can influence how much the smoke will affect them. These factors include the component technology and packaging, physical board protection, and environmental conditions such as the amount of smoke, temperature of burn, and humidity level. The likelihood of circuit bridging was tested by measuring leakage currents and converting those currents to resistance in ohms. Hermetically sealed ceramic packages were more resistant to smoke than plastic packages. Coating the boards with an acrylic spray provided some protection against circuit bridging. The smoke generation factors that affect the resistance the most are humidity, fuel level, and burn temperature. The use of CO_2 as a fire suppressant, the presence of galvanic metal, and the presence of PVC did not significantly affect the outcome of these results.

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Acknowledgments

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List of Acronyms

PTA	Comb pattern A with 160-V bias
PTB	Comb pattern B with 50-V bias
PTC	Comb pattern C with 5-V bias
PTD	Comb pattern D with 0-V bias except 5 V during measurement
LCC	Ceramic leadless chip carrier
CDIP	Ceramic dual-in-line package
CFP	Ceramic flat package
TOC	Transistor outline can
TTL	Transistor transfer logic (0- to 5-V logic)
PDIP	Plastic dual-in-line package
SOIC	Plastic small outline integrated chip package
PLC	Plastic leaded chip carrier package

Introduction

Smoke can adversely affect the electronics in telecommunications and computer equipment. In a fire, smoke can spread easily and quickly, hence it may cause equipment failure over a widespread area. Many of the instrumentation and control systems in nuclear power plants are based on old technologies and replacements are no longer being manufactured. Instead, digital (microprocessor-based) technologies are being proposed. As a result, the U.S. Nuclear Regulatory Commission (USNRC) has determined that the potential for smoke damage to digital systems warrants investigation. As a part of an ongoing assessment of environmental qualification guidelines to determine their applicability to microprocessor-based equipment, a study of the impact of smoke was initiated. A user-need letter to the Office of Nuclear Regulatory Research included a request to specifically study the effects of smoke along with other environmental stressors to confirm the adequacy of the qualification process for advanced instrumentation and control (I&C) systems.

Consequently, an overall program to confirm the qualification process for digital I&C systems was initiated. The program has been coordinated through Oak Ridge National Laboratory (ORNL), which has performed susceptibility tests for electromagnetic interference (EMI), temperature, humidity, and smoke (conducted with the author) on an experimental digital system (Korsah et al., 1996). ORNL has also investigated likely designs for future digital safety systems (Korsah et al., 1994). The overall program includes a study by Brookhaven National Laboratory (BNL) to determine the risk sensitivities of environmental stressors. To determine the risk sensitivities of selected environmental stressors on the safety systems, BNL studied the reliability of digital electronics in different environments and their relative contribution to the power plant risk (Hassan and Vesely, 1996).

In order to assess the impact of smoke on digital I&C systems, Sandia National Laboratories (SNL) is conducting studies and tests on digital I&C equipment exposed to smoke. This research includes background studies on the smoke scenarios that are postulated to occur in nuclear power plants, smoke damage to electrical equipment, and typical microprocessor equipment that should be tested. The letter reports to the USNRC on these studies are included as Appendices A, B, and E in this report. Two series of preliminary smoke exposure tests have also been conducted: one on an active multiplexer board and the other on ORNL's experimental digital safety system. These results are included as Appendices C and D of this report. The results from all of the appendices are briefly summarized below. The main objectives of this report are to consolidate these previous results and to report on the first series of component exposure tests.

"Defining Credible Smoke Exposure Scenarios" (Appendix A) describes the scenarios that are postulated to occur in a nuclear power plant. It is difficult to define the exact nature of smoke because it is so dependent on the fire conditions and the surrounding environment. The scenarios are defined in terms of factors that are of primary importance for generating smoke in different areas of a plant. These include configuration of fuel, quantity of fuel, the type of fuel, the size of the fire, and the duration of the smoke exposure. Other factors are fire suppression agents and humidity levels. This report has formed the basis for the smoke exposure tests. Because the scenarios are defined in terms of factors in smoke production rather than the smoke products, they are easier to reproduce.

"A Review of Smoke Damage to Electrical Equipment" (Appendix B) surveys the public literature on the results of accidental fires, controlled fire tests, and smoke corrosivity tests. Accidental fires in the telecommunications industry and in the U.S. Navy prompted this study of smoke corrosivity because much of the damage in these fires was caused by smoke. Although there are detailed reports on the results of accidental fires, the uncontrolled nature of the events makes it difficult to draw conclusions on how electronic equipment functioned during a fire and what the levels of smoke exposure were. There were few controlled fire tests that monitored the functioning of electronic equipment while it was exposed to smoke. Most of the testing identified was concerned with salvage of equipment after fires rather than performance during a fire. Despite the interest in the effects of smoke on electronics by the telecommunications industry and the U.S. Navy, there are no existing military specifications for smoke survivability; however, they do exist for temperature and humidity survivability.

"Preliminary Tests of the Impact of Smoke on Digital I&C Equipment" (Appendix C) reports the results of exposing an operating multiplexer board to smoke. The board configuration was designed by ORNL, as was the software to test functionality, and it is similar in function to equipment that is likely to be used for advanced I&C safety systems. The multiplexer board was connected to a personal computer (PC), which was outside the smoke chamber, through a serial communications port. The multiplexer's task was to measure the current output from a similar board that was placed outside the smoke chamber and to report digitized current output values to the controlling PC. The multiplexer board was exposed to a relatively high smoke level produced by burning three different types of cable—ethylene propylene rubber, chlorosulfonated polyethylene, and polyvinyl chloride (PVC). A new multiplexer board was used for each test.

The multiplexer boards performed flawlessly during the exposures to the first two types of cable smoke, but the program that ran the measurements halted several times during the smoke exposure with PVC. The program indicated that communication errors occurred between the PC and the multiplexer board. The program could be restarted and the multiplexer continued to work correctly for the next month. The intermittent failures suggest that the electronics could be experiencing circuit bridging by the smoke, causing intermittent shorts.

"Smoke Exposure Conditions for an Experimental Digital Trip System" (Appendix D) describes the smoke conditions that were used to expose the ORNL experimental digital trip system. The results are described in a report by ORNL (Korsah et al., 1996) and a paper (Tanaka et al., 1996). There were eight smoke exposures for three different modules of the experimental digital trip system, which consisted of computers linked by a fiber optics network. A host computer that was not exposed to smoke logged the state of a reactor trip channel. Multiplexer boards similar to those tested and reported in Appendix C provided the input signals to the computers. The smoke affected the communications on the network, causing temporary error states for lighter smoke exposures, and failures for some of the heavier exposures. Because of the cost of the system, the modules were exposed to smoke several times and cleaned between exposures. After the first exposure, error states occurred even after the modules were cleaned, leading to some uncertainty in the overall results. These tests showed that smoke will affect a digital safety system, but it is unclear how much exposure will result in failures.

Results from both preliminary smoke tests (Appendices C and D) showed that, in addition to the corrosion of metal contacts that can occur weeks to months after exposure, computer systems fail during smoke exposures. The failures were intermittent in many cases and primarily affected the communications between computers or between computers and multiplexer boards. Communication links between computers or between a computer and a multiplexer board are especially vulnerable to the effects of smoke because these components are typically made so that the connectors can be rapidly connected and thus they are not highly protected. Digital communications depend upon high-speed variation in voltages in the output circuitry. If any connector pin is momentarily shorted, the communication may be interrupted. Analysis of the failures indicates that the smoke was bridging contacts that should have been electrically isolated.

All of these preliminary tests were performed on systems that included several operations such as voltage measurement (analog measurement), conversion to digital output, and digital communications. By testing systems, all possible failure points are exposed, but the tests are complicated and expensive because it is difficult to analyze the errors in a large system. Ideally, an entirely new system should be used for each smoke exposure, but this is expensive for a large system. It is easier to test smaller subsections of the systems, such as components or circuits, but such tests can only be useful if the expected failure mechanisms are identified and monitored. The balance of this report describes the results of one series of component tests.

Circuit Bridging Tests on Components

Overview

Since circuit bridging by smoke was isolated as an early failure mechanism, it is important to study factors in smoke generation that affect circuit bridging. The SNL program is based on two series of tests to explore this question. The first series of tests has been completed and is the focus of this report. "Impact of Smoke on Advanced I&C: Selection of Sample Components and Test Matrix" (Appendix E) summarizes the tests and the equipment that were chosen for studying component reliability and the tests that are planned for studying functional board reliability. Results of the first series of tests are discussed in the following sections. The second series of tests on functional circuits is under way.

Experience with shorts in the preliminary tests indicated that intermittent pathways develop between contacts as a result of smoke. Thus the objective of the component-level tests was to determine the smoke-related factors that are important in causing failures from shorts. Components were exposed to smoke, and responses indicative of the formation of leakage paths that would lead to shorting or loss of function were measured. Leakage of current indicates a drop in resistance. In these tests the leakage currents are expressed in terms of resistance for seven chip packages and four comb patterns with different voltages. Loss of function for the optical isolator chip was determined by changes in the amplitude, delay, and rise time of an output pulse. The functionality of memory chips was measured before and after the smoke exposures.

It is known from surface insulation resistance tests that current leakage increases at high temperature (85 °C) and humidity (85% RH) (Iman et al., 1995). Typical pretest resistance measurements are $>10^{12}$ ohms, which drop to approximately 10^{8} ohms within hours after introduction of environmental conditions. This experiment raised two issues in the measurement of current leakage for chip packages and comb patterns: (1) given the temperature and humidity levels for these tests, the levels to which the resistance will drop are unknown, and (2) the expected resistance levels for the components exposed to smoke are unknown. Because of these issues, the circuit bridging tests had no predicted output and no predetermined pass or failure limits for the measurements. Instead, smoke generation factors were varied to determine which factors had significant impact on the electrical characteristics of components and leakage between contacts.

The factors that were tested included the amount of fuel, the presence of PVC in the fuel, the burning temperature, the humidity, introduction of CO_2, and the presence of galvanic material. Some of the factors that were varied directly affected the smoke production; however, humidity, CO_2 and galvanic metal were included because they were likely to interact with the smoke and affect electronic components. High humidity is known to affect electronics and is commonplace after a fire if sprinklers or water-based fire extinguishers were used. CO_2 is another common fire suppressant. It has been proposed that CO_2 may affect electronics by suddenly cooling the electronics and cracking the bonds. It has been included in some of the smoke exposures to determine if it would cause problems for the electronics. Zinc in galvanized metals has been known to combine with chlorides that are frequent components of smoke. $ZnCl_2$ is hygroscopic and will absorb water from the air. The $ZnCl_2$-water mixture forms a syrup, which can drip onto components under the right conditions.

The test objects included seven chip packages, four comb patterns at different voltages, optical isolators, and 16 K memory chips. To determine whether coatings or housings had any effect on the chips or comb patterns, some of these test components were coated with an acrylic spray or housed in a computer case.

The tests were similar to the smoke exposure tests that were conducted for the digital safety system for ORNL (Appendix D). The components to be exposed were placed in a Lexan smoke exposure chamber which was connected by stainless steel chimneys to the combustion chamber underneath the exposure chamber (Figures 1 and 2). Smoke was produced by heating the fuel with radiant heat lamps. The smoke was produced over a period of 15 minutes to an hour and the components were exposed to the smoke for approximately 1 hour. Then the smoke was vented and the exposure chamber was opened, exposing the components to the controlled temperature and humidity of the environmental chamber. The components were monitored before each smoke exposure and at least every 5 minutes throughout the test for 24 hours from the beginning of the exposure. During this monitoring period the components were either in the controlled environmental chamber or in the sealed smoke exposure chamber.

This experiment was not a standardized test and no baselines for acceptable or unacceptable performance exist. However, the test and the current leakage measured for the various chip packages, comb pattern bias conditions, and control parameters have yielded a considerable amount of information that can be used to analyze the effect of smoke on electrical components.

Components Tested

The components tested consisted of seven chip packages (Figure 3a), four comb patterns at different voltages, an operating optical isolator chip, and two 16-K memory chips. The chip packages included a ceramic leadless chip carrier (LCC, U1 in Figure 3a), a ceramic dual-in-line package (CDIP, U2), a ceramic flat package (CFP, U3), a transistor outline can (TOC, U4), a plastic dual-in-line package (PDIP, U5), a small-outline integrated circuit (SOIC, U6), and a plastic leaded chip carrier (PLCC, U7). The ceramic packages and the TOC were empty packages while the PDIP and SOIC both contained four hex inverter circuits. These components were chosen because they typify modern microprocessor electronics. They represent both surface and plated-through-hole mounting schemes and standard patterns used to measure soldering process quality and surface insulation resistance.

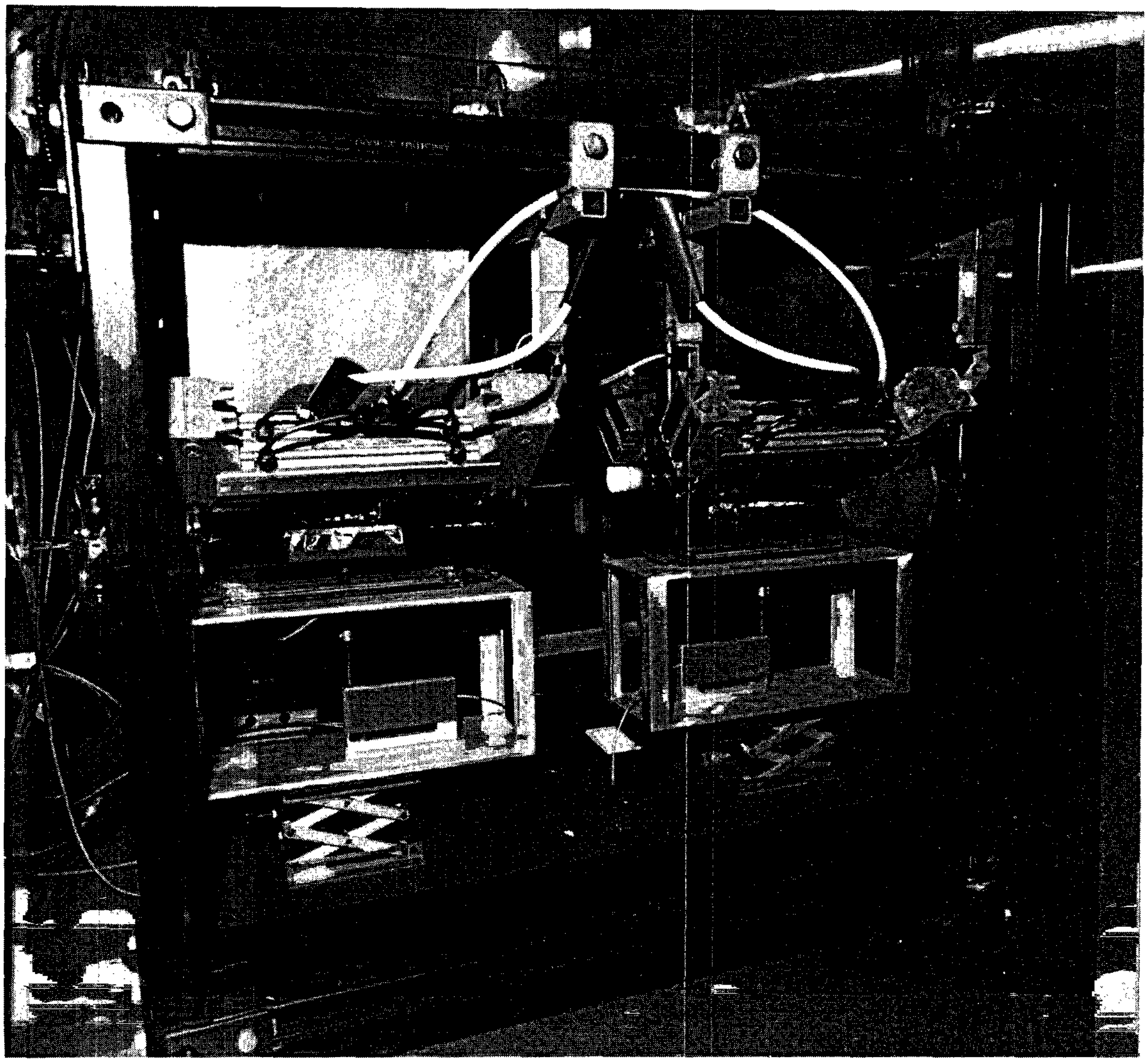

Figure 1. Combustion chambers (quartz cylinders) underneath the exposure chamber. Fuel (pieces of cable) was placed in the center of the chamber inside aluminum foil-lined stainless steel trays and burned by lamps immediately above the quartz chamber. Load cells to measure the weight of the fuel are located beneath the quartz chambers and are connected by a rod.

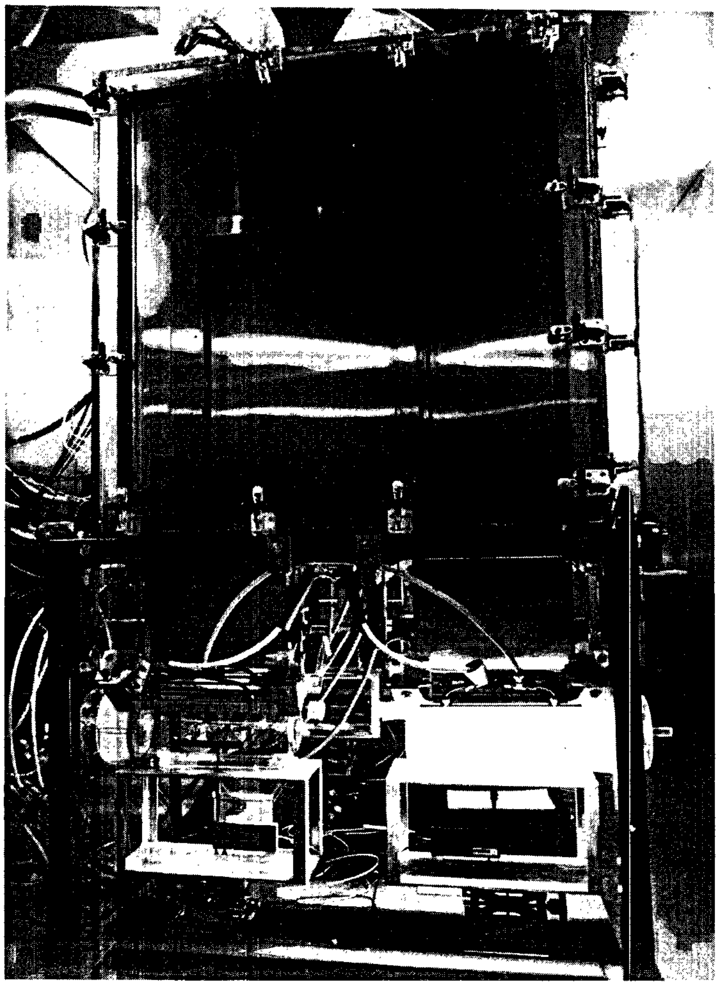

Figure 2. Exposure chamber of Lexan on top of combustion chamber. The Lexan is opaque because the chamber is filled with smoke. The lower right quartz lamp is emitting heat to burn fuel.

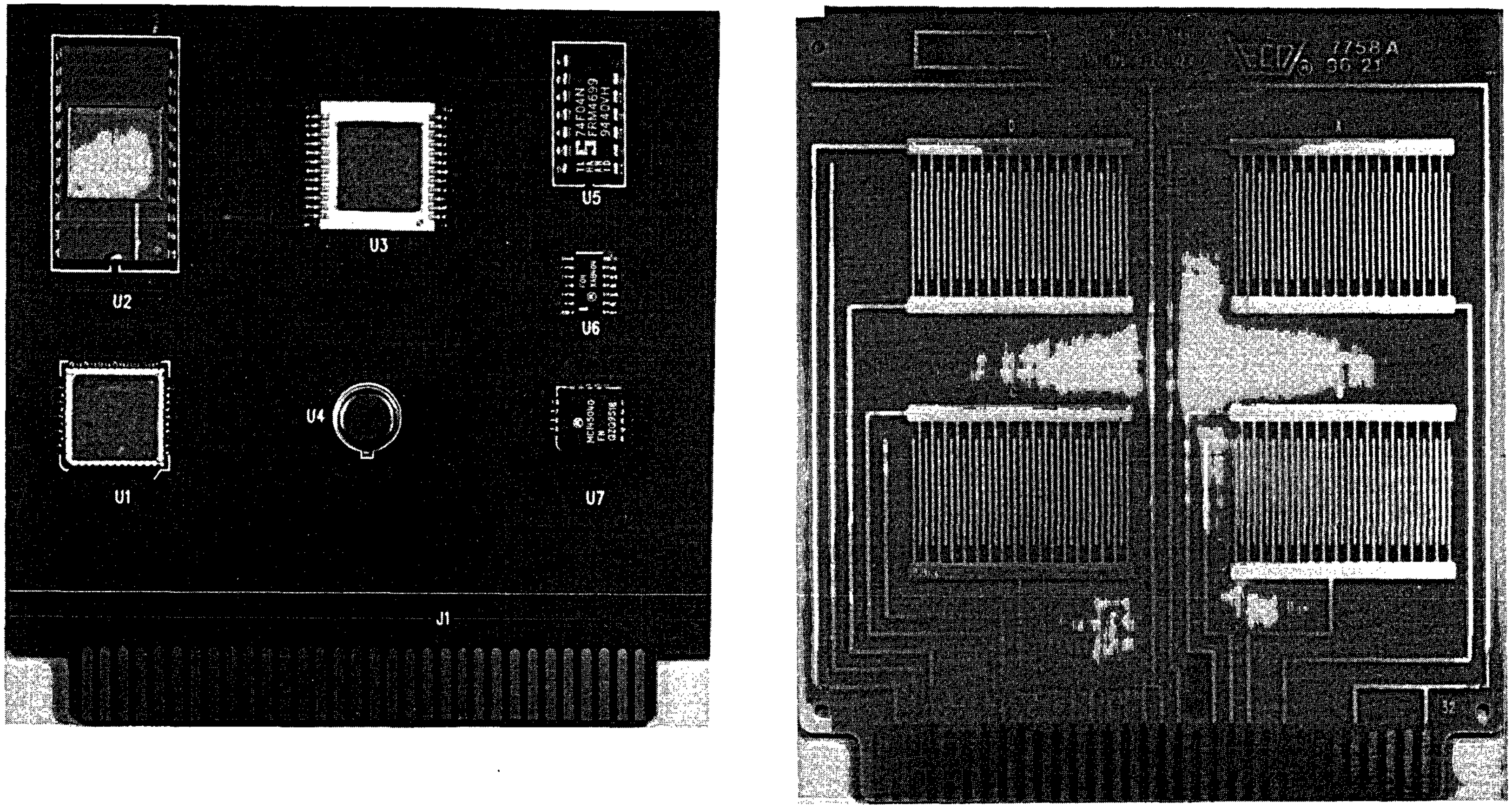

Figure 3. (a) Chip mounting board. (b) Comb pattern board.

Chip Packages

The objective of the chip package experiments was to measure the changes in resistance due to smoke between contacts in components. A chip mounting board was designed that allowed the leakage current between adjacent conductors to be measured while 5 V of dc was supplied to the contacts. There were between 7 and 44 contacts for the seven chips. (Appendix E describes these packages.) Since any pair of contacts may be bridged, as many contacts as possible were monitored.

When plastic chip packages are made, the chip and pins are manufactured first, and then the plastic package is molded around the electronics. For metal or ceramic packages, the package is fabricated first, and then the chip is mounted within the package. The easiest packages to monitor were the four empty chip packages; every other conductor was connected by paths on the printed circuit board. The three plastic packages contained integrated chips; therefore, only adjacent conductors that were independent of one another were monitored. The leadless plastic chip carrier (PLCC) was especially complicated, because it contained an 8-bit A/D converter with serial interface with 1370 field effect transistors. Both through-hole and surface-mounted components are represented in this list of chip packages. The LCC, CFP, SOIC, and PLC are surface-mounted packages and the CDIP, PDIP, and TOC are through-hole-mounted packages.

For the empty packages, all of the even-numbered pins were connected to a 5-Vdc supply and all of the odd-numbered pins were connected to ground. For the hex inverters, the power and ground pins were allowed to float, the inputs to the inverters were connected to 5 V, and the outputs were connected to ground. The PLC chip has 11 analog input pins; alternate input pins were connected to the power and ground while the chip was powered with 5 V. The chip-mounting boards were connected by ribbon cables and card edge connectors to the instrument measuring current leakage, which was located outside of the environmental chamber.

For each smoke exposure, four chip-mounting boards in different configurations were tested (Figure 4). Three boards were mounted inside the smoke exposure chamber; these boards were either bare, coated with an acrylic spray, or housed in a personal computer chassis (Figure 5) with an operating fan (i.e., a typical chassis "muffin" fan). A bare control board was located inside the environmental chamber, but outside the smoke exposure chamber. The boards were placed in position approximately 1 hour before the test in most cases. The card edge connectors were wrapped in black electrical tape to prevent smoke from corroding the connectors.

The resistances were measured with a Keithley 617 multimeter and two HP switcher/controllers. The multimeter, used as an ammeter, was switched between the chip packages and comb patterns. The switching was controlled so that the chip packages always had 5 V between the pins. The ammeter was switched into a circuit for 3 seconds before each measurement to allow it to reach to a stable condition. To ensure that the power supplies were not overloaded by chip package shorts, limiting resistors were included in the circuit.

Comb Patterns

Surface insulation resistance was measured on comb patterns on Institute for Interconnecting and Packaging Electronic Circuits (IPC) B-24 printed circuit boards. The IPC-B-24 boards (Figure 3b) contain four identical comb patterns. The comb teeth were 0.4 mm wide with 0.5-mm spaces between opposing teeth. The resistances of the

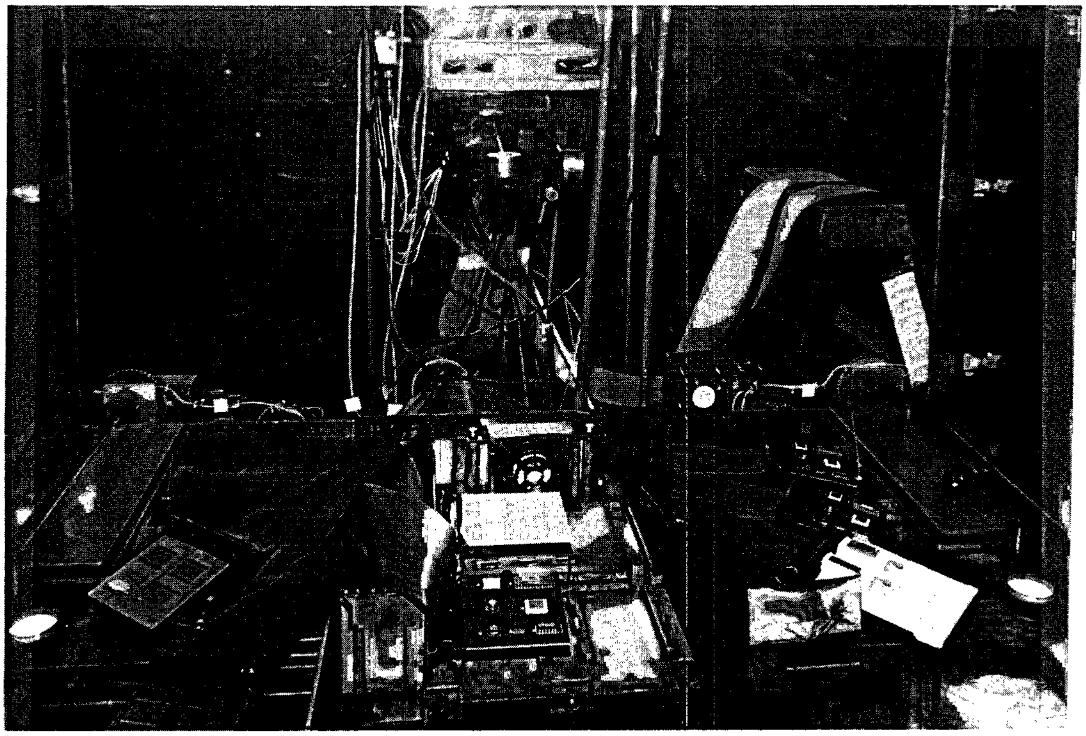

Figure 4. Setup for smoke exposure test. The bare and coated chip-mounting boards and comb patterns are on left and right sides, respectively. The PC chassis with the cover removed is located in the center of the exposure chamber. The bare control board, located outside of the chamber, is draped over the ladder at the right rear.

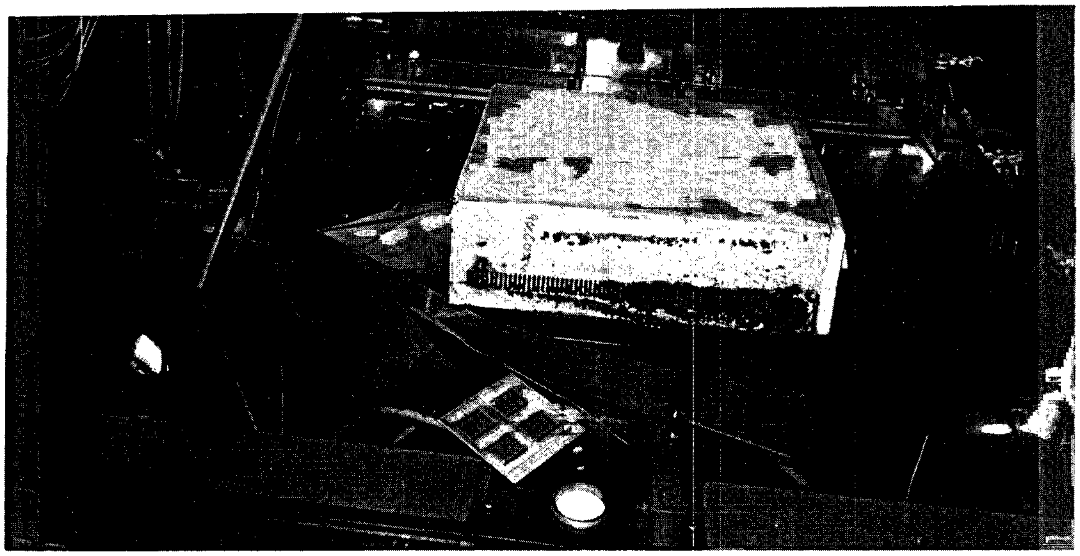

Figure 5. The PC unit covered with housing for the test. The discoloration is the result of earlier tests since the units were reused.

comb patterns were measured similarly to those of the chip packages except that the voltages were different. (One hundred sixty volts were applied to comb pattern A, 50 Vdc to pattern B, and 5 Vdc to pattern C.) Pattern D was grounded except during measurements, when 5 Vdc was applied. The different voltages allowed evaluation of the effect of electric field strength on circuit bridging during and after smoke exposure.

As with the chip boards, four boards were included for each test: a bare board, an acrylic-coated board, a board housed in the PC chassis, and an unexposed control board (see Figure 4). The boards were connected to the power and measurement circuit in the same manner as the chip boards and were measured by the same ammeter.

Optical Isolators

A functioning 6N138 optical isolator, which provides a coupling for electrical circuits with a direct electrical connection, was included in all of the smoke exposures. This device operates by using a light-emitting diode and a photodetector that are built into a plastic DIP body. The 6N138 is a low-input current, high-gain optocoupler built for transistor-transistor logic (TTL) applications. The test circuit consisted of a square wave input pulse, and the resistors and capacitors necessary to provide a switching test circuit as shown in Figure 6 (Hewlett-Packard, 1993).

For each exposure, a new optical isolator chip was placed in a socket containing the supporting circuit. The input and output wave form parameters, pulse rise time, amplitude, and delay from the input pulse were measured on a digital oscilloscope. A starting wave form was recorded, and if the values of rise time, delay, or amplitude varied by more than 5% from the starting values, a new wave form was recorded.

Memory Chips

Two package types for 16-K memory chips were exposed during each test: a plastic-packaged commercial chip and a ceramic-packaged chip developed at Sandia National Laboratories. The two chips had identical circuitry. They were subjected to a potential of 5 V across their voltage supply and ground pins, but were not operated during the exposure. Standard functional tests were performed on the chips before and after the tests.

Scenarios Tested

The factors that were varied for the smoke exposures were fuel amount, presence of polyvinyl chloride as part of the fuel, burn temperature, humidity, addition of CO_2, and presence of galvanic metal. Fuel load, burn temperature, and humidity factors were either at a high or low level. The levels were chosen to span a range for a credible fire. For CO_2 and galvanic metal, the material was either present or absent. Because of the high number of parameters, every possible permutation was not performed; instead, only conditions that corresponded to likely scenarios in plants were produced.

A fire condition matrix was generated according to likely smoke scenarios, and tests 1 to 15 followed this procedure until CO_2 and galvanic metal were determined not to be detrimental to the components. The experimental design matrix was then modified so that PVC could be included as a parameter and other combinations of factors could be tested, such as the combination of high burn temperature and high fuel load. In all, 27 tests were performed.

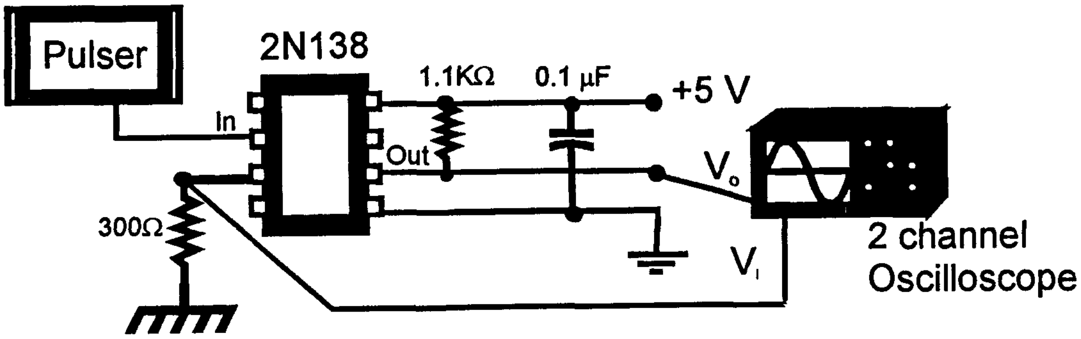

Figure 6. Switching test circuit. (Adapted from Hewlett-Packard Optoelectronics Designer's catalog.)

Fuel Level

Two standard amounts of cable were used as fuel in these tests as the high and low levels: 3 g and 100 g of plastic insulation and jacket material. The fuel consisted of a mixture of cables that are typical of nuclear power plants. The exact amount of plastic that was available for burning is not known because the plastic was not stripped from the cable conductors and measured directly; however, the mass loss of the fuel was measured for each test. The proportion of each type of cable was determined by the number of plants that use the cable as reported by EPRI in their study, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report; Revision 1" (Bustard and Holzman, 1994). Table 1 shows the total mass of the fuel samples used to produce smoke for the tests.

Burn Temperature

The cable material was burned at either high (50 kW/m^2) or low heat fluxes (25 kW/m^2). At low heat flux the cables just smoldered, but for high heat flux tests the cables were ignited if possible with a butane pilot light. For all high-heat flux burns, at least part of the burn took place with a flaming fire; however, the flame did not last the full time that the radiant lamps were on, presumably because the amount of oxygen available in the combustion cell had dropped.

Humidity

High (75% RH) and low (<20% RH) humidity levels were controlled by an environmental chamber that housed the smoke exposure chamber. The humidity was always set before the test, but the humidity within the smoke exposure chamber was not controlled during the smoke exposure since the chamber was entirely enclosed to control the corrosive smoke. After the smoke was vented, the smoke exposure chamber was opened and the environmental chamber controlled the humidity and temperature. The humidity level before the test can affect the resistance of the circuit bridging measurements before the smoke is introduced.

Table 1. Cable Fuel Weights Total (g)

Cable Name	Insulation	Jacket	Low Fuel no PVC	High Fuel with PVC	High Fuel no PVC
Rockbestos Firewall III	FRXLPE	CSPE	1.8	38.6	57.0
Anaconda Flameguard 1kv	EPR	CSPE	1.0	17.3	30.4
Brand Rex XLPE	XLPE	CSPE		20.0	
Okonite Okolon	EPR	CSPE		16.3	
Kerite HTK			0.8	16.7	23.3
Rockbestos Coax (le)			0.5	13.8	15.6
Raychem XLPE	XLPE		0.4	9.9	10.2
Dekoran Dekorad	EPDM	CSPE	0.7	11.7	23.3
BIW	EPR	CSPE		8.11	
Kerite FR				7.0	
PVC	PVC	PVC		4.4	

Suppression (CO_2) and Galvanic

Additional effects were added by flooding the exposure chamber with CO_2 from a fire extinguisher after the fuel was burned and adding a piece of corrugated galvanic roofing material above the test articles. When the CO_2 was added, 60% of the volume of the smoke exposure chamber was filled with CO_2, a standard percentage of the volume that automatic fire suppression systems will flood a room with in the case of a fire. This corresponds to 2.5 lb of CO_2 in the smoke exposure chamber.

The galvanized roofing material was included in some of the tests to simulate industrial environments. Zinc in the galvanized coating could combine with chlorides in smoke to form $ZnCl_2$, which readily absorbs water from the atmosphere to form syrupy deposits. In past fires (Reagor, 1992), the presence of galvanic metal has increased damage to electronics because droplets of $ZnCl_2$ and water have deposited on the electronics. The roofing material was cut so that it was above all of the test samples, but did not cover the chimney areas of the chamber. This metal piece was suspended approximately 1 foot above the test samples and covered almost the entire smoke exposure chamber.

Other Measurements

Temperature, humidity, smoke deposition, smoke optical density (turbidity), and fuel mass loss were measured, and soot samples were chemically analyzed. Descriptions of the methods used for these measurements can be found in Appendix D under smoke environment measurements. The results of these measurements are presented in Appendix F.

Test Matrix

The test matrix for all exposures performed is presented in Table 2. A value of 1 indicates a high level for fuel, burn, or humidity. A value of 1 for PVC, suppression, or galvanic indicates the presence of these conditions. Results of the tests were evaluated in terms of these bipolar indicators rather than individual values. Test numbers were assigned in order of the test performance.

Results

Resistance Measurements

Smoke exposure caused changes in resistance in all components and comb patterns. Figure 7 shows exposed chip-mounting boards from several different tests. The upper left board is a control board (unexposed to smoke) from test 25, the upper right board is the coated board from test 16, the lower left board was in the PC chassis during test 25, and the lower right board was in the PC chassis during test 17. During test 25 the soot from the fan tended to form clumps, fly off the fan, and deposit on the boards housed inside the chassis. The lower right-hand board from test 17 experienced very nearly the same environment as the lower left-hand board from test 25, differing only in that the fuel mixture for test 17 contained PVC while that for test 25 did not.

The comb pattern boards shown in Figure 8 are arranged according to the same tests as the boards in Figure 7, with soot discoloration more evident on these lighter colored printed circuit boards. Although the effects of different voltages are not evident in these reproductions, the higher voltage comb patterns (160 and 50 Vdc) collected more soot than the lower voltage patterns (5 and 0 Vdc). The voltage on the 160-Vdc comb pattern was sufficiently high that when large pieces of soot landed on the bare board, sparks were observed.

The resistances of 44 components (7 types of chips and 4 combs in each of 4 configurations: bare, coated, in housing, and control) per test were measured for a 24-hour period. In this period, approximately 450 measurements were made on each component.

The pretest values of resistance were expected to be the same between chips of the same type; however, this was not the case. In addition to differences caused by pretest humidity, the resistances of similar components were also different.

Figure 9 shows the plot of $\log_{10}$ [resistance(R)] against time of the four 160-V comb patterns for test 23. This plot can be used to draw some conclusions about the differences between the surface insulation resistance of the board that was bare and exposed to smoke, the coated board that was exposed to smoke, the bare board that was mounted in a PC chassis, and the control board, which was not exposed to smoke. The control board had very high resistance throughout the exposure; although some variation was evident, all values were quite high and changes were insignificant compared with the boards exposed to smoke. The coated board and the board housed in a PC chassis behaved similarly; they both started at high resistance values and then their resistance values fell by 3 or 4 orders of magnitude when the smoke was produced. The bare board had the lowest resistance of all of the boards.

Resistances measured in these circuit bridging tests varied over many orders of magnitude, from a maximum of almost 1 petaohm (10^{15} ohms) to a minimum of 1 milliohm (10^{3} ohms). This large range was easier to analyze in terms of logarithms of resistance. By analyzing the data in terms of logarithms of resistance rather than resistance itself, more emphasis was placed on the smaller values of resistance than would have been the case if the data were analyzed in terms of just resistance. Henceforth, all discussion in this report is in terms of the $\log_{10}(R)$.

Table 2. Test Matrix

Test No.	Fuel	PVC	Burn	Suppression	Galvanic	Humidity
1	0	0	1	0	0	1
2	0	0	0	0	0	1
3	0	0	0	0	0	1
4	1	1	0	1	0	1
5	1	1	0	0	0	1
6	0	0	1	0	1	1
7	1	1	0	0	1	1
8	0	0	1	1	0	1
9	0	0	0	0	1	1
10	0	0	0	1	0	1
11	0	0	1	1	1	1
12	1	1	0	0	0	0
13	1	1	0	0	1	0
14	1	1	0	1	0	0
15	0	0	1	0	0	1
16	1	1	0	0	0	1
17	1	1	1	0	0	1
18	1	0	1	0	0	1
19	0	0	1	0	0	0
20	0	0	0	0	0	0
21	1	0	0	0	0	1
22	0	0	0	0	0	0
23	0	0	1	0	0	0
24	1	1	0	0	0	0
25	1	0	1	0	0	1
26	1	1	1	0	0	1
27	1	0	0	0	0	1

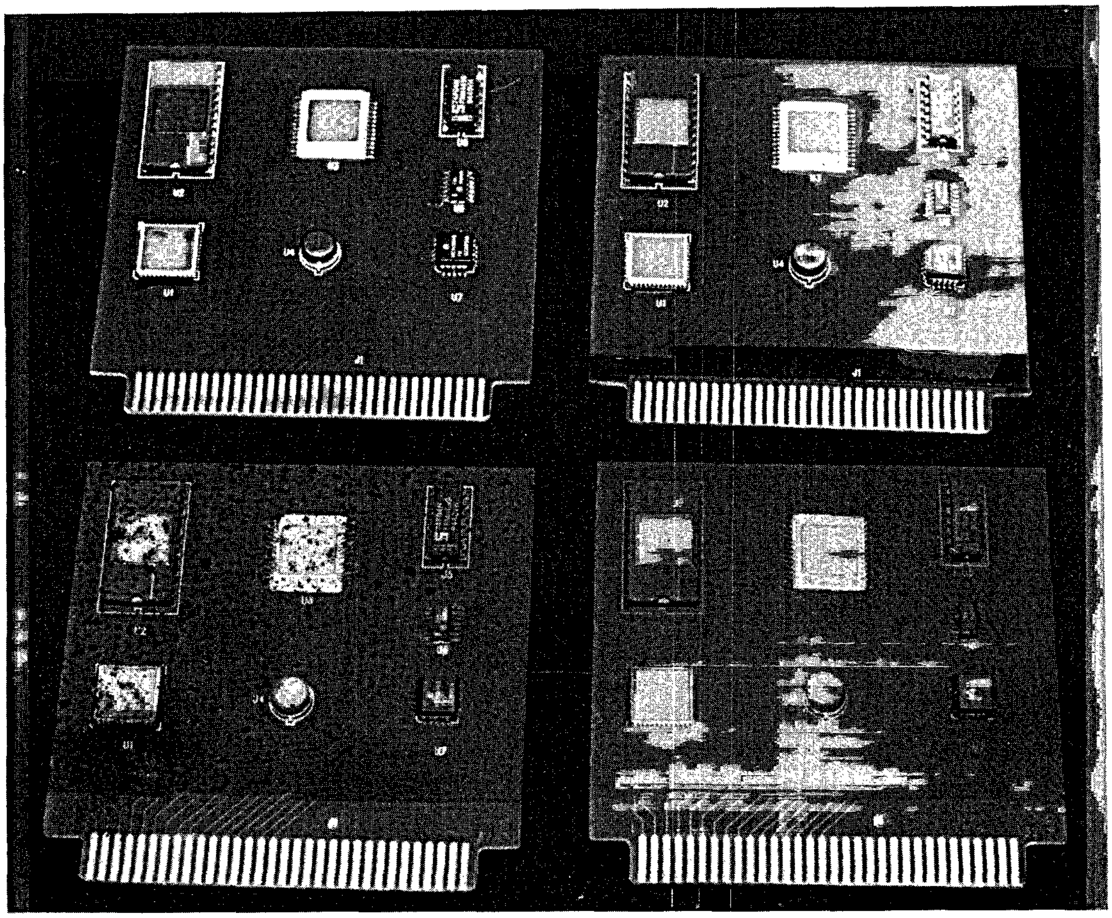

Figure 7. Exposed chip-mounting boards from different tests. Upper left: control. Upper right: test 16. Lower left: in PC chassis for test 25. Lower right: in PC chassis for test 17.

Scatter Diagrams

$\text{Log}_{10}(R)$ was plotted against time from all 27 tests, but the plots are not reproduced here because of the large number (27 x 11=297 in all). Instead, scatter plots have been developed to condense the data into fewer pages. For each component, the $\log_{10}(R)$ at pretest, the $\log_{10}(R)$ averaged during the smoke production, and an average $\log_{10}(R)$ starting 2 hours after the smoke exposure for 24 hours were determined for each test. Scatter plots of these averaged resistances (on a log scale) are presented in Figures 10, 11, and 12 for the 160-V comb pattern for all tests. All of the points represented by the solid circles are bare patterns, all of the squares are coated patterns, all of the triangles are patterns placed inside the PC housing, and all of the asterisks are control patterns.

The averaged values that are plotted in the scatter diagrams represent a varied number of points. In many cases the pretest value was only one measurement, whereas the after-smoke value represents the average of as many as 430 data points. Analysis of each data point as a function of time would have been an overwhelming task; therefore, all of the analysis henceforth deals with the averaged values of pretest, during smoke, and after smoke.

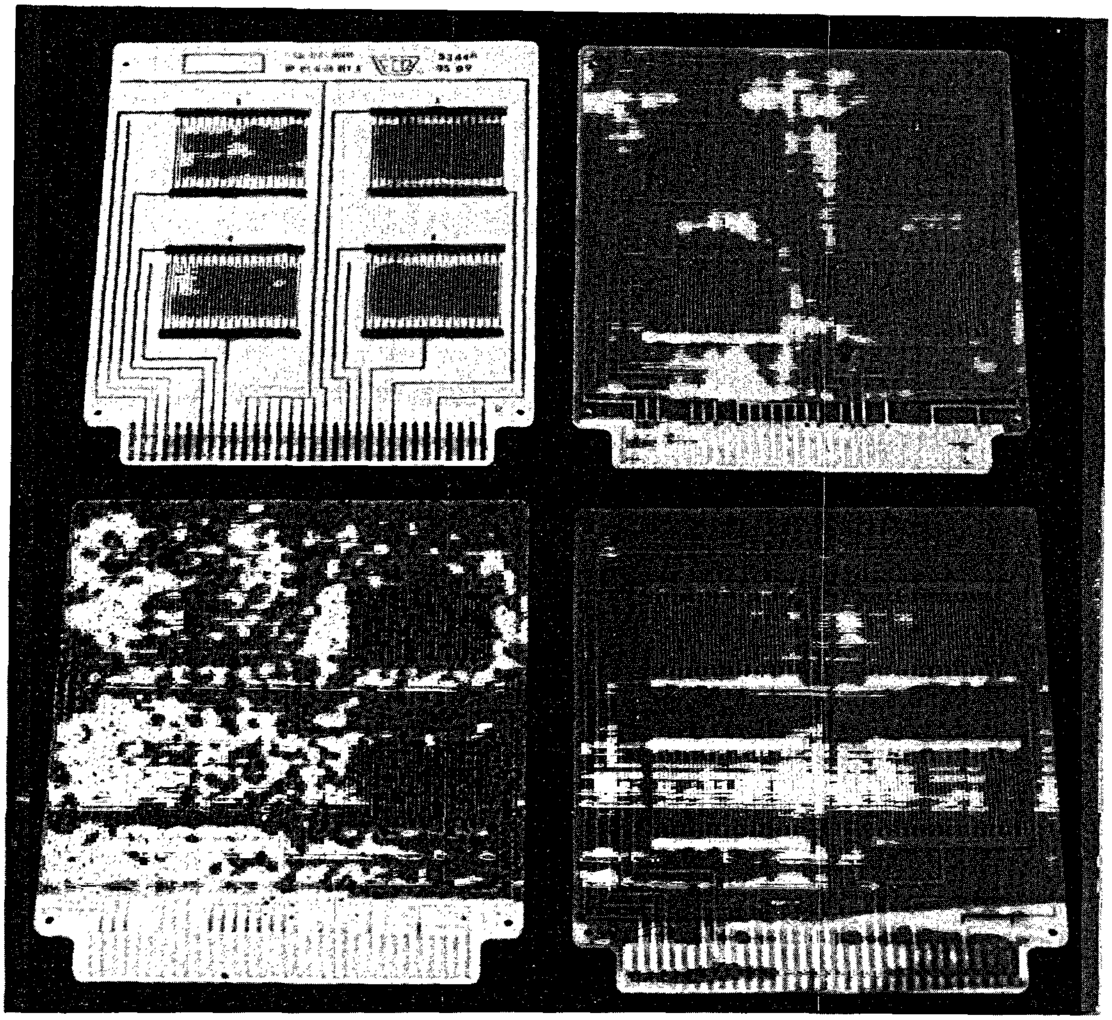

Figure 8. Exposed comb pattern boards. Arranged as in Figure 7.

Figure 10 compares $\log_{10}(R)$ during smoke production with pretest levels. Values located along a line between (0,0) and (15,15) correspond to patterns whose resistance did not change because of the addition of the smoke. It had been expected that all of the points represented by * (control) would be located along this diagonal because these patterns were not exposed to smoke. As shown by the scatter plot, many of the control patterns did not change value significantly, but some of the resistances increased, as indicated by their position above the diagonal line. The points that are below the line indicate that the resistance fell as a result of the smoke. Note that the pretest values range between 8 and 15 while the $\log_{10}(R)$ during smoke exposure ranges between 3.5 and 15. The range of resistances for the presmoke patterns is much smaller than the resistances during the smoke exposure.

Figure 11 compares the $\log_{10}$(resistance) pretest with the average after the smoke was vented (2 to 24 hours after the smoke exposure began). In this figure it is interesting to note the clump of solid dots (bare board) at approximately 10^{10} ohms along the diagonal line. This indicates that the resistances of the bare boards reverted back to their starting

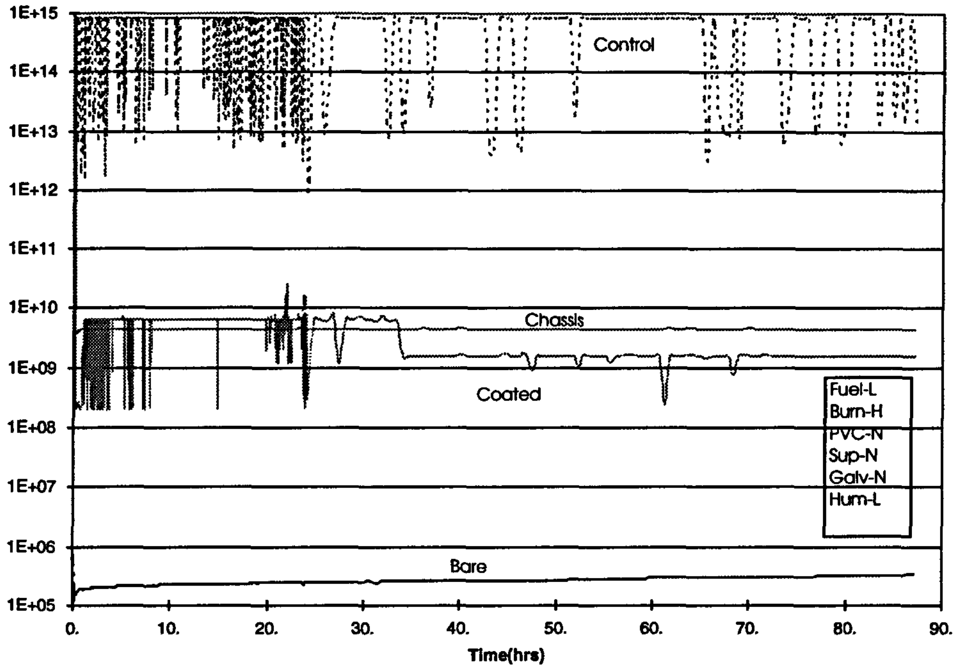

Figure 9. Plot of resistance against time for comb pattern (test 23).

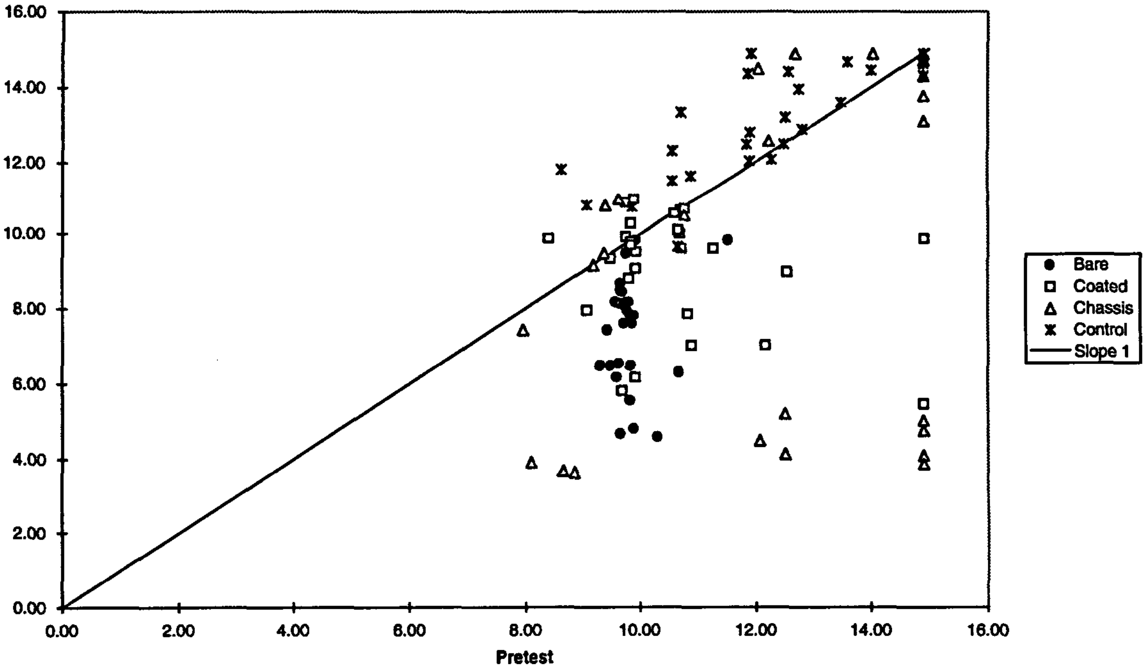

Figure 10. $\mathrm{Log}_{10}(R)$ during smoke production compared with pretest levels for a 160-V comb pattern.

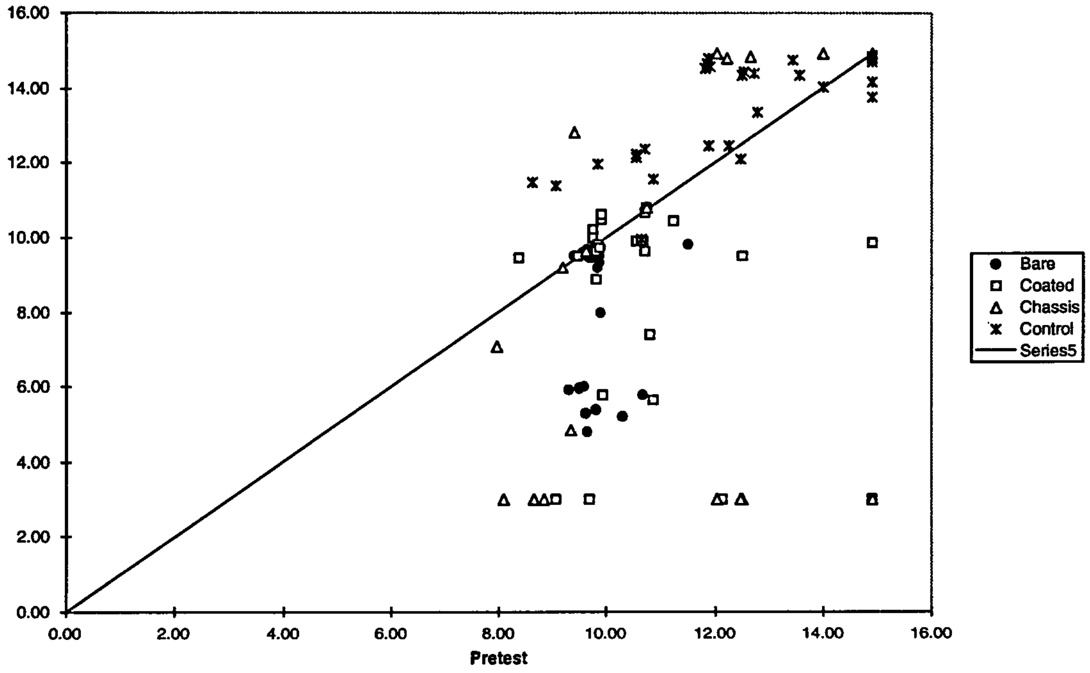

Figure 11. Log_{10}(R) after exposure compared with pretest for 160 V comb patterns.

value after the smoke was vented. The dots were not as tight on the previous figure. In general, most of the resistance measurements were higher after the smoke was vented than they were when the smoke was being produced, indicating some recovery.

Figure 12 shows the comparison of the average resistance during the smoke production with the average after the venting period. In this figure a large number of points are located above the diagonal, indicating that the resistance was lower during the smoke exposure than during the venting period. For these boards, after the smoke exposure, the resistances recovered to some extent. For the values below the diagonal, the resistances became worse as time went on even though the smoke was vented from the chamber. It is interesting to note that the boards that had lower resistance values (higher degradation) during the smoke exposure did not recover as well as those that had higher resistances (lower degradation) during the smoke exposures. This would indicate that, for lighter smoke exposures, the electronics may recover from the smoke exposure, whereas for heavier smoke exposures, they may not. Similar figures for all of the component packages and comb patterns are included in Appendix F, figures 1 to 33.

Parameter Modeling

The scatter plots provide a good intuitive grasp of the effects of smoke in general throughout these tests and show the differences among different protective measures for the boards, but in order to determine which of the smoke generation, environmental condition, or board condition factors were most significant, variances in resistance were analyzed using general linear models. The effect of these different factors is determined by assessing the contribution of each factor to resistance in the linear models.

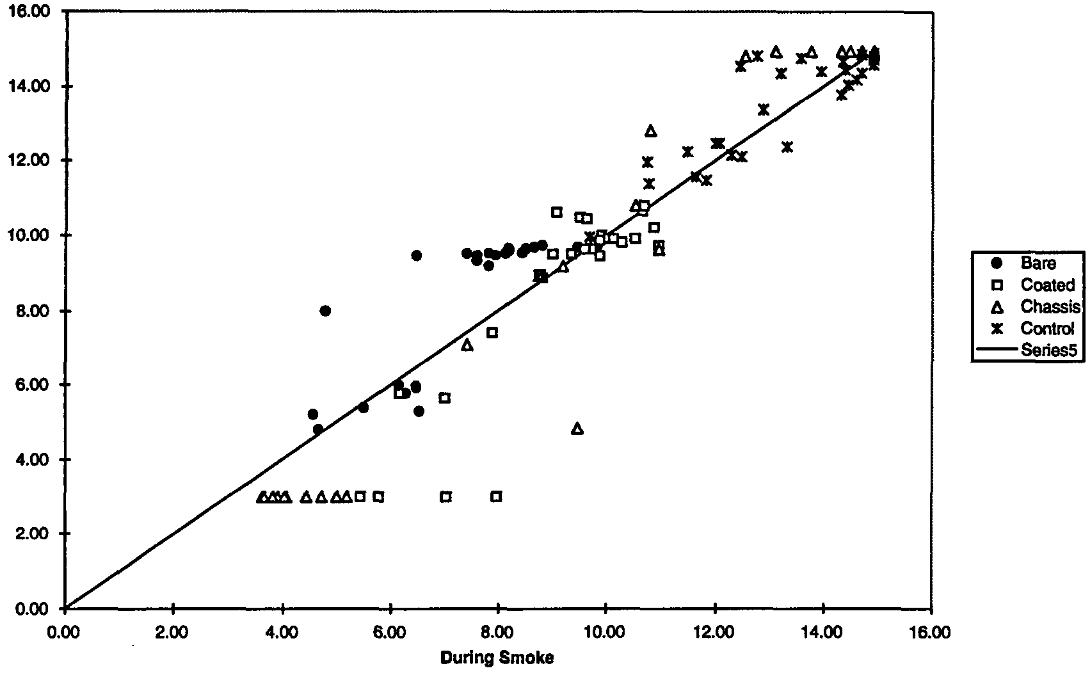

Figure 12. Comparison of average resistance during smoke production and after venting.

Equations were derived from the averaged $\log_{10}(R)$ values that model resistance of each of the eleven components and comb patterns at pretest, during smoke exposure, and after smoke exposure. These 33 models (11 components and combs at 3 periods each), are presented in Appendix F, Table 4. The models indicate the factors that had an influential effect on the resistances of these test samples.

These tests involved seven factors: fuel level, PVC, burn temperature, humidity, suppression, galvanic metal, and board condition (bare, coated, housed in chassis, and control). General linear models use indicator variables for the factors. For these tests two-level factors were used; therefore indicator variables of values, 1 for high or present levels, and 0 otherwise, were used. (See Table 2 for the values of the indicator variables for each test.) The four board conditions are also represented by four two-level indicator variables, one each for bare, coated, or chassis. For example, if *bare* = 1, then all other board condition indicators such as *coated* or *chassis* must be 0. All three board conditions set to 0 indicates the control board.

General linear models use stepwise least-squares regression analysis of these indicator variables to produce equations for the resistance value. The final model is a linear combination of the indicator variables. The model determines the best combination of significant factors; coefficients for factors that are insignificant are dropped from the equation. Cross products of up to three factors at a time, representing third-order interaction effects, were included in the model. For example, the combination of high fuel loads and a bare board can result in more significant changes in resistance than either a bare board or high fuel load considered separately. The mathematical equivalent of the combination of a high fuel load and a bare board would be *fuel* x *bare*. If the combination of high fuel and a bare board is more significant than either high fuel or bare board alone, a coefficient for this combination of factors appeared in the model. This modeling process determines the most significant factors influencing test results.

The following empirical general linear model shows the relationship between resistance and the significant factors for the transistor outline can (TOC) for all conditions before smoke exposure:

$$\begin{aligned}\log_{10}(R) &= 12.27 - 4.61 \times \text{humidity} \\ &+1.09 \times \text{chassis} \\ &+3.82 \times \text{bare} \times \text{humidity} \\ &+3.05 \times \text{coated} \times \text{humidity}\end{aligned}$$

This model includes a constant value that was based on the control board, and coefficients that are added or subtracted from the constant depending on whether any of the factors are in their "high" state (indicator variable value = 1). The constant corresponds to the resistance of the control TOC for low humidity.

This model can be used to determine a value for the control TOC in high humidity. In this case, the contributions from *bare*, *coated,* and *chassis* would be 0 because for the control board, the indicator variables of *bare, chassis,* and *coating* are 0, and only the contribution due to high humidity, -4.61, would remain because *humidity* would be 1. The model would give a value of:

$$\log_{10}[R(\Omega)] = 12.27 - 4.61 = 7.66$$

When all of the models are analyzed on an individual basis, they may yield confusing information. For example, for the ceramic leadless chip carrier during pretest, the control, bare, and chassis boards are all exposed to the same environments. Table 4 in Appendix F shows that the values "before" the test are different, as noted by the value -4.04 under the column marked "bare." This large variation between the different conditions of the ceramic leadless chip carrier is again modified for the case of a high burn temperature by the value +4.28 under B×Bare, and by the value -4.81 for the high-humidity, high-burn temperature case (B×H×Bare).

To obtain an overall understanding of the most influential effects, a Pareto analysis was performed (Figure 13) on all 11 components taken as a whole. The height of the column indicates the number of times that each factor or combination of factors appears in the 33 models. A separate column was graphed for each period that was analyzed: presmoke, during smoke, and after smoke. Single occurrences of any factor were not included in the graph. Since there were 7 chip components and 4 comb patterns, 11 is the maximum possible number of times that a factor or combination of factors could appear in the models. Figure 13 does not indicate whether the factor will increase or decrease the resistance, it merely indicates whether the factor is significant. Significant factors appearing most frequently in the different resistance models had more influence on the overall test results.

Not only do the models provide information on significant factor effects, they also provide insight into the experimental test conditions, the conduct of the experiment, and data variability. For example, the constant term corresponding to the control board at the

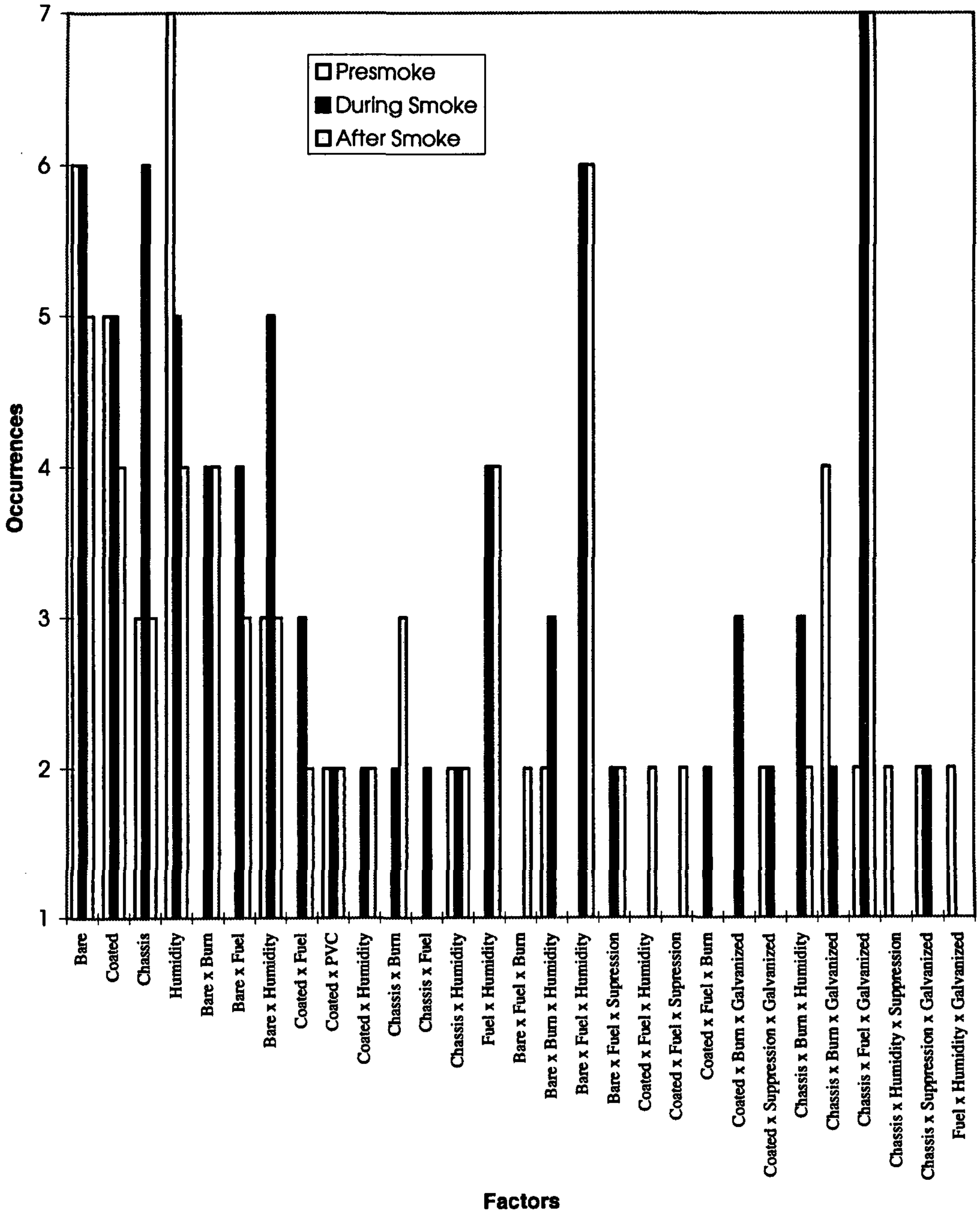

Figure 13. Pareto analysis of significant factors.

low or absent levels varies widely—the 5-V comb pattern is particularly low, as can be seen in Appendix F.

The models also show the four different boards to be significantly different from each other before the smoke exposure began, which was unexpected. The coated boards were sprayed with an acrylic coating, so they may have been different, but differences in the bare, chassis, and control boards are probably the results of variation in the testing circuitry. A low-resistance measurement could be caused in two ways, leakage across the chip or comb pattern, or leakage in the measurement circuit such as shorts in the connectors or cables. Although the circuits were checked before testing began, they were not checked regularly between tests. Stray wires or solder may affect the leakage current measurements because the leakage currents for these components are very low to start with.

Another issue brought out by the models is the identification of some exposure factors as being significant at pretest, before the exposure begins. For example, in the presmoke 160-V comb model, coefficients for *burn* and *fuel* should not be included because the amount of fuel and the burn temperature should not have any effect on leakage before the fuel is ignited. The analysis should not have allowed these factors to enter the models. Their inclusion in some of the models indicates that they account for some of the variation in the response variables. Further investigation into the inclusion of these spurious factors at pretest was not possible due to insufficient sample size and lack of repetition.

Summary of Factors Important to Change in Resistance

The coefficients for all of the components were considered together to determine which factors were the most significant during the different periods of the exposures. The factors that were significant before the smoke exposures were the type of board and the humidity level. The humidity was applied to all boards prior to the test, and the high level of humidity lowered the resistance. The type of board (bare, coated, or chassis) also was significant, but unlike humidity, the values of the coefficients were not consistently negative or positive, possibly reflecting the variation in test circuitry or in the boards themselves.

During the smoke exposure, more factors became significant for resistance. These factors included burn temperature, amount of fuel, a combination of fuel level and humidity, and a combination of burn temperature and galvanic metal. In the modeling of the relationships of significant factors, these additional factors appeared as products with board type, indicating that the control boards were not influenced by these factors. The "high" or "present" state for all of these factors tended to lower the resistance (increase degradation).

The same factors that were significant during the exposure were significant for resistance after the smoke exposure: type of board, humidity, burn temperature, fuel, and a combination of fuel and humidity. The presence of galvanic metal was not significant for the after-smoke resistance.

The factors that appear to be most significant overall are humidity, fuel level, and burn temperature. Humidity appears alone, which is reasonable since the humidity was applied to all boards, including the control board, but fuel level and burn temperature appear as products with board condition or with humidity and board condition. The condition of the board strongly affected how much these factors influenced the resistance. For example, the combination of fuel and humidity had a larger effect on bare and chassis boards than on the coated boards after the smoke exposure. Also, the combination of fuel and humidity was stronger than the effect of fuel or humidity alone, indicating a synergistic effect on the circuit bridging.

Optical Isolator Chip

The amplitude, rise time, and delay of the output of the optical isolator was recorded once for each scan of the resistance measurements. The recorded measurements were averaged for 16 consecutive traces by a digitizing oscilloscope and recorded with the resistance measurements by the computer. When the change in the amplitude, rise time and delay were large enough, the wave form was also recorded. The following equation, which in effect averages the changes of all of the measured parameters, provides the criterion for recording a wave form:

$$\sqrt{\left(\frac{\Delta A}{A}\right)^2+\left(\frac{\Delta t_d}{t_d}\right)^2+\left(\frac{\Delta t_r}{t_r}\right)^2} > 5\%$$

where A is the amplitude, t_r is the rise time, t_d is the delay time, and Δ indicates the change in the corresponding value from the last recorded wave form.

The values of rise time and delay are plotted in Figures 13 to 16 for tests 27 and 5 and illustrate how the rise time and delay are affected by smoke. Both of these tests had high fuel humidity, high fuel loads, and low burn temperature. During test 27, the optical isolator ceased pulsing during the smoke exposure, resulting in the rise time and delay values approaching infinity. The optical isolator in test 5 did not quit functioning, but some jitter in rise time is shown. Such jitter may affect the performance of the communications between digital systems, but the reliability of those systems will depend upon the particular circuits that are involved. Table 3 presents some of the measurements taken during the smoke exposures. The columns that start with "1st" ratio, rise, or delay are pretest values. Note that the pretest ratios generally dropped as the tests progressed, presumably due to some degradation in the chip-mounting fixture that was reused, with new chips, in each test. The same was true in general for the pretest rise and delay times. The average values represent averages during the entire test and the "STD" values are the standard deviations. No statistical evaluation of these data has been performed.

Memory Chips

The 16-K memory chips were tested both before and after the smoke exposures, but were not tested during the exposures, though 5 V was applied during the exposures. Table 4 lists the pass/failure (1 stands for pass and 0 stands for failure) of each chip. More failures occurred for the plastic-bodied chips than the ceramic-bodied chips. The hermetic seal on the ceramic-bodied chips may have increased their reliability. The optical isolator output is also presented in the table in terms of passing or failing. The criterion used for the optical isolator was whether the chip continued to put out a signal.

The optical isolator and both memory chips were dual in-line packages (DIPS), so comparisons can be made between the failures of these chips and the resistance measured for the plastic DIP on the bare chip mounting board for particular tests. The modeling equation for a bare plastic DIP was used to derive the resistances in Table 4. The failures

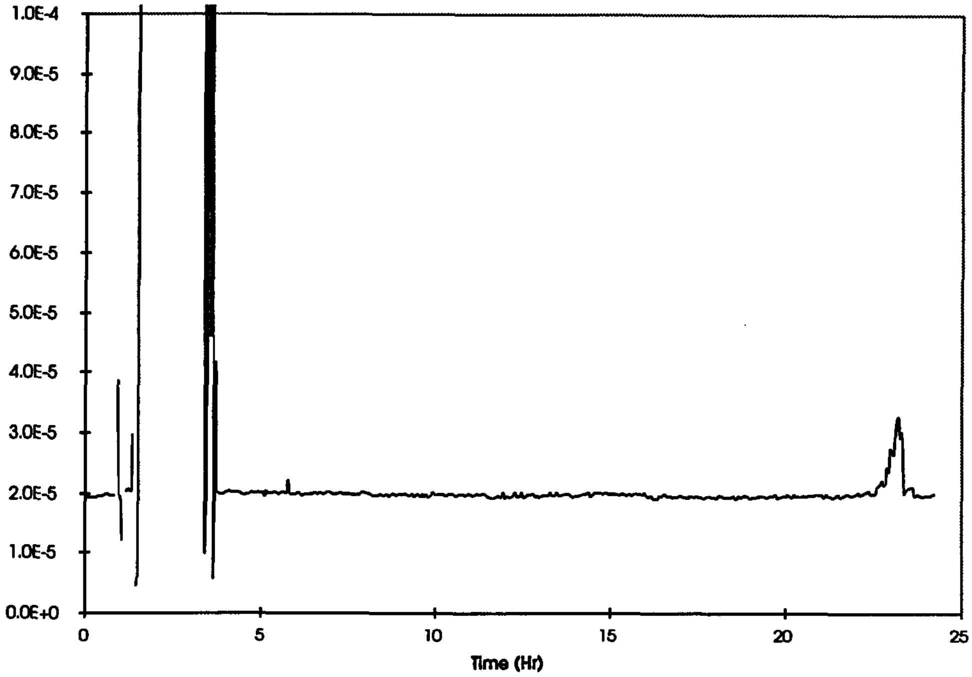

Figure 14. Optical isolator delay from test 27.

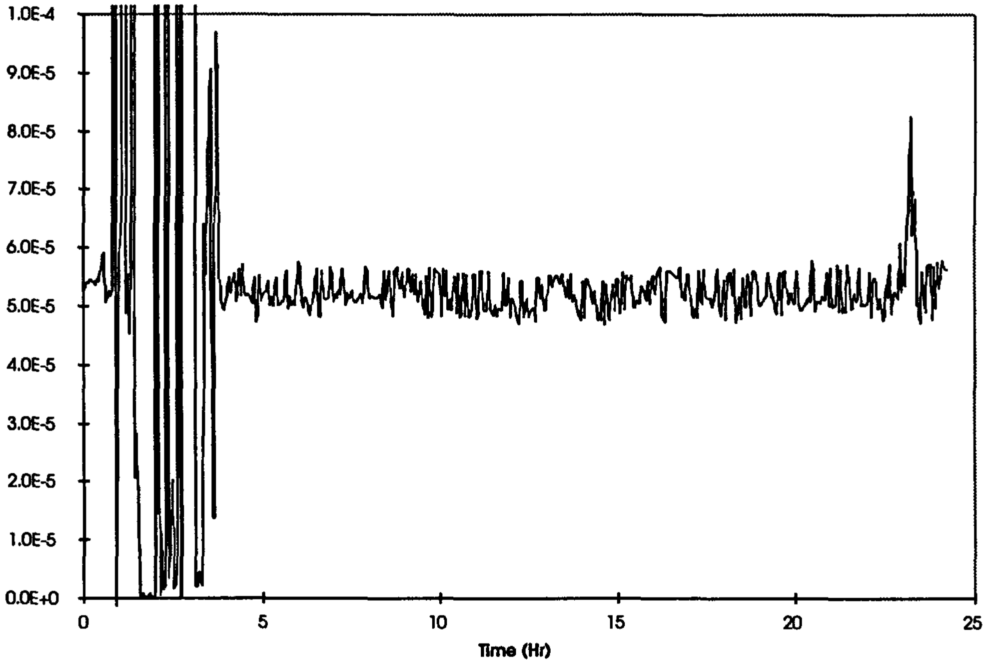

Figure 15. Optical isolator rise time from test 27.

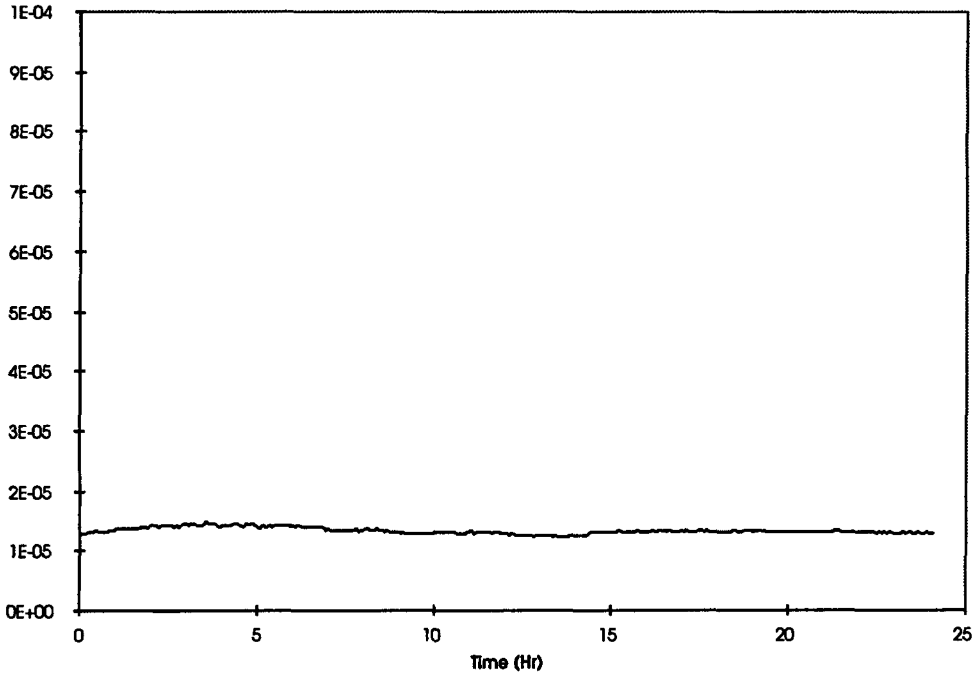

Figure 16. Optical isolator delay from test 5.

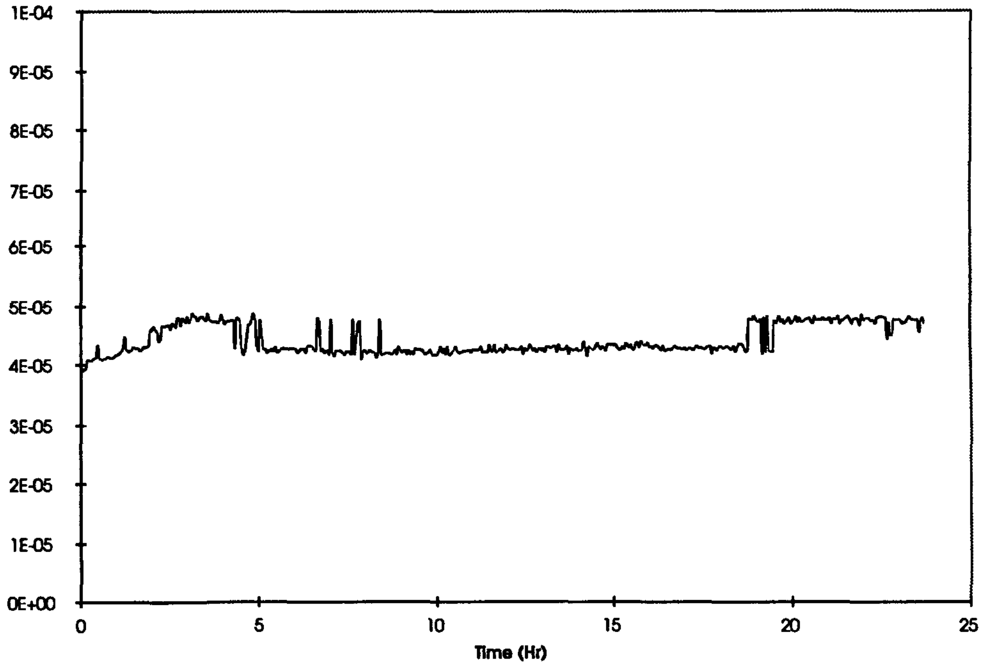

Figure 17. Optical isolator rise time from test 5

Table 3. Optical Isolator Measurements

Test	1st ratio	ave ratio	STD ratio	1st rise	ave rise	std rise	1st delay	ave delay	STD delay
1	1.00E+00	0.992	1.32E-02	3.79E-05	3.60E-05	2.30E-06	1.11E-05	1.11E-05	1.21E-07
2	9.92E-01	0.992	1.27E-02	3.61E-05	3.71E-05	2.19E-06	1.19E-05	1.22E-05	1.47E-07
3	1.00E+00	0.992	9.78E-03	3.77E-05	3.59E-05	2.24E-06	1.09E-05	1.10E-05	1.22E-07
4	9.92E-01	0.989	1.11E-02	3.39E-05	4.05E-05	2.06E-06	1.07E-05	1.28E-05	3.79E-07
5	9.84E-01	0.995	8.34E-03	3.90E-05	4.41E-05	2.40E-06	1.27E-05	1.34E-05	5.18E-07
6	9.76E-01	0.981	9.95E-03	4.64E-05	4.75E-05	2.23E-06	1.53E-05	1.55E-05	1.71E-07
7	9.84E-01	0.985	1.00E-02	4.48E-05	4.73E-05	2.39E-06	1.49E-05	1.56E-05	1.73E-07
8	9.84E-01	0.976	1.03E-02	5.04E-05	5.10E-05	2.47E-06	1.77E-05	1.80E-05	1.36E-07
9	9.59E-01	0.973	6.41E-03	4.90E-05	5.00E-05	1.28E-06	1.79E-05	1.77E-05	1.81E-07
10	9.59E-01	0.978	6.64E-03	4.48E-05	4.73E-05	1.72E-06	1.57E-05	1.58E-05	1.51E-07
11	9.84E-01	0.979	9.83E-03	5.43E-05	5.46E-05	2.56E-06	1.81E-05	1.87E-05	1.31E-07
12	9.76E-01	0.991	1.10E-02	3.98E-05	4.22E-05	1.68E-06	1.42E-05	1.43E-05	1.43E-07
13	9.76E-01	0.993	8.94E-03	4.02E-05	4.26E-05	1.60E-06	1.40E-05	1.43E-05	1.56E-07
14	9.92E-01	0.990	7.61E-03	4.18E-05	4.00E-05	1.33E-06	1.38E-05	1.39E-05	1.41E-07
15	9.59E-01	0.749	3.80E-01	4.79E-05	3.05E+36	1.71E+37	1.77E-05	3.05E+36	1.71E+37
16	9.75E-01	0.638	4.35E-01	5.64E-05	1.23E+37	3.27E+37	1.86E-05	1.26E+37	3.30E+37
17	9.59E-01	0.962	6.16E-03	5.13E-05	5.34E-05	2.70E-06	1.92E-05	1.95E-05	3.90E-07
18	9.59E-01	0.967	1.04E-02	5.12E-05	5.33E-05	2.96E-06	1.91E-05	1.93E-05	3.71E-07
19	9.59E-01	0.970	1.07E-02	5.20E-05	5.47E-05	3.33E-06	1.94E-05	1.95E-05	1.97E-07
20	9.59E-01	0.971	9.84E-03	5.15E-05	5.51E-05	2.88E-06	1.94E-05	1.95E-05	1.83E-07
21	9.43E-01	0.960	4.59E-03	5.42E-05	5.34E-05	2.00E-06	2.03E-05	1.98E-05	3.12E-07
22	9.84E-01	0.979	8.38E-03	5.65E-05	5.55E-05	2.35E-06	1.90E-05	1.93E-05	2.30E-07
23	9.59E-01	0.977	9.37E-03	5.50E-05	5.57E-05	2.83E-06	1.96E-05	1.95E-05	1.92E-07
24	9.75E-01	0.975	8.97E-03	5.38E-05	5.54E-05	2.25E-06	1.93E-05	1.94E-05	2.51E-07
25	9.19E-01	0.947	1.15E-02	5.10E-05	5.43E-05	3.02E-06	2.00E-05	2.02E-05	4.79E-07
26	9.59E-01	0.855	2.54E-01	5.35E-05	2.38E+36	1.52E+37	2.00E-05	2.17E+36	1.45E+37
27	9.67E-01	0.778	2.81E-01	5.26E-05	2.62E+36	1.59E+37	1.92E-05	2.62E+36	1.59E+37

of the optical isolator and memory chips occurred during tests where log(R) < 10 in all cases except for test 15; however, failures did not occur every time log(R) < 10. [Log(R)=3 in these measurements corresponds to shorting of at least one pair of contacts. The test setup did not allow for measurement of resistance below 100 ohms.] Although

Table 4. Memory Chips and Optical Isolator

Test No.	Calculated log (R)	Ceramic Mem	Plastic Mem.	Optical Isolator
1	12	1	1	1
2	12	1	1	1
3	12	1	1	1
4	3	1	0	1
5	3	1	1	1
6	12	1	1	1
7	3	1	0	1
8	12	1	1	1
9	12	1	1	1
10	12	1	1	1
11	12	1	1	1
12	13	1	1	1
13	13	1	1	1
14	13	1	1	1
15	12	1	1	0
16	3	1	1	0
17	3	1	0	1
18	3	1	0	1
19	13	1	1	1
20	13	1	1	1
21	3	1	1	1
22	13	1	1	1
23	13	1	1	1
24	13	1	1	1
25	3	0	0	1
26	3	1	1	0
27	3	1	0	0

the chips package measurements indicated that the contacts of the plastic DIP shorted for certain tests, the optical isolator and memory chips did not always fail on the same tests. The chip package measurements were more sensitive because they monitored all pairs of contacts rather than only those required for a chip to operate. The chip packages were also placed in slightly different locations in the smoke exposure chamber than the memory and optical isolator chips (both were on the right side of the chassis as shown in Figure 4), exposing the different chips to different amounts of smoke and in different orientations. No measurements were made of amount of smoke or soot in the immediate vicinity of these chips, so no conclusions can be drawn regarding the effect of different locations in the exposure chamber. Also, no thermocouples were located close enough to the chip boards to resolve differences between them.

Summary of Results

Technology and Packaging

Digital I&C components are available with many different technologies and packages. Metal and ceramic packaging, which are hermetically sealed, tend to be more reliable than plastic packages. The data from the 16-K memory chips show that the ceramic packages were more robust than the plastic packages in a smoke environment. Differences between ceramic and plastic packages were not evident from the resistance measurements; therefore, the higher failure rate of plastic packages may be due to penetration of the plastic by humidity rather than shorting of contacts with soot. Most common digital electronics, however, use inexpensive plastic packages. Hermetically sealed packages are significantly more expensive and are not typically available unless used for military applications.

The voltages at which the digital electronics operate vary according to the digital chip technology. Resistance measurements on the comb patterns indicate that patterns are affected by smoke more if the applied voltage is higher. The higher voltage lowers the resistance before the smoke is applied and continues to produce more leakage current throughout the exposure. Visually, soot tends to accumulate more around the high voltage patterns, and the 160-V pattern was observed to be arcing during the smoke exposure.

Two hex inverter chips were included on the chip mounting board to determine the difference between an SOIC package and a DIP. The data indicated no appreciable difference between these two packages: when the fuel was high, both packages shorted; when the fuel was low, the resistance dropped slightly for both packages, and then recovered. Little difference was observed among all of the chip packages. A reason for not being able to determine differences may be that the low fuel loads were too low to cause much change in resistance, while for a high fuel load, virtually all of the packages shorted.

These tests measured leakage currents that determined the change in resistance between contacts on components. Loss of resistance can cause problems in many components and circuits; for example, if the resistance between a contact to supply voltage and one to an input signal drops, a false signal may be received by the device input from the voltage supply. The likelihood of this happening depends on many factors such as the amount of smoke, location of the contacts, and humidity level. In general, loss of resistance between contacts will cause serious problems in any digital circuit. The exposures of several different circuits will be tested next in this project.

Protection

Bare boards were highly affected by smoke while coated boards seemed to be less affected. Housing the boards in a PC chassis, which contained a fan, only minimally protected them. Visually, some of the boards that were placed within the chassis looked worse than those that were unprotected because clumps of soot were deposited on the board. For the high fuel tests, however, virtually all components in the PC chassis were shorted in these situations and little difference could be observed in the resistance measurements.

Significant Factors in Determining Circuit Bridging

Several observations can be made from the component tests; the most significant factors are humidity, fuel level, and burn temperature. High humidity has been shown to affect the surface insulation resistance of printed circuit boards in environmental testing (Iman et al., 1995). Other fire corrosivity tests that used comb patterns also showed that the resistance of exposed comb patterns is highly affected by humidity (Caudill et al., 1995).

As more fuel is burned, resistance drops. Smoke from plastic leaves a film, which is black and powdery if the plastic is burned in the flaming mode with adequate oxygen. The film is white and oily if produced without a flame and black and oily if produced with a flame but the flame extinguishes due to lack of oxygen. For low fuel loads, the resistance generally dropped during the smoke exposure but recovered after the smoke was vented. This recovery was not often the case with the high fuel loads; once the circuit was shorted, it never recovered.

The burn temperature (flaming vs. smoldering) did not affect the resistance as much as the humidity or fuel amount. The burn temperature would be expected to change the smoke products in two ways: different chemical products can be produced at different temperatures, and the mass loss rate of the fuel is slower if the fire is smoldering. Chemical analyses for Cl, Br and SO_4 show a low correlation between burn temperature and the amount of these chemicals in the soot (Appendix F). Analysis of the amount of fuel that was burned shows that neither the burn temperature nor the fuel level alone determines the percentage of fuel that is burned. If a large amount of fuel was burned at a low temperature, approximately 20% of the fuel was consumed, while if a small amount of fuel was burned at either temperature or a large amount of fuel was burned at high temperature, approximately 40-50% of the fuel was burned. These results are presented in Appendix F.

The circuit bridging tests showed that the synergistic effects of smoke and humidity are higher than for humidity alone. This observation is supported by the frequency with which the modeling equations contain the combination of fuel level and humidity coefficients. If each factor, *fuel* and *humidity*, reduced the resistance in an additive way instead of synergistically, the effect of these two factors could be adequately modeled by each factor alone.

PVC (included as part of the fuel load on the high fuel tests only) showed very little effect on resistance. Only a small proportion of the fuel was PVC in these tests and, with the high fuel load, many of the components shorted without PVC. There is also little correlation between the Cl deposition found by chemical analysis and the presence of PVC. Although the other cable materials did not contain PVC, some had high proportions of Cl and Br, which are typically used as fire retardants. No other cable materials were singled out for study in these tests.

The addition of CO_2 as a fire suppressant did not affect the resistance adversely, supporting results from the ORNL smoke exposures. The addition of CO_2 may be beneficial to the electronics by cooling the room and blowing away some of the soot deposition. These findings are supported by tests on the effect of CO_2 on computers (Arvidson and Persson, 1993).

The galvanic metal was expected to trap Cl in the form of $ZnCl_2$, form a thick liquid, and drip onto the electronics (Reagor, 1992). Although a greasy film formed on the galvanic metal that was suspended in the smoke exposure chamber, the film never accumulated enough water to drip. Instead, the metal piece formed a surface upon which some of the smoke deposited. The overall effect was to reduce deposition on the surface of the electronics and reduce the negative effect of the smoke. On some high-humidity tests, water appeared to be collecting at the base of the PC chassis. This water did not affect any of the components. Overall, these tests were found to be of an inadequate scale to properly assess the importance of this factor.

Resistances of control board components varied during the smoke exposures. It is not clear if factors other than humidity affected these boards. Other possibilities include EMI. For the functional circuit tests planned for fall 1996, several "dry" runs are planned. These runs will include tests of humidity only and tests in which the radiant heat lamps are turned on but no fuel will be available to create smoke.

Some of the resistance values were lower than expected even before the smoke was applied. The electrical circuitry had leakage currents that were not resolved before testing. Although most of these problems were resolved before testing the circuits, leakage remained in a few. This indicates circuits should be carefully tested before each smoke test.

The card edge connectors and sockets for the functional chips were not changed between tests although they were protected by electrical tape. These connectors were still affected by smoke and were replaced once during the test series. Accumulated smoke can cause current leakage paths over time with repeated exposures.

Conclusions

The tests described in this report studied factors that could possibly affect circuit bridging in typical digital electronic components. The factors that were studied can be divided into three categories: component technology and packaging, circuit board protection with coatings or enclosures, and smoke generation factors. Several conclusions may be drawn from the results of these circuit bridging tests and the previous tests described in the appendices to this report. These conclusions include:

1. Smoke causes circuit bridging in components. Circuit bridging increases leakage currents and can cause failures because stray currents cause errors in digital circuitry.

2. Factors that affect circuit bridging are the amount of smoke, humidity level, and burning mode.

3. Although surface deposits cause some circuit bridging, the presence of smoke in the air also causes increased leakage.

4. The effect of circuit bridging on digital I&C equipment depends on the particular components and circuits. Component packaging (plastic, ceramic, or metal) and technology (CMOS, FET, or fast Schottsky) are only a few of the factors that determine the likelihood of survival of a circuit or component.

5. Conformal coatings add some protection to circuits.

6. Mechanical protection may also protect circuits, depending on the presence of a ventilation fan. A fan may draw more smoke into the electronics.

Smoke may have a very destructive impact on digital electronics, producing immediate circuit bridging and, after several weeks, corrosion of metal parts. The component tests focused on circuit bridging in typical components and the factors that can influence how much the smoke will affect them. These factors include the component technology and packaging, physical board protection, and environmental conditions such as the amount of smoke, temperature of burn, and humidity level. Hermetically sealed ceramic packages were less affected by smoke than plastic packages. Coating the boards with an acrylic spray provides some protection against circuit bridging. The most significant factors were humidity, fuel level, and burn temperature. The use of CO_2 as a fire suppressant, the presence of galvanic metal, and the presence of PVC did not significantly affect resistance measurements. The next series of tests will include a study on functional circuits and will be reported in a separate NUREG/CR.

References

Arvidson, M., and H. Persson. 1993. Koldioxids (CO_2) paverkan pa elektronik - slackning med laga koncentrationer. [Carbon Dioxide Suppression Systems - Risk of Damage to Electrical Equipment.] Swedish National Testing and Research Institute, SR Report 1993:20.

Bustard, L., and P. Holzman. 1994. Low-Voltage Environmentally Qualified Cable License Renewal Industry Report; Revision 1, Electric Power Research Institute, Palo Alto, CA.

Caudill, L. M., J. T. Chapin, R. B. Comizzoli, et al., 1995. "Current State of Fire Corrosivity Testing: Preliminary Electrical Leakage Current Measurements," in *Proc. International Wire & Cable Symposium*, pp. 432-437.

Hassan, M., and W. E. Vesely. 1996. *Risk-based Prioritization of Environmental Stressors Which Can Affect Advanced Digital I&C Equipment in Nuclear Power Plants*, Technical Report L-1908, T6, Brookhaven National Laboratories, Upton, NY.

Hewlett-Packard, 1993. Optoelectronics Designer's Catalog: U.S.A., Hewlett-Packard Co. 5091-4573E.

Iman, R. L., R. V. Burress, D. J. Anderson, et al., 1995. "Evaluation of Low-Residue Soldering for Military and Commercial Applications: A Report from the Low Residue Soldering Task Force," Sandia National Laboratories, Albuquerque, NM.

Korsah, K., R. L. Clark, and R. T. Wood. 1994. *Functional Issues and Environmental Qualification of Digital Protection Systems of Advanced Light-Water Nuclear Reactors*, NUREG/CR 5904, Oak Ridge National Laboratories, Oak Ridge, TN.

Korsah, K., T. J. Tanaka, T. L. Wilson, and R. T. Wood. 1996. *Environmental Testing of an Experimental Digital Safety Channel*, NUREG/CR 6406, Oak Ridge National Laboratories, Oak Ridge, TN.

Reagor, B., 1992. "Smoke Corrosivity: Generation, Impact, Detection, and Protection," *Fire Sciences*, v. 10, pp. 169–179.

Tanaka, T. J., K. Korsah, and C. E. Antonescu. 1996. "Preliminary Studies on the Impact of Smoke on Digital Equipment," in *Proc.Twenty-Third Water Reactor Safety Information Meeting*, U. S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, pp. 85-99.

Appendix A
Defining Credible Smoke Exposure Scenarios

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Abstract

This letter report defines smoke threat scenarios which are likely to be experienced by advance electronic circuit components during a fire event in a nuclear power plant. Smoke is, in general, a very poorly understood material. The direct definition of the composition of the smoke likely to be generated during any given fire event is not possible based on the current state of knowledge. Hence, for this report, the approach taken is to identify and define those factors which are considered of primary importance to the generation of "representative" smoke, rather than attempting to define the exact nature of the smoke itself. This definition includes the consideration of the "quantity," "quality," and duration of the smoke exposure. Smoke quantity is defined in terms of the ratio between the mass of fuel burned during a given fire scenario and the volume of air into which the fire products will be distributed. Smoke quality is defined as those aspects of the threat scenario which will influence the chemical composition of the smoke. These include the materials likely to be burned, the anticipated modes of burning, and synergistic interactions with transport surfaces and fire suppressants. The duration of the exposure considers both the duration of the component exposure to the actual smoke-filled environment, and the post-exposure period during which continue exposure to the accumulated deposits would be expected. The smoke threat scenario definitions provided represent a range of conditions which are expected to encompass the likely smoke threat scenarios for nuclear power plant fires.

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I. Introduction

A. Objective

The objective of this report is to define smoke exposure scenarios representative of those likely to be encountered in the event of a fire within a nuclear power plant. These scenarios are expected to be used as the basis for testing nuclear power plant equipment, and in particular advanced types of integrated circuit and fiber optic based components, for smoke damage vulnerability.

B. Scope of Definition

In the definition of smoke exposure scenarios, the factors considered to be of primary importance are those which will determine the quantity, quality, and duration of the smoke exposure. Quantity is associated with both the gross amount of smoke generated and with the dilution of that smoke into the affected air volume. Quality is related to the physical nature of the smoke itself, and in particular, to its chemical composition. The duration of the exposure will include consideration of the fire growth and suppression periods, as well as the post-fire recovery times. A number of parameters can be identified which will influence these aspects of the smoke exposure environment. This study has attempted to identify and characterize those parameters that will be of primary influence.

It must be recognized at the outset that the current state of knowledge regarding the nature of smoke is relatively poor. This primarily affects those issues associated with smoke quality. In fact, even the definition of what constitutes smoke varies. Smoke is often considered synonymous with soot, that is, the carbonaceous particulate formed as a part of the combustion process. However, in this study a more liberal definition of smoke will be used. That is, smoke will be defined in a broader sense to include both soot and any other combustion products that have the potential to become surface deposits, or to interact with surface deposits, during a fire. This definition will also include the consideration of chemical changes induced through interactions with enclosure surfaces during the process of smoke transport, and though interactions with fire suppression agents.

Under this fairly broad definition, smoke will be composed of a wide variety of chemical species, and a definition of a smoke threat scenario must include some consideration of this chemical composition. To the extent possible, expected chemical species and interactions will be discussed as documented in both experimental research and information based on actual fire experience. However, it is well beyond the scope of this study to provide a full definition of the anticipated chemical composition of surface deposits.

Instead, the definition of smoke threat will be addressed primarily through the source of the smoke, rather than through the smoke itself. That is, rather than defining the exact composition of the smoke, this study will define smoke by identifying (1) the type and mass of materials most likely to be the source of smoke, (2) how smoke might be generated and transported to the site of the component, and (3) how long the smoke exposure is likely to last. These factors correspond to the quantity, quality, and duration of the smoke exposure as defined above. It is expected that by reproducing these factors in testing, the chemical composition of the smoke generated will be representative of that which would be encountered in an actual fire incident, even though the exact composition of the smoke may remain poorly defined at the outset of testing. It is expected that testing will include a variety of diagnostic measures to assess the actual nature of the smoke generated and hence will greatly improve our overall understanding of smoke generation and characteristics.

II. Equipment Threat Issues

A. Overview

Before considering those aspects of a fire that are important to the definition of credible smoke threat scenarios, it is useful to consider the mechanisms by which a device might be disabled by smoke. In particular, this project is interested in the impact of smoke on the performance of advanced types of electronic components. Such devices are unique in comparison with older-style electromechanical devices that have typically been the focus of past fire vulnerability investigations [1,2,3]. The factors that make advanced circuit components unique include the compact nature of the devices, the nature of the individual components which comprise an overall device, and the nature and sensitivity of the device's operation.

Because the advanced electronic devices are unique in their construction and operation, unique modes of component failure are to be expected. The following sections identify those mechanisms which are expected to represent important potential modes of failure for integrated circuitry-based devices and systems.

B. Direct Corrosive Attack

One of the principal means by which smoke can threaten the operability of electronic equipment is through direct corrosive attack on the metallic surfaces of the components. In general, such attack has not been considered a short-term concern. That is, for the older style electromechanical devices most commonly used in current reactor applications, the relatively massive nature of the components implies that extensive levels of corrosion would be required to compromise component functionality. The time frame required for such extensive corrosion was considered inconsistent with the short time frames typically considered risk important (fire risk is generally dominated by short-term scenarios). Hence, direct corrosive attack has not been considered as a potential contributor to plant fire risk.

However, when advanced electronic circuits are considered, a potential does exist for short-term corrosive attack to compromise circuit performance, and hence, to represent a significant contributor to plant fire risk. For example, circuit miniaturization efforts are resulting in smaller circuit path traces being used in the fabrication of printed circuit boards. For these small circuit traces, even a relatively limited and short-term corrosive attack, particularly if the attack is in the form of "pitting" corrosion rather than general surface corrosion, may result in the short-term loss of circuit functionality. Hence, for advanced circuit board-based devices, direct corrosive attack is of potential concern.

In general, fire-induced corrosion has been attributed primarily to acidic combustion products (acid gases). In fact, the German DIN 57 472 Part 813 standard simply makes a direct measurement of acid gas content of material combustion products and assumes a direct correlation between acid gas content and corrosive potential [4]. In a similar fashion, the French CNET test will also provide corrosion assessments that are directly correlated to the acid gas content of the fire products (due to the high moisture content of the test cell and to the induced condensation of moisture directly onto the measurement target) [5].

For the purposes of this project, a somewhat broadened view of the corrosive attack issue is appropriate in order to support realistic assessment of threats to components. For example, experience in the telecommunications industry [6] has shown that interactions of the acidic smoke from a cable fire with the galvanized surfaces of common air-handling ductwork can introduce galvanic salts into the smoke stream. These galvanic salts readily deposit onto component surfaces, resulting in direct and aggressive corrosive attack.

Another important consideration is the potential that fire suppressants might accelerate the rate of corrosion through synergistic interactions with the smoke deposits. One such synergistic effect is clearly anticipated in the case of water-based suppressants. Acid gases are generally very hygroscopic. Moisture condensation onto a component surface will act to "scavenge" acid gases from the airborne smoke onto the components, and will promote the formation of acid on the components. As a second example, consider that many nuclear plants utilize carbon dioxide fire suppression systems in either a room-flooding or manual distribution mode. The presence of high concentrations of carbon dioxide in combination with moisture can lead to the formation of carbonic acid deposits, and carbonic acid can be an aggressive corrosion agent. This is hypothetical only, there is no known experience.

Interaction of a fire with Halon may also be of concern because Halon has a relatively high bromine content. Thermal breakdown of the Halon will result in the generation of acidic HBr. However, it should also be noted that the importance of Halon as a fire suppressant agent is decreasing rapidly due to concerns that fluorocarbons are attacking the Earth's ozone layer. Halon is one of the products targeted for removal from use as a result of the international Montreal Accords on the use of fluorocarbons. Hence, it is not recommended that extensive investigations of Halon interactions be undertaken at this time.

C. Circuit Bridging Faults

The deposition of smoke onto a component carries a potential for the creation of electrically conductive short circuit or circuit bridging paths [1]. Such paths may be formed at any point on a component, but would be of particular concern where smaller physical separation distances are present. For advanced electronic circuits, small separations will be quite common. In particular, closely packed circuit traces on the surface of a printed circuit card would be vulnerable to bridging unless protective coatings are applied to these traces. Also, the "pin outs" or connection pins associated with various integrated circuitry devices (chips, transistors, resistors, capacitors, selector switches, etc.) are typically quite close together and hence will also be vulnerable to circuit bridging failures.

It is likely that scenarios involving water used as a fire suppressant will be the most aggressive environment for circuit bridging faults. As discussed above, the formation of a condensation droplet on a printed circuit card will likely act as an agglomeration point for soot particulates and acid gases. Such a droplet could easily bridge several exposed contact points on closely packed printed circuit boards such as those typically used in the construction of advanced electronics. Such failures have been noted in prior experimental studies [1].

Attack by "dry" smoke in the absence of water sprays is less likely to result in circuit bridging failures. However, as discussed further below, test experience with cable fires in particular has revealed that even in the absence of water sprays, cable fire smoke can be heavily laden with tar-like substances which may also act as circuit bridging agents [1].

Another mechanism for circuit bridging faults derives from the observation that smoke interactions with galvanized air handling ducts can result in the formation of galvanic salts. The deposition of these salts onto a printed circuit card may also induce circuit bridging failures. Such deposits have been observed in recently documented telecommunications industry fire events [6]. It is currently unclear whether such deposits resulted in circuit bridging faults during these events.

D. Contact Fouling

Another potential mechanism for electronic component failure due to smoke deposition would be contact fouling. That is, the deposition of smoke particulates onto open contact pairs may result in degraded contact resistance or contact fouling. Such a failure mechanism is, perhaps, of relatively minor concern for integrated circuitry devices because of the more typical use of solid-state switching devices. However, the potential for contact fouling should be considered should a device include open, unprotected contact pairs in its design.

E. Degradation of Fine Movement

In past testing [1], it has been observed that the deposition of smoke onto a device can result in the degradation of fine mechanical movements. In particular, one mode of failure identified for a strip chart recorder exposed to the smoke from a cable fire was the fouling of the mechanical indicator pen, preventing proper operation.

In the case of advanced circuitry components, this mechanism is likely to be of relatively minor concern. In general, such components would be expected to be less dependent on fine mechanical movements, but rather, would be primarily dependent on the operation of solid state devices. However, in certain cases vulnerabilities might exist. In particular, output or indicator devices associated with such systems may incorporate such fine mechanical movements in their operation. Degradation of these outputs may constitute failure of the system.

F. Interactions at Elevated Temperatures

In general, the older-style electromechanical devices that have been used in current reactor designs have relatively high thermal damage limits. In comparison, advanced electronic circuits are much more sensitive to elevated temperatures, and may experience a loss of function at relatively modest temperatures. Many of the fire scenarios likely to be considered important with regard to smoke damage will involve relatively modest elevated temperatures.

In particular, note that during a fire event a loss of the normal enclosure HVAC air flow is likely. That is, most ventilation supply and exhaust systems will be designed to shut down during a fire event to contain the spread of smoke and fire beyond the room of origin. Such control may be exercised either through mechanical dampers actuated by a fusible link, or through the ventilation control system based on actuation of smoke detectors either in the room of fire origin or in the ventilation duct work. Hence, a loss of enclosure ventilation is a likely occurrence in the event of a fire, and manual recovery of the system may take a significant period of time. This will likely lead to an increase in the general room temperature for even a relatively small fire.

Given the likelihood that room temperatures will be increased for even a small fire, it is important to consider the potential for interactions involving a combination of smoke exposure and modest temperature increases. In particular, exposure to modest temperature increases may place advanced electronic devices in a generally more fragile operational state and hence may make the components more susceptible to other forms of degradation, including smoke-induced damage in a synergistic manner.

III. Characterization of Smoke Quantity

A. Introduction

The first step in the process of defining credible smoke threat scenarios for advanced electronic equipment is to define the quantity of smoke to which a component is likely to be exposed. In this context, quantity refers to the amount of smoke per unit volume one would expect a component to become immersed in. This will vary depending on the type of fire scenario one is attempting to represent. Hence, the definition of the "quantity" of the smoke exposure considered appropriate will be approached by first defining those general fire threat scenarios that might lead to such exposures. Based on the types of fire threat scenarios that are considered relevant, many other aspects of the expected fire threat can be defined. In particular, this would include factors such as the types of materials burned, the amount of material burned, mode of combustion, suppression interactions, and likely transport interactions. There are many additional factors which could also be included in this list (e.g. configuration of combustible material and air supply.) However these are considered the most significant.

There are any number of possible fire scenarios that might be considered threats to nuclear power plant operations. However, in the context of the current study, only a limited subset of these scenarios is likely to be of significant concern. In particular, this study is concerned with the potential exposure of advanced electronic components to smoke. Hence, only those areas which will house such equipment, or which might lead to a smoke exposure for that equipment (e.g., adjacent rooms), will be of interest. This narrows the range of relevant fire scenarios which must be considered.

There are four general fire scenarios that could result in the exposure of plant equipment to smoke. Each of these four scenarios would lead to a somewhat different smoke threat. These general fire scenarios are described in the following sections. These descriptions include a discussion of the likely progress of each fire event, and other important fire parameters.

Also presented is a discussion of the total amount of material likely to be burned in each scenario. This value is then coupled to an assessment of the volume of air into which the combustion products are likely to be distributed. Hence, the final assessment of smoke "quantity" is given as a mass of combustible materials burned per unit volume of affected air.

B. Small In-Cabinet Electrical Control Panel Fire

1. General Scenario Description

This scenario would involve a very limited fire which remains confined to a small subset of an overall electrical control panel. In this case, it is postulated that the fire would have virtually no impact on the environment within the overall fire area, but that modest heat input and significant amounts of smoke might be generated and contained within the electrical control panel itself. Thus, those components housed within the same electrical control panel but not involved directly in the burning process would be exposed to a combined mild-to-moderate thermal exposure and smoke deposition environment.

The most likely source of such a fire would be a self-ignited electrical fire initiated by the failure of a component within the cabinet. Hence, the fuels which might burn would be those associated with the construction of electrical components, and potentially, a limited quantity of instrumentation and control wiring. For fires of this type, the early stages are likely to be characterized by overheating of a component which might experience an extended period of smoldering combustion. This might be followed by a brief period of open flaming. The fire might be extinguished naturally (self-extinguishing) or through a fire suppression agent.

In most cases, fires of this type would be expected to be short lived. That is, if the fire remains confined to a small subset of the available fuel, then that fuel will be quickly exhausted, and even barring suppressant intervention, self-extinguishment would be expected in a short time. (By definition, a cabinet fire that grows to involve a significant fraction of the available in-cabinet fuel load would be classified as a large cabinet fire. This scenario is presented in Section 3.3 below.)

It is somewhat difficult to establish bounds on fuel involvement associated with a "small" fire. During the SNL cabinet fire test program [7,8], preliminary testing to assess the impact of various cabinet and fuel loading parameters on fire development often noted that on the order of 5-15% of the available fuel would be consumed during fire tests for which very limited fire growth was observed. For tests in which more extensive fuel involvement was noted, it was also noted that continued fire growth would occur and eventually virtually all of the available fuel would be consumed. That is, a threshold type of behavior was noted.

Based on actual in-plant experience, much smaller fires than those observed in the SNL test program have been experienced [12]. In some cases, self-extinguishing fires have been observed that involved only a single electrical component (e.g., a relay or single printed circuit card). While no actual value of the quantity of fuel burned in these events was given, a lower limit on fuel involvement will be established as 1% of the available cabinet fuel load. Hence, these values of 1-15% will be used as upper and lower bounds on fuel involvement for the small cabinet fire scenario.

Also note that in most of the limited-involvement SNL tests, the fire would typically continue for no more than 15 minutes before self-extinguishing. If an initial period of smoldering combustion were included, then a maximum time interval on the order of 30 minutes during which actual combustion takes place might be expected.

If a fire suppression agent is involved, it may be applied though a fixed general area system, a fixed local system, or through manual intervention. If manual suppression methods are employed, the most likely approach would be application of a hand-held extinguisher. Since this scenario involves an electrical equipment fire, the most likely suppression agent would be CO_2 or dry chemical. Water might also be used to suppress such a fire, but only if the particular area were protected by a fixed fire suppression system triggered by either area or in-cabinet smoke detectors. Note that both water and dry chemicals would be less likely agents given current plant practice. (Even a cross-zoned detection system would be likely to actuate in this situation.) In this case, the components might also experience an increase in humidity to essentially saturation conditions, but would not likely be subject to direct sprays.

Plant areas subject to this type of fire would be any area that houses electrical control panels. Of particular interest to the current study, this would include the main control room and the remote shutdown areas. Also of potential interest might be areas immediately surrounding the containment structure in which one might find electronic multiplexing equipment.

2. Quantity of Combustible Materials Involved

In this scenario, the fire is postulated to remain confined to a small subset of a single electrical control panel. Hence, the quantity of material burned will be relatively small. However, the smoke is also assumed to remain largely confined to the fire cabinet itself, and hence, the volume of air into which the combustion products are distributed is similarly small.

In general, there are three types of control panels used in the nuclear industry. These are vertical, benchboard, and console type cabinets [7]. A wide variety of cabinet sizes are used, depending on the particular application. In general, a typical single electrical control panel may have a volume ranging from about 30 to 300 cubic feet. Much larger cabinets may also be encountered, although beyond this limit, it is relatively common to employ some form of internal partitioning. Cabinets may also have either open back or closed back designs. For the purposes of this scenario, it will be assumed that the cabinet has a closed back. In this case, the cabinet will typically be equipped with open air flow louvers which allow for the natural ventilation of the cabinet.

The fuel loadings contained within a control panel may also vary widely [7]. Some cabinets, such as switchgear, motor control center, and breaker cabinets, will have minimal combustible fuel loads. However, those panels associated with instrumentation and control will typically have much higher fuel loads due to the concentration of control and instrumentation wires and components within the cabinet.

In the SNL cabinet fire test program [7,8], fuel loads were calculated on the basis of the heat content of the available fuel per unit of floor area in the cabinet (MJ/m^2 or Btu/ft^2). The fuel loadings that were tested were based on an extensive review of industry practices. The maximum fuel loads for control panels were determined to be 258 MJ/m^2 (22,700 Btu/ft^2) with a typical load determined to be 170 MJ/m^2 (15,000 Btu/ft^2).

For the purposes of this program, it is of greater interest to express these values in terms of the fuel mass per unit volume of enclosed cabinet space. These values can be "re-normalized" by assuming two values. First, the "typical" heat of combustion for a cable insulation material used in the SNL study was 30 kJ/g. Second, a typical cabinet was identified in that same study as having a height of approximately 2.3 m (7.5'). Using these values, one can calculate that the maximum fuel load in a control panel would be approximately 3.7 kg/m^3 (0.23 lb/ft^3) and a typical fuel load would be approximately 2.5 kg/m^3 (0.15 lb/ft^3).

As discussed above, in the scenario involving a limited in-cabinet fire, it is assumed that from 1 to 15% of this fuel will be consumed in the fire. Using these values the range of fuel burned per unit volume of affected air space (in this case, the cabinet air volume) can be determined. For a cabinet with the maximum fuel load, values ranging from 0.038 to 0.56 kg/m^3 (0.0024-0.035 lb/ft^3) are obtained. For the typical fuel load, values ranging from 0.026-0.38 kg/m^3 (0.0016-0.023 lbs/ft^3) are obtained. Hence, the range of fuel loadings recommended for testing to simulate this scenario is from 0.026 to 0.56 kg/m^3 (0.0016-0.035 lb/ft^3).

Note that in calculating these values the effects of natural circulation through the cabinet have been ignored. Such circulation would be expected to dilute the smoke to some extent, although the rate of dilution is unknown. The values obtained assuming that no dilution takes place would represent a conservative upper bound value.

C. *Large Electrical Control Panel Fire*

1. General Scenario Description

In the second scenario of interest, it is postulated that a large fire occurs within an electrical control panel, but that the fire remains confined to that one panel. This fire would be the type experienced in certain of the fire tests performed by SNL as a part of an experimental investigation of electrical control panel fires [7,8]. This type of scenario has been postulated as representing the most severe fire that might be experienced in the main control room, for example [9]. Such fires might also be experienced in other plant areas as well [12].

In this scenario, it is postulated that a fire has been ignited through either a small transient fuel source or through an electrical fault. However, in contrast to the small cabinet fire scenario, it is postulated that the fire grows beyond the initial ignition source, and eventually consumes all of the combustible materials within the cabinet in the fire. In the SNL tests, growth times from the onset of open flaming to peak fire intensity of approximately 10 to15 minutes were experienced for fires of this type. Total fire duration of from 15 to 30 minutes were recorded before all of the available fuel was consumed. (No fire suppression attempts were employed in these tests.)

In this scenario, the most important aspect of the smoke exposure question will be associated with the equipment located in the balance of the fire area, rather than that housed within the burning cabinet itself. That is because it is postulated that a relatively large fire has occurred, it would also be postulated that all of the equipment within the fire source cabinet would be destroyed by direct thermal exposure. Hence, the smoke exposure question would be associated with the balance of the equipment within the affected fire area. This equipment might experience only a modest increase in temperature, but may experience significant and extended smoke exposures [9,10].

In this scenario, the most important aspects of the fire will be those associated with growth of the fire and fully developed fire stages. Ignition may involve initial smoldering followed by open flaming, but in terms of the overall fire area exposure, the smoke generated during this stage will be relatively unimportant. Once open flaming begins and the fire begins to grow, however, the enclosure environment will rapidly deteriorate, and a dense layer of smoke is likely to form in the room as a whole. In testing, it was observed that the smoke layer descended to the floor of the test enclosure within approximately 6-12 minutes of ignition [10].

Once the fire becomes fully developed, it is also likely that a period of oxygen-limited combustion may be experienced. This would generally result from local ventilation effects associated with the burning cabinet itself, rather than global oxygen depletion within the overall fire area. This effect may be particularly pronounced for cabinets which have closed doors so that only limited natural ventilation opening are available. Hence, in the fully developed stages of the fire, a relatively inefficient combustion process may be experienced, resulting in the generation of significant amounts of soot and other unburned pyrolysates.

The methods likely to be employed in the suppression of such a fire would depend on the area in which such a fire occurred. For example, if the fire occurs within the main control room, then manual suppression by operators using hand-held extinguishers or by the fire brigade is the most likely response. Fixed fire suppression systems are very rarely installed in the main control room. For other plant areas, either manual response or fixed fire suppression system response may occur. Hence, these fires would be subject to the full range of potential suppression agents (see further discussion of suppressant interactions in Section 4 below).

2. Quantity of Combustible Materials Involved

The large cabinet fire scenario involves a fuel source quite similar to that discussed in Section 3.3.2 above, except that a full involvement of the cabinet is expected. In particular, the control panel fuel loads which have been described above would also apply to this scenario. The maximum fuel loading which was cited in the SNL study [7,8] was a total fuel heat content of 1.53×10^6 kJ (1.47×10^6 Btu). Again using a nominal cable heat of combustion value of 30 kJ/g, this heat content value corresponds to a fuel mass loading of 51 kg (112.2 lb). Using a similar procedure, the minimum fuel loading utilized in any test which was intended to represent a full control panel mockup was approximately 25 kg (55 lb). (Note that other tests did involve lighter fuel loads, but that these tests were intended to assess specific aspects of cabinet fire growth behavior and did not represent full cabinet mockups.) These values will be used to represent the minimum and maximum amounts of material which would be expected to burn under the conditions set forth for this fire scenario.

The second aspect of this fire scenario which must be quantified is the volume of space into which it is expected that the combustion products would be dispersed. For this scenario, the smoke is assumed to remain confined to the room that houses the burning cabinet. Unfortunately, the volume contained in a typical nuclear plant fire area can vary widely. The range of consideration can be reduced somewhat by considering only those areas likely to be of interest in the context of this scenario. This would include the main control room, auxiliary shutdown area, switchgear rooms, and potentially cable spreading areas (many cable spreading rooms will include various electrical panels).

In 1985 Brookhaven National Laboratory (BNL) performed a study to assess the typical size and configuration of nuclear power plant enclosures.[1] Three types of generic enclosures were identified; the vault, corridor, and bay areas. Of these, the vault configuration is of interest here because it included those types of areas identified as relevant to the current study immediately above. Based on a statistical sampling of 80 vault-type rooms at 8 different power plants, BNL determined that the mean configuration of an enclosure of this type was a rectangular room measuring 24.4x12.2x6.1 m (80x40'x20') (LxWxH). Therefore, the volume of a typical enclosure would be 1816 m^3 (64,000 ft^3).

Using this room volume as representative, a range of fuel mass to air volume ratios can now be calculated. Based on consumption of the minimum cited cabinet fuel load from the SNL tests, a value of 14 g/m^3 (8.7×10^{-4} lb/ft^3) is obtained. Using the maximum full cabinet fuel load cited yields a value of 28 g/m^3 (1.7×10^{-3} lb/ft^3).

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[1] This information was gathered as a part of an NRC-sponsored fire model development and validation effort undertaken during the 1985-1987 time frame. The information was communicated by BNL to the USNRC and SNL through internal memoranda, and through presentations at working group meetings. SNL retains copies of this documentation.

Note that in developing these fuel mass to air volume ratios, it has been assumed that the ventilation system will not dilute the smoke exposure. This assumption is appropriate for general plant areas where the normal ventilation system would typically be shut down automatically upon fire detection. However, this assumption would not reflect the conditions that would prevail in the main control room where the ventilation system would likely be placed in a full exhaust, emergency smoke purge mode of operation. In this case it would be appropriate to assume that some dilution of the smoke would occur. A typical control room ventilation system will provide a smoke purge mode ventilation rate of approximately 10 room air changes per hour [11]. Hence, for a 15-30 minute fire scenario, it would be appropriate to assume that the smoke would be diluted by a factor of approximately 2.5-5. Incorporating these values into the above estimates of fuel mass to air volume ratio yields control room scenario values of from 2.8 g/m^3 (1.7×10^{-4} lb/ft^3) to 11.2 kg/m^3 (7.0×10^{-4} lb/ft^3).

D. General Fire Area Scenarios

1. General Scenario Description

In addition to the large electrical control panel fires, one might also expect that significant room-wide smoke exposures could also occur as a result of a more generalized fire within a fire area. In this case, the most likely materials to be involved would be electrical cables (see further discussion of likely fuel sources presented below). Fires may also involve an initial transient fuel or electrical panel fire which then spreads to nearby electrical cables.

The parameters of a fire of this type would be quite similar to those discussed above for a large electrical panel fire. Differences might include somewhat larger and longer lasting fires, and higher enclosure temperatures. Thus, a more severe smoke exposure environment might be experienced. As with the large electrical panel fires, the full range of fire suppression systems utilized by the industry may come into play in such a fire. In particular, the use of water for a more generalized fire would be much more likely than in the case of the large electrical panel fire.

Most any fire area in the plant would be subject to fires of this type [12]. The one exception would be the main control room. That is, the main control room is unique in several ways which will significantly reduce the likelihood of a large generalized area fire occurring. First, the main control room is continuously manned, and hence, very rapid fire detection and intervention times are expected. This will also imply that a transient fuel source will be very effectively controlled and limited. Second, high-energy electrical equipment is not typically housed in the control room, and hence, the number of potential high energy fire sources is very limited. Based on these factors, the occurrence of a large, generalized fire in the main control is not considered likely, and hence, this scenario would not generally be considered applicable to the main control room.

2. Quantity of Combustible Materials Involved

In this case, the quantity of combustible materials involved would include both the transient combustibles if such fuels are involved, and the *in situ* fuels. A wide range of fuel involvement levels is possible. Recall that this scenario is associated with general area fires which are of sufficient size to present a smoke exposure threat to the entire fire area. The objective here, then, is to establish reasonable upper and lower bounds on significant general area fire fuel consumption values. Hence, very small fires will not be considered because they are unlikely to produce sufficient quantities of smoke to represent a threat to an entire fire area.

As a rough estimate, the minimum fuel involvement for a significant general area fire will be assumed to correspond to the minimum fuel loads cited above for the full-simulation cabinet fire tests. Recall that the minimum full-simulation cabinet fuel load evaluated in the SNL cabinet fire test program was 25 kg (55 lb). Note that the peak heat release rate measured by SNL for this particular test was approximately 840 W [8]. However, in the cabinet fire test program, a significant fire intensity enhancement occurred due to the containment of some of the fires' heat output within the cabinet and radiative feedback from the heated cabinet surfaces [7,8]. In an open fire configuration, the same fuel configuration would not benefit from the enhanced feedback, and might be expected to yield a peak heat release rate on the order of 500-600 kW, a reasonable lower bound intensity for significant fires.

For the upper bound, it would be appropriate to consider a fire that might involve a stack of cable trays, perhaps in addition to a electrical panel fire as an initiation source. Hence, as an upper bound, one might consider a fire involving the maximum full-simulation cabinet fire loads cited above, in addition to supplemental fuel from overhead cable trays. The amount of overhead cable fuel that might become involved in such a fire could, again, vary widely depending on the plant-specific conditions which prevail. As a rough estimate, it will be assumed that an additional cable tray fuel load equal to that available in the cabinet might become involved. Hence, the upper bound fuel consumption will be set at twice that cited above for the most heavily loaded of the full-simulation cabinet fire tests. This would correspond to 102 kg (224 lb) of fuel.

In the assessment of the typical enclosure volume into which the fire products might be distributed, the same arguments presented above would also directly apply to this scenario. Hence, a typical enclosure of the type of interest here will be assumed to have a total volume of 1816 m^3 (64,000 ft^3). Based on these values, the lower bound on fuel mass to air volume ratio for the significant general area fire scenario would be the same as the lower bound cited above for the large cabinet fire in the absence of ventilation dilution effects, 14 g/m^3 (8.7×10^{-4} lb/ft^3). The upper bound value would correspond to 56 g/m^3 (3.4×10^{-3} lb/ft^3).

Note that these values include no consideration of ventilation system diluting effects. In this case, the scenario is not considered applicable to the control room, and hence, ventilation shutdown would be expected. No additional dilution due to ventilation effects would be recommended for this scenario.

E. Smoke Spread from an Adjacent Fire Area

The final fire threat scenario of potential interest would involve the spread of smoke from one fire area into an adjacent fire area. The most likely paths for such spread would be transport through ventilation ductwork (should the fire dampers not close), or transport through doorways that might be opened for manual fire fighting and post-fire recovery access.

In this fire scenario, the fire source could be either the large cabinet fire or the general area fire as discussed above. However, in this case the smoke exposure would involve a lower density of smoke, and a reduced thermal threat. Fire suppressant interaction would also be less important because the adjacent area components would not be subject to direct application of fire suppressants unless a spurious actuation of a fixed fire suppression system in the adjacent area were to occur. Components might be subjected to very high levels of humidity, however, if water is used to fight the fire in the adjacent space.

For this scenario, a significant dilution effect would be expected. That is, as the smoke spreads from the room of fire origin, it would mix with the fresh air in the adjacent space. Under conditions in which both rooms became equally involved in the spread of smoke, a doubling of the affected air volume would occur (assuming the rooms are essentially the same size). Hence, dilution of the general enclosure fuel mass to affected air volume ratios cited above by a factor of 2 would be appropriate. This would yield values ranging from 7 g/m^3 ($4.3x10^{-4}$ lb/ft^3) to 28 g/m^3 ($1.7x10^{-3}$ lb/ft^3).

F. Summary of Scenario Fuel Mass to Air Volume Ratios

For each of the fire scenarios identified, a range of values on the anticipated fuel mass consumed to affected air volume ratio has been provided. Table 1 summarizes these results.

Note that by far the most severe ratios are associated with the localized effects within an electrical control panel due to a small electrical fire occurring within that cabinet (the small cabinet fire scenario). This results primarily from the fact that a very small volume of space (that within the cabinet only) is assumed to be involved in the distribution of smoke. Hence, relatively large fuel mass to affected air volume ratios are predicted, despite the fact that as little as 5% of the cabinet fuel load is assumed to burn.

In contrast, the least severe exposures are those associated with a large cabinet fire occurring within the main control room. In this scenario, it is postulated that the smoke generated by the burning of a single control panel is distributed throughout the full room

Table 1. Summary of recommended fire scenario fuel mass to affected air volume ratios.

Scenario (affected area)		Fuel mass to affect air volume ratio	
		Lower Bound	Upper Bound
Small Cabinet Fire (in-cabinet effects)		26 g/m^3 1.6x10^{-3} lb/ft^3	560 g/m^3 3.5x10^{-2} lb/ft^3
Large Cabinet Fire (room effects)	Control Room	2.8 g/m^3 1.7x10^{-4} lb/ft^3	11.2 g/m^3 7x10^{-4} lb/ft^3
	General Areas	14 g/m^3 8.7x10^{-4} lb/ft^3	28 g/m^3 1.7x10^{-3} lb/ft^3
General Area Fire (room effects)		14 g/m^3 8.7x10^{-4}lb/ft^3	56 g/m^3 3.4x10^{-3} lb/ft^3
Adjacent Area Fire (room effects)		7 g/m^3 4.3x10^{-4}lb/ft^3	28 g/m^3 1.7x10^{-3} lb/ft^3

air volume and that the ventilation system would continue to operate in an emergency smoke purging mode. The high rates of air exchange associated with this mode of control room ventilation system operation would significantly dilute the smoke exposure, even though a smoke layer would still be expected to form.

The difference between the lower and upper bounds for all of the cases cited represents a factor of 200. That is, the overall lower bound cited is 2.8 g/m^3 (1.7x10^{-4} lb/ft^3) and the overall upper bound cited is 560 g/m^3 (3.5x10^{-2} lb/ft^3). This wide range of values reflects the wide variability in the types of fire scenarios which might be encountered, and is considered representative of actual plant conditions. As a result, it is recommended that a very wide range of fuel mass to test enclosure air volumes be evaluated to ensure that this wide range of anticipated behavior is assessed.

IV. Identification and Characterization of Critical Smoke Quality Parameters

A. Overview

The issue of smoke quality is the issue of the chemical composition of the smoke, including the changes in composition that might take place during the processes of generation, transport, and deposition. As discussed above, the definition of smoke quality will be significantly affected by the general lack of knowledge regarding the chemical nature of smoke. Hence, in this study, smoke quality will be addressed through the definition of the source of the smoke and through identification of potential transport and suppressant interactions that might alter the nature of the smoke exposure.

Consistent with this approach, those parameters which are considered critical to the proper characterization of smoke quality are identified in the following subsections. In particular, the following parameters are discussed in detail below:

- the type of material burned,
- the mode of combustion experienced,
- suppressant interactions, and
- transport interactions.

B. Type of Materials Burned

Perhaps the most critical parameter in the determination of smoke quality will be the nature of the material(s) which is(are) actually burned. A variety of combustible materials are likely to be encountered in a nuclear power plant fire. The smoke generated by different materials will be inherently different. That is, while virtually all the materials of interest will produce some quantity of carbonaceous soot, the balance of the smoke chemical composition will vary widely. The range of potential chemical combustion products will depend on the chemical composition of the burning material(s). In general, the combustible materials of interest in a nuclear power plant can be divided into four fuel categories; namely, combustible gases, liquid fuels, solid transient fuels, and solid *in situ* fuels.

1. Combustible Gases

Combustible gases are often present in a power plant. The most common would be hydrogen which is present as both a component coolant (particularly as a turbine-bearing coolant), and as a by-product of the reactor operation (through dissociation of water). Many fire events have involved combustible gases, and particularly hydrogen fires and explosions [12].

However, in terms of the generation of smoke and the threat to plant equipment represented by that smoke, the importance of combustible gases is minimal because these fuels tend to be very clean burning and introduce no exotic chemical species into the combustion products. Hence, while such fires may generate significant quantities of smoke, the smoke generated by the combustible gases themselves will generally be composed of relatively "clean" carbonaceous soot. Such soot will not likely result in a significant threat to electronic equipment because of the minimal potential for corrosive attack or creation of electrical short circuit paths. Some difficulties with contact pair fouling and restriction of fine mechanical movement can be anticipated, but as discussed above, these degradation modes are not considered critical for advanced electronic components.

The importance of combustible gases as a fuel is much more significant if they are a source of fire exposure for the other *in situ* fuels that might become involved in such a fire. Even issues of fire suppressant interactions are of secondary concern because virtually all of the fires that have involved combustible gases have been controlled by simply isolating the source of the gas [12]. The remaining concerns would center on any other local fuel source, as discussed below, which had become ignited during the initial gas fire. The smoke threat to electrical equipment represented by the direct combustion of gaseous fuels is not considered significant and will not be discussed further.

2. Liquid Fuels

Liquid fuels would include such items as lubricating and cooling oils, cleaning solvents, and diesel fuel. These items are commonly used in pumps, hydraulic-operated equipment, diesel-driven motors, and other equipment requiring lubrication. Fires involving such fuels are relatively common for plant areas housing such equipment (generally due to leakage problems) [12]. These types of materials are generally composed of relatively simple chemical species, primarily hydrocarbons. Hence, the smoke generated by fires involving such fuels will be composed largely of carbonaceous soot. The only other significant chemical species that might be evolved would be associated with any additives included in the material's formation. Such additives are relatively uncommon for most fuels of interest and hence invasive chemical compounds are not likely to be produced during their burning. Based on these observations, conclusions similar to those cited above for gaseous fuel sources would apply to liquid fuels as well, and no further consideration will be given to such fuel sources.

3. Transient Fuels

Solid transient fuels would include general trash, paper waste, wood, plastics, cloth, etc. These fuels can generally be found in small quantities in most plant areas at any given time. However, plant fire protection procedures typically will include administrative controls that actively limit the extent to which such items are allowed to accumulate within critical plant areas. While the smoke from transient fuel fires may contain a variety of chemical species (depending on the exact materials present at the time of the fire), fires involving such fuels will generally be limited in both extent and duration. Due to the limited availability of such fuels, a fire that remains limited to transient fuels is unlikely to produce sufficient quantities of smoke to result in short-term equipment damage problems. Because of these factors, conclusions similar to those cited above for gaseous fuels would also apply to transient fuels. In this case, the transient fuels would be considered of secondary importance, and would be of interest primarily for the extent to which they represent a potential fire exposure source for the other *in situ* fuel items.

4. *In situ* Solids

The final, and by far most important, category of fuels is the *in situ* solid fuel elements. Of these materials, the majority will be in the form of cable insulation and jacketing materials. Several factors combine to support a conclusion that cable insulation and jacketing materials will represent far and away the most important materials to be considered in assessing a smoke threat to electrical equipment. Of secondary interest will be the materials used in the construction of the other types of electrical components (including phenolics and other types of hardened plastics).

A variety of cable insulation materials are commonly employed in the nuclear industry. Each of these materials is likely to introduce unique constituents when burned. Hence, it is expected that testing might be expected to involve both individual materials assessed on a relative basis, and the use of combinations of materials to assess potential synergistic effects. Cable insulations popularly applied in the nuclear industry include materials based on the following compounds [13,14]:

- Cross-linked polyolefin (XLPO) (including the more specific class of cross-linked polyethylene (XLPE))
- Polyvinyl chloride (PVC)
- Ethylene-propylene rubber (EPR)
- Chlorosulfonated polyethylene (CSPE or Hypalon)
- Teflon
- Silicone and silicone/rubber compounds

Virtually any significant fire scenario in a nuclear power plant will involve cable insulation materials to some extent. In particular, those fire scenarios expected to result in the exposure of advanced electronic components are likely to involve the burning of cables. This would include control room and remote shutdown area fires, and fires associated with electrical penetration areas of the containment structure where signal processing and multiplexing systems are likely to be located [15]. Hence, cable insulation and jacketing materials are considered the single most important class of fuel to be considered in this program. Most of the other materials used in plant construction are noncombustible.

The importance of cables as a threat to electronic equipment also derives from the nature of the smoke produced in a cable fire. Today cable insulation and jacketing materials are generally composed of either rubber-based, silicone-based, or polymer-based materials. Typical production processes for multiconductor cables will also include some type of physical binding material such as nylon or cellulose strands or a cellophane-type overwrap. In the formulation of cable insulations, a wide range of chemical species are added for use as plasticizers, aging performance enhancers, and fire retardants. Fires involving cable insulations are particularly "dirty" in comparison with fires involving other types of fuels because these various chemical species are also liberated during the fire. Of particular concern, a variety of acid gas species are likely to be produced during any such fire due to the wide use of halogen additives [chlorine (Cl), fluorine (F), bromine (Br), iodine (I), etc.] as fire retardant agents. The extent of chemical production is dependent on the specific chemical composition of a particular cable.

For example, polyvinyl chloride (PVC) materials are composed of as much as 40% by weight chloride. This chloride is released during a fire, and much of it eventually becomes bound to the soot particulates in the form of soluble chloride ions [1]. Upon contact with water, a hydrochloric acid (HCl) solution is readily produced. While PVC is no longer popularly used as a cable insulation for new applications, it is commonly present in most areas of nuclear power plants constructed prior to 1980. (PVC fell out of favor in the U.S. nuclear industry as a result of the 1975 Brown's Ferry fire and the ensuing regulatory actions.)

For other cable insulation types, other chemical species will be of predominant concern. It is expected that these acidic combustion products will play a key role in the problem of smoke damage to advanced types of electrical equipment. This role will likely involve both direct corrosive attack on the components and the formation of electrical current leakage or shorting paths as discussed above.

The presence of these varied chemical species can also lead to interactions of the smoke with other materials in the plant. For example, experience in the telecommunications industry [6] indicates that the interaction between acidic smoke from a cable fire and galvanized ventilation ducts can result in the formation of galvanic salts, which can in turn be deposited on electrical equipment. This has been identified as the source of significant nonthermal fire damage in this industry. (This issue is discussed further below as associated with transport issues.)

Further, fires involving cable insulation materials are typically low-efficiency fires. That is, due to the nature and the arrangement of fuel, the fires produced are inefficient in converting fuel to heat. This means that the combustion process results in the release of many intermediate combustion products (see further discussion of burning mode effects below). These products are often composed of relatively massive molecules that agglomerate easily, accelerating the process of surface deposition. Hence, the accumulation of tar-like deposits has been noted in cable fire tests [13].

The final class of *in situ* solid fuel which is also of potential interest would be those materials used in the construction of other types of electrical equipment. In particular, those materials used in the construction of such items as printed circuit boards, relays, switches, indicators, plastic cable routing devices, wire ties, and cable splicing connectors are also generally composed of a variety of polymeric materials. These materials are also likely to produce a relatively aggressive form of smoke when burned, although relatively little information on the burning of these materials is currently available.

5. Material Identification Conclusions

Based on these considerations, it is concluded that, far and away, the most significant threat of smoke damage to electrical equipment will be associated with the burning of cable insulation and jacketing materials. This conclusion is based on both the dominant role cables play in the overall plant combustible fuel load, and on the nature of the combustion products expected. Of secondary importance are other materials use in the construction of other types of electrical equipment.

C. Combustion Mode

When materials burn, that burning can take place in different ways. In particular, burning has classically been divided into open flaming and smoldering modes of combustion. Open flaming is generally the more efficient mode of burning and is typically associated with more volatile fuels, larger fires, and higher temperature fires. Smoldering is generally a less efficient mode of burning, and is often associated with less volatile fuels, lower temperature exposures, and either the very early or late stages of a fire event. Smoldering combustion will also dominate the early stages of an electrical fire initiated through component failure.

However, in the consideration of the smoke threat, it would also be useful to consider the impact of oxygen availability on fire burning. That is, fires can also be classified in terms of fuel surface controlled and oxygen-limited fires. In a fuel surface-controlled fire, the rate of combustion is limited only by the quantity of fuel that has actually been ignited. In oxygen-limited burning, the fire intensity will be limited to that which the available oxygen can support. In general, a fuel-surface controlled fire is associated with more efficient burning. Oxygen-limited burning may occur during the later stages of a fire, and a decrease in combustion efficiency will typically result. Oxygen-limited burning conditions may prevail as a result of either limited availability of oxygen in the fire area as a whole, or due to more localized ventilation limitations. For example, a closed electrical control panel in which a significant fire occurs is likely to involve oxygen-limited burning even though the room as a whole may be well ventilated.

Both of these factors, flaming versus smoldering and fuel surface versus oxygen-limited burning, are expected to affect the type of smoke generated during a fire. For example, the overall efficiency of the fire will determine the extent to which combustible compounds are actually oxidized. Fires with low burning efficiencies will result in many unburned pyrolysates being generated. This can be a very important factor because these unburned pyrolysates tend to be relatively heavy (dense) compounds and will quickly deposit onto the available surfaces, including the electronic components. In a high-efficiency fire, the products of combustion will be more heavily dominated by gaseous species such as CO_2, CO, and water vapor. One would also expect the particulate in a high-efficiency fire to be dominated by carbonaceous soot, which is likely to remain airborne much longer.

The effects of open flaming versus smoldering may also be important beyond the question of combustion efficiency. Under open flaming conditions, it would be expected that virtually all of the combustible material would be burned over a relatively short period of time, and much more of the carbonaceous material would be liberated as airborne gases and soot. This would imply that all of the chemical species likely to be generated would be generated simultaneously making subsequent chemical interactions more likely. Under smoldering fire conditions, the material will burn much more slowly with the most volatile compounds liberated first. A larger fraction of the carbonaceous material would likely remain as char as well. Unfortunately, the more volatile compounds include the plasticizing and flame retardant additives that are likely to result in significant production of acid gas.

As a result of these anticipated differences, it is recommended that investigations be undertaken to assess the impact of burning mode on the smoke threat. That is, each mode of combustion is likely to result in a somewhat different smoke threat, and it is not clear which mode might be most significant. Controlled tests should be performed to explore each mode to ensure that the most significant mode of combustion is identified and understood.

D. Suppressant Interactions

In most fire events, some form of active fire suppression is likely to come into play. The most commonly applied suppressants in the nuclear industry are water, water-based foams, and carbon dioxide (CO_2). Each of these types may be used in either hand-applied devices (hose streams, fire extinguishers, and hand-held CO_2 discharge nozzles) and in fixed fire suppression systems (area coverage and directed spray systems for the water-based systems and room flooding or local discharge systems for CO_2). Also commonly encountered are hand-held fire extinguishers that use dry chemical powder. This is a fire suppression agent often used to fight electrical equipment fires. Each of these systems represents a unique potential for interactions involving combustion products. To a much lesser extent, Halon systems may also be used.

1. Water-Based Suppressant Interactions

For the water-based systems, the obvious effect will be to increase the general humidity levels within the fire area to near saturation levels. The suspended droplets can act as agglomeration points for the soot in the air and hence can lead to an increased rate of soot deposition on exposed surfaces. Moisture droplets will also form on the various exposed surfaces, including the surfaces of the advanced electronic components. Due to the highly hygroscopic nature of acid gas molecules, the deposited moisture will then act to scavenge acid gas molecules from the environment, creating liquid acid deposits. These acidic deposits can cause direct corrosive attack, and can create short circuits and circuit bridging faults. Hence, the interactions with moisture are expected to be a general increase in the rate of soot deposition, and the formation of liquid acid deposits.

2. Carbon Dioxide Suppressant Interactions

For CO_2 systems there are three potential modes of interaction that might be observed. First, the discharge of a CO_2 system can introduce very high levels of static electric charge on surfaces that are not fully grounded. Such static charges may induce very large current surges, which could easily destroy solid-state chips (note that even relatively mild static charges can cause failures in various types of solid-state chips). This potential may be enhanced by smoke deposits, which can partially bridge circuit paths. Second, the discharge of CO_2 will introduce a pronounced and very abrupt cooling effect. This would be expected to lead to water vapor condensation and the formation of moisture droplets, or even frost, as surface deposits. Third, the increased concentration of CO_2 gas could result in the formation of carbonic acid in surface moisture droplets. Carbonic acid is an aggressive, albeit short-lived, corrosion agent that might aggressively attack circuit components. This aggressive attack, when combined with smoke, might increase the vulnerability of circuit components to damage.

3. Dry Chemical Powder Interactions

Dry chemical powder is a suppression agent which is commonly used to fight electrical equipment fires. It is one of the most commonly encountered fire suppressant agents used for hand-held extinguishers. Hence, its use in fighting smaller electrical fires is quite likely.

Dry chemical powder is generally considered an aggressive corrosion agent. Often, electrical equipment sprayed with dry chemicals will be destroyed in a relatively short time if it is not cleaned. Hence, it is likely that dry chemical powder may introduce a significant threat to electronic equipment in and of itself. In addition, it may introduce synergistic interactions with the smoke deposition, which might accelerate the rate of component degradation.

It is recommended that some tests be performed to assess the potential for synergistic effects involving fire-fighting powders. However, because the powders themselves represent a potential threat to electronic equipment, it may be necessary to test such materials in the absence of smoke to determine whether synergistic effects with the smoke exposure are significant. Hence, testing in both the presence and absence of a smoke exposure is recommended.

4. Halon Suppressant Interactions

To a lesser extent Halon is also used as a fire suppressant by the nuclear industry. Halon is a fluorocarbon compound with a particularly high Br content. It is well known that when it is discharged into a high-temperature environment, or brought into contact with high-temperature surfaces, Halon will break down, releasing this Br as an acidic gas. Hence, an increased acid attack potential could be introduced by Halon release. In addition, Halon discharge will result in a pronounced localized cooling effect, though not as severe as that expected for CO_2 discharge. However, it is not recommended that an experimental investigation of Halon and smoke interactions be undertaken at this time. Halon has been identified as an ozone threat, and hence, it being phased out of all use in response to international accords on the protection of the ozone layer. It is anticipated that the use of Halon in nuclear power plants will become more and more rare in the near future, and the importance of Halon as a fire suppressant will be largely negated. It should be noted that efforts to find a replacement for Halon are being pursued by various industrial concerns. Should such replacements be brought to the market and find application in the nuclear industry, then the new materials should be reviewed to determine whether an investigation of potential adverse effects might be warranted.

E. Transport Interactions

The transport of smoke from the fire source to the component of concern is an important aspect of the smoke quality definition. This transport may take place through simple passive spread of the smoke within the fire cabinet or fire area, or through the local ventilation and air-handling systems. There is one important potential interaction associated with this transport process which should be considered. That is, chemical interactions may take place between the smoke and the various surfaces involved in the movement of smoke from one location to another.

In many fires involving cables in communications facilities [6], it has been observed that the acidic smoke will interact with galvanized metals, resulting in the formation of galvanic salts. These salts are hygroscopic and in a humid environment, can attract water from the air, forming a liquid zinc chloride solution. This solution can run or drip onto electronics. Once these deposits form on a component, an aggressive and debilitating attack will begin. In a nuclear power plant, extensive galvanized metals will typically be present. This will certainly include the cable trays and conduits, and may also include certain of the electrical control panels themselves. Ventilation air handling ducts are also typically constructed from galvanized sheet metal.

Testing should be performed to assess this interaction. It is recommended that sheets of galvanized metal be place within the test enclosure during some of the controlled tests. Placement of metal platens in the general smoke environment should be sufficient to simulate interactions remote from the fire source, such as those that might occur with air-handling ducts. It is also suspected that elevated temperatures might significantly increase the rate of these interactions. Hence, it is recommended that some of these tests be performed with the metals in close proximity to the actual fire source in order to simulate situations in which, for example, the burning cables are housed in galvanized cable trays or in close proximity to galvanized conduits.

F. Summary of Smoke Quality Insights

The issue of smoke quality has been approached by defining those factors considered important in determining the nature of the smoke to which components would be exposed in a nuclear power plant fire. It is anticipated that by reproducing these factors in the laboratory, a representative smoke exposure will result, even if the *a priori* knowledge of the smoke composition remains poor.

The first factor identified was the type of materials that are likely to be burned. Cable insulation and jacketing materials were identified as the single most important material based on both their dominance of the *in situ* plant combustible fuel loads and on the nature of the smoke produced when these materials are burned. Of secondary importance were other types of polymeric materials used in the construction of general electrical and electronic equipment. Other fuels, including combustible gases, liquid fuels, and transient fuels, were considered of minimal concern based on the limited quantities present in a plant and/or based on the relatively "clean" nature of the smoke such fuels produce (i.e., gases and liquid fuels in particular will generally produce a smoke composed primarily of carbonaceous soot).

A second factor identified was the mode of burning. It was noted that factors particularly associated with the efficiency of the fuel burning are expected to significantly affect the nature of the smoke produced. Incomplete combustion products are expected to result in more massive smoke particles, more varied chemical species, and faster deposition onto exposed surfaces. It was recommended that testing be performed to encompass a range of fuel burning conditions including smoldering, open flaming, and oxygen-limited combustion.

Suppressant interactions were also identified as a potential issue. In particular, likely synergistic interactions associated with water-based suppressants, CO_2, and PKP powder were discussed. Testing to assess the importance of these interactions is recommended.

Finally, it was noted that experience in the telecommunications industry has indicated that the interaction of acidic combustion products with the surfaces of galvanized metals can result in the generation of galvanic salts that can be readily deposited onto exposed surfaces. Based on the wide use of galvanized metals, it is recommended that testing be performed to assess this issue.

V. Duration of Smoke Exposure

A. Overview

In considering the duration of smoke exposure, two time periods are relevant. First, the period of time required to detect and suppress the fire, and to then remove the smoke from the fire environment will determine the time during which the component is directly exposed to the smoke-filled environment. Second, the extent and timing of post-fire equipment recovery actions will determine the extent to which a post-fire equipment exposure threat will continue. Each of these two time periods presents the potential for equipment damage.

In terms of the direct impact on fire risk, the earlier period, that period during the fire itself, will be of primary concern. In general, the dominant fire risk scenarios are relatively short lived and take place during a 1 hour or less [9]. Hence, the short-term equipment damage questions are of primary concern. However, longer term damage questions should also be considered. That is, one of the questions that should be addressed as a part of this program is the potential that smoke deposition might lead to component failures at some time after the fire. The following subsections discuss various aspects of the exposure duration question during each of these time periods

B. Smoke Purge Time

In the first case, the time required to purge the smoke from the environment, a wide range of exposure duration times should be expected. These will be directly related to the magnitude of the postulated fire event, and would be significantly affected by such factors as the availability of detection and fixed fire suppression systems.

The shortest time frames expected for smoke purging would be associated with the small cabinet fires in which the only actions required to remove the smoke would be opening of the cabinet doors and suppression of the fire. In this case, the postulated fire remains quite small and hence no significant smoke accumulation in the general area is assumed. Once the cabinet has been opened, the smoke will dissipate and be handled by the normal ventilation system. Times on the order of 15-30 minutes would be considered typical for such scenarios [12].

The time to purge smoke from the environment would increase as the magnitude of the fire threat increased. For the fire scenarios involving a large cabinet fire and the resulting general area smoke exposure, times on the order of 1 to 2 hours might be expected to fully purge the environment of smoke for general plant areas [8,9]. This includes the time required for manual suppression and for manual recovery of the ventilation system. If the fire is postulated to occur in the main control room, somewhat shorter time frames would be expected, on the order of 30-60 minutes, because faster intervention and continued ventilation system operation are expected.

For scenarios involving generalized room fires and the potential for the spread of smoke to adjacent areas, times of anywhere from 30 minutes to 4 hours might be anticipated. In this case, a very broad range of fire suppression and ventilation recovery times can be expected given the variety in fire threats, fire detection capability, and fire suppression availability which could be encountered [12].

In summary, the minimum time frame required to purge smoke from the environment in the event of a fire is expected to be on the order of 15 minutes. This would correspond to the scenarios involving small in-cabinet fires which are very quickly detected and suppressed. The maximum time required to purge smoke is considered to be on the order of 4 hours. This assessment is based largely on past fire experiences and includes an assumption that manual recovery of the ventilation capability will be required. This would also correspond to the most severe and generalized of the fire scenarios postulated. It is recommended that electronic components be tested to encompass this range of actual smoke exposure durations.

C. *Post-Fire Recovery Times*

Once a fire has been suppressed and smoke has been purged from the environment, a potential still remains that some equipment failures might occur at some time after the fire. Clearly, the extent and timing of post-fire equipment recovery actions will play a critical role. In particular, studies have shown that immediate intervention to reduce ambient humidity levels can minimize the extent of corrosion damage [16]. It has also been shown that much equipment can be cleaned and restored to operation if such efforts are begun shortly after the fire (within on the order of 24 hours of the fire event) [16]. However, it is currently unclear to what extent plant operating procedures provide for such actions to be taken in the nuclear industry.

Hence, it should be expected that an extended period of exposure to smoke deposits may be experienced with only minimal post-fire intervention. This could lead to subsequent unanticipated equipment failures, which might result in triggering of a plant transient.

However, it must also be recognized that, based on the results of past fire risk assessments, the most important fire scenarios from a plant risk perspective occur during time frames of roughly one hour or less [9]. Hence, the issue of longer term exposures will be more important to the question of general post-fire equipment reliability, and considered of secondary concern. Nonetheless, it is recommended that the smoke exposure testing include an assessment of equipment performance over a minimum period of 24 hours.

It is also recommended that, should the scope of work allow, certain of the exposed components be monitored for extended periods of time (on the order of a month) after the exposure. This would provide an additional assessment of the long-term failure potential of smoke-exposed equipment. This approach could also be used to assess the effectiveness of various component cleaning procedures.

D. *Transport/Exposure Duration Interactions*

It should be noted that there is a direct relationship between the issues of exposure duration and smoke transport. That is, the duration of the smoke exposure may be directly affected by the manner in which the smoke reaches the component of interest. If, for example, the component is contained within an electrical panel in which a small fire occurs, then much of the smoke may remain contained within the cabinet for extended periods. If the component is affected by a more generalized smoke layer developed during a larger fire impacting a full room, similarly long residence times should be expected. In contrast, certain fire scenarios may involve only minimal exposure times if, for example, a component is located directly in the path of the fire plume from a relatively small fire. In this case, smoke exposures lasting no longer than the fire itself may result.

The second aspect of the smoke transport/exposure duration issue is that smoke is a dynamic material whose properties will change with time. The smaller smoke particles will agglomerate into larger particles over time, and the larger particles will deposit more quickly than the smaller particles. Also, it has been observed in testing [1,17] that the acid gases generated in a cable fire will become bound to the soot particles in relatively short times (on the order of minutes). Thus, the deposition of soot becomes a mechanism for the deposition of acid products as well. In this case, it is important that the smoke exposure be of sufficient duration to simulate these smoke "aging" effects.

It is recommended that testing be performed to simulate a range of exposure durations. In the ASTM smoke corrosivity standard that is being used as a guide to construction of the smoke test chamber [18] it was specifically intended that a sample of smoke would be captured and held for an extended period in order to assess corrosive smoke potential. A standard smoke exposure period of 1 hour is used. This exposure is expected to represent a reasonable duration for many fire scenarios. However, the period of exposure can be varied by the experimenter with virtually no effort. It is for this reason that this particular standard has been identified as the preferred test "model" for use in this program.

E. Summary of Exposure Duration Times

The recommended range of smoke exposure durations has been addressed in two parts. First is the time period during which the component is actually exposed to a smoke-filled environment. It is recommended that the actual smoke exposure duration used in testing should be varied between 15 minutes and 4 hours to encompass the fire scenarios identified as of interest. Second, the time after exposure to the smoke-filled environment during which the accumulated smoke deposits would continue was assessed. A minimum monitoring time period of 24 hours of functionality is recommended. In addition, it is recommended that some of the components be periodically monitored for functionality for an extended time after exposure. Periodic testing of the exposed components for an extended time (preferably several months) would provide an assessment of the likelihood that component failures could occur a significant amount of time after a fire event. If the scope of work allows, it is also recommended that the effectiveness of component recovery (cleaning) efforts be assessed in this way as well.

VI. Summary of Exposure Characterization Insights

In attempting to characterize credible smoke threat scenarios to which advanced electronic components might be exposed, a number of factors were considered. In general, the definition that has been presented is based on the characterization of three aspects of the smoke threat; namely, the "quantity", "quality" and duration of the smoke exposure.

"Quantity" was defined in terms of the quantity of smoke per unit volume of affected air to which a component might be exposed. In practice, the definition was based on an assessment of the mass of fuel that would be consumed in the fire scenarios of primary interest, and on an assessment of the size of the air volume into which the resulting fire products would become distributed. The resulting fuel mass consumed to affected air volume ratios ranged from 2.8 g/m^3 ($1.7x10^{-4}$ lb/ft^3) to 560 g/m^3 ($3.5x10^{-2}$ lb/ft^3). The lower bound value was associated with a postulated large control panel fire within the main control room, and included an assumption that the smoke would be diluted by continuous operation of the ventilation system in an emergency smoke purge mode. The upper bound value was associated with a small cabinet fire that consumed 15% of the available fuel in a single control panel, and an assumption that all of this smoke would remain confined within the fire panel. The assumption was that the rest of the components in the fire source panel might not be damaged by direct involvement in the fire, but that they would be exposed to the smoke from the fire.

The question of smoke "quality" refers to the actual composition of the combustion products, and in particular, the chemical composition of the smoke. It was noted that the general state of knowledge regarding the chemical composition of combustion products for most materials is quite poor. In particular, most such efforts have focused on the characterization of toxic fire products rather than on fire products in general. Hence, the approach taken for this study was to define the types of materials that would be expected to burn in a nuclear plant fire, and the interactions that might alter the chemical composition of the materials that would eventually be deposited onto the electronic components of interest. The one fuel material identified as of overriding interest was cable insulation. Of secondary importance were other materials used in the construction of electrical and electronic equipment. Of more limited interest were transient fuels (e.g., trash, wood, various plastics) and other *in situ* fuels (e.g., lubricants, solvents, and flammable gases). It was also noted that various modes of combustion can be expected, including in particular smoldering, open flaming, and oxygen-limited combustion. Important interactions were identified that involve fire suppressants (in particular CO_2, water, water based foams, and fire fighting powders) and transport of the smoke (in particular interactions with galvanized metal surfaces).

The final question, that of exposure duration, was addressed in two parts. First, the actual time during which a component might be exposed to a smoke-filled environment was assessed. The range of times cited was from 15 minutes to 4 hours. It is recommended that the exposure testing encompass this range of exposure durations. Second, the time associated with continued exposure to the accumulated deposits in the absence of additional smoke exposure was considered. It was recommended that a minimum postexposure monitoring period of 24 hours be allowed for all tests. It was also noted that periodic longer term monitoring (on the order of monthly testing) of some of the test samples would also be prudent. This long-term monitoring would help to assess the potential that components might be damaged by long-term corrosive attack well after a fire event has been experienced. If the scope of work allows, the effectiveness of component recovery (cleaning) measures could also be assessed by long-term monitoring of components.

VII. References

1. *Screening Tests of Representative Nuclear Power Plant Components Exposed to Secondary Fire Environments*, SAND86-0394, NUREG/CR-4596, Sandia National Laboratories, June 1986.

2. *Investigation of Potential Fire-Related Damage to Safety- Related Equipment in Nuclear Power Plants*, SAND85-7247, NUREG/CR-4310, Sandia National Laboratories, November 1985.

3. *Prioritization of Reactor Control Components Susceptible to Fire Damage as a Consequence of Aging*, SAND93-7107, NUREG/CR-6103, Sandia National Laboratories, January 1994.

4. "Corrosivity Test Methods for Polymeric Materials. Part 3- Modified DIN Test Method," *Journal of Fire Sciences*, V12, No. 2, pp. 155-174, March/April 1994.

5. "Corrosivity Test Methods for Polymeric Materials. Part 2- CNET Test Method," *Journal of Fire Sciences*, V12, No. 2, pp. 134-154, March/April 1994.

6. *Hinsdale Central Office Fire Final Report*, Joint report of the Office of the State Fire Marshal (Illinois) and the Illinois Commerce Commission Staff, March 1989.

7. *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets, Part I - Cabinet Effects Tests*, SAND86-0336, NUREG/CR-4527/V1, Sandia National Laboratories, April 1987.

8. *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Cabinets, Part II - Room Effects Tests*, SAND86-0336, NUREG/CR-4527/V2, Sandia National Laboratories, October 1988.

9. *Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues*, SAND88-0177, NUREG/CR-5088, Sandia National Laboratories, December 1988.

10. *Enclosure Environment Characterization Testing for Base Line Validation of Computer Fire Simulation Codes*, SAND86-1296, NUREG/CR-4681, Sandia National Laboratories, March 1987.

11. *A Review of Regulatory Requirements Governing Control Room Habitability Systems*, SAND84-0978, NUREG/CR-3786, Sandia National Laboratories, August 1984.

12. *Users Guide for a Personal-Computer-Based Nuclear Power Plant Fire Data Base*, SAND86-0300, NUREG/CR-4586, Sandia National Laboratories, August 1986.

13. *A Summary of the USNRC Fire Protection Research Program at Sandia National Laboratories; 1975-1987*, NUREG/CR-5384, Sandia National Laboratories, December 1989.

14. *Aging, Condition Monitoring, and Loss-of-Coolant Accident (LOCA) Tests of Class 1E Electrical Cables*, SAND91-1766/1-3, NUREG/CR-5772, Sandia National Laboratories, August 1992 (report in three volumes).

15. *Functional Issues and Environmental Qualification of Digital Protection Systems of Advanced Light-Water Nuclear Reactors*, ORNL/TM-12164, NUREG/CR-5904, Brookhaven National Laboratory, April 1994.

16. "Damage Management," *Fire Surveyor*, June 1992, pp. 20-23.

17. " Transport and Decay of Hydrogen Chloride: Use of a Model to Predict Hydrogen Chloride Concentrations in Fires Involving a Room-Corridor-Room Arrangement," *Fire Safety Journal*, 16 (1990), pp. 33-52.

18. "Standard Test Method for Measuring the Corrosive Effect of Smoke fro the Burning or Thermal Decomposition of Materials and Products," ASTM E05.21.70, Draft #2, November 1992.

Appendix B

A Review of Smoke Damage to Electrical Equipment

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A letter report for the USNRC Office of Research

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Abstract

This report reviews literature on smoke damage to electrical equipment. Smoke can damage electrical equipment because soot and acidic gases can corrode metals, coat contacts, and cause shorts. Smoke damage to electronics is not limited to immediate failures, but also includes long-term failures. Some smoke damage statistics are available from accidental fires, but detailed information on long-term damage from accidental fires is not readily available because best practices for fire recovery include immediate cleaning of electronic equipment to halt corrosion. Detailed information on long-term damage from smoke is available from controlled fire tests and has also been correlated with damage due to ionic substances in the air. Nuclear power plant operators should be aware of both the short-term and the long-term failures that can result from smoke exposure.

Introduction

This report summarizes information available in the public literature on smoke damage from both actual fires and smoke damage testing. A related subject, corrosion of electronic components and assemblies, is also discussed here because the contamination produced by a fire can be compared to long-term contamination from a polluted atmosphere.[1] Other aspects of smoke damage considered include cleaning of smoke-exposed equipment, and methods used to monitor the amount of corrosion that equipment experiences in order to predict the equipment's useful lifetime. These aspects will be touched on briefly.

Assuming that all fires cannot be prevented, minimization of smoke damage to electrical equipment may be approached in four ways: (1) regulate the type of fuel available to ensure that the smoke will be noncorrosive, (2) control the smoke propagation so that the electronics will not be exposed, (3) protect the electronics with conformal coatings or otherwise encase it to prevent smoke deposition, and (4) immediately following a fire, take aggressive measures to clean and recover smoke-exposed components. Some industries use combinations of smoke damage prevention and equipment recovery. Once electrical equipment has been exposed to smoke, it is important to determine whether the equipment must be replaced or can be cleaned. This report includes findings by other researchers on the amount of chemical deposition that can be tolerated by electrical equipment.

Smoke Damage Reported from Accidental Fires

This section reviews the smoke damage information available in the public literature from the nuclear power, telecommunications, shipboard, and other industries. Reports on fire events in the nuclear power industry are unique in that the reports concentrate on root causes of the fire and actions by personnel during the fire rather than on the total cost and personal injury, as in other industries. As a result, fire damage reports from the nuclear power industry have little information on the type of damage to equipment experienced or on the long-term effects of a fire. This singular viewpoint by the nuclear power industry reflects its emphasis on public safety rather than economics.

Nuclear Power Industry

Two databases on fire events in nuclear power plants are available: the EPRI database,[2] which includes fire events dating from 1965 to 1988,and the Sandia National Laboratories (SNL) database,[3] which includes fire events from 1965 to June 1985. The information reported in these databases was obtained from several sources, including the licensee event reports (LERs), American Nuclear Insurers, nuclear power experience, power reactor events, and several probabilistic risk assessments. The main function of these databases is to provide information on the frequency, severity, locations, and ignition sources of fires in nuclear power plants for risk assessment analyses. Although these databases include a field to list the damaged equipment, the reporting of such information tends to be sparse and the mode of damage is not given. Damage reported in these databases was mainly the result of direct effects such as burned equipment.

The LER database does not reveal any specific information on equipment damaged by smoke or the synergistic effects of smoke and other chemicals introduced during fire suppression. Smoke damage probably occurs, but because the LER is more related to the root cause of a problem rather than the resulting damage, not much analysis of the damage is reported.

Nuclear industry surveys contained little information on smoke damage to electrical equipment. Smoke damage is probably a factor in the failure of equipment after a fire; however, little attention has been paid to the failure mechanisms of electronics in a fire.

Telecommunications Industry

The telecommunications industry currently leads the nation in the investigation of smoke damage to electrical equipment. Several telephone central offices have been severely damaged by fire and smoke.[4,5,6] Studies of these events have revealed that smoke can account for up to 95% of the total equipment damage.[7] The most extensively studied central office fire, in Hinsdale, Illinois, in 1988, resulted in lost communication for 42,000 customers for several days, although the fire was confined to cables in an area about 6 feet in diameter and several punch card bins directly below the fire source. Included in the loss of communication was contact with the fire station and the FAA air traffic control center for O'Hare airport.

Smoke induced failures were observed within 6 hours at the Hindsdale fire. Although much of the switching equipment was functional after the fire, the equipment was badly corroded and had to be replaced in a matter of weeks. The switching system used electromechanical switches (relays). Much of this damage arose from acid gases, produced primarily from the burning of polyvinyl chloride (PVC) cable insulation. Burning PVC generates hydrochloric acid because PVC is 35% chlorine by weight. Hydrochloric acid attacks electronics by forming metal salts that both weaken the metal structure and erode the conducting metal. The hydrochloric acid corroded the switch contacts, allowing them only 1 month of life after the fire.

Bellcore (Bell Communications Research) has been a leader in the studies on smoke damage for the telecommunications industry.[6,7] Reagor from Bellcore reports that the level of chloride attack is the most important parameter in determining if equipment should be cleaned. The expected total amount of zinc chloride (a metal salt) that a piece of equipment will accumulate on its surface from the environment over a lifetime is 30 to 60 $\mu g/in^2$. In contrast, fires can contribute between 30 and 600 $\mu g/in^2$ in a matter of minutes to hours. Bellcore research has shown that if contamination levels are below 200 $\mu g/in^2$, the equipment can be restored easily, and at levels between 200 $\mu g/in^2$ and 600 $\mu g/in^2$, it can also be restored with some effort, but levels above 600 $\mu g/in^2$ are uneconomical to salvage.

Comizzoli and Sinclair, at AT&T Bell Laboratories, have studied corrosion of electronic components and assemblies.[8,9,10] Comizzoli proposed that the corrosion of metal contacts on electronic equipment such as integrated circuits is accelerated by the combination of exposure to atmospheric contaminants and an environment above a critical relative humidity of about 60%.

Atmospheric contaminants include dust and acid gases such as sulfur dioxide, nitrogen oxides, and chlorides. Above the critical relative humidity, dust and moisture combine to form electrolytic solutions. These solutions cause electrical leakage and corrosion on the component or assembly. Comizzoli also proposed some test methods to determine how well the electronic components are protected by assembly designs and coatings. These tests involved controlled application of ionic particles by a forced air system.

The oil fires in Kuwait offered Comizzoli *et al.*[11] an opportunity to study the effects of oil smoke on electronics. The Kuwait oil fire experiments showed that H_2S from the burning oil was a significant contributor to corrosion of silver and copper coupons and to contact resistance of pin and socket connectors. Coupons and connectors that were housed in filtered areas showed far less corrosion. These results suggest that electronic equipment should be protected by either coating the electronics with materials that will not allow the penetration of ionic substances and humidity or controlling the air flow so that smoke will not come into contact with the electronics.

The telecommunications industry has emphasized the reduction of fuels that produced corrosive smoke as a method to limit smoke damage to their equipment. For example, most telephone companies now require that cable suppliers for the telecommunications industry manufacture cables that produce less corrosive smoke. As a result, both the plastics industry[12] and Factory Mutual Research Corporation (FMRC) have become heavily involved in testing the relative corrosivity of the smoke from different materials. The efforts of the plastic manufacturers to produce standards for testing the corrosivity of materials are documented in a later section.

Most research into the effects of smoke on telecommunications systems has concentrated on the long-term effects of smoke exposure, such as corrosion, rather than short-term effects, such as circuit bridging. This may be a result of the amount of attention paid to the Hinsdale fire where the power was turned off before the fire could be extinguished; it was this power loss that led to the most extensive loss of function. During the fire, some smoke exposed switching equipment failed, but little research has been devoted to prevention of immediate failures of the electrical equipment. Instead the telephone industry has concentrated on reducing the losses from corrosion after the fire. Although the telephone industry stressed the need for continuous service, they can tolerate a temporary loss of service. The need for continuous service at a nuclear power plant is much more critical.

Shipboard Fires

Shipboard fires have caused extensive loss of life and damage to equipment. Damage in the British Navy in the period 1988 to 1989, for example, included 279 fires of different sizes and amounted to £121K in losses.[13] Pivotal fire events leading to changes in the cable material specifications for the British navy were fires started by missiles during the Falkland Islands war in 1982.[14] The *HMS Sheffield* and *HMS Ardent* were both hit with missiles and sank because the heavy black smoke from PVC cabling and linoleum prevented sailors from extinguishing the fires. PVC (a halogenated compound) is considered inherently flame retardant because it is approximately 35% chlorine by weight. However, given enough heat, PVC will burn and produce black sooty smoke and large quantities of hydrochloric acid. Halogenated compounds (those compounds which include fluorine, chlorine, bromine, and iodine) and Halon suppress fires by action of the halogen ions. Halogen ions react with hydrogen faster than oxygen, preventing the oxygen from reacting with the fuel, thus extinguishing the fire.[15] In the process of extinguishing the fire, however, toxic and corrosive acid gases form. Since smoke from halogenated cables (such as PVC) is especially black and toxic, the British Navy has eliminated PVC cables from their ships.

Fire-resistant cables that are nonhalogenated have been developed in the past 10 years. These cables are doped with metal hydrates instead of halogens. Aluminum trihydrate and magnesium hydroxide are two fillers that reduce the flammability of polyethylene, but do not contain halogens. The flame retardancy is the result of (a) a smaller proportion of polymer, (b) absorption of heat by the metal hydrates, and (c) release of water upon decomposition.[16] Cables filled with metal hydrates produce less smoke, are less corrosive, and are less toxic than halogenated cables.

The U.S. Navy has studied fire and smoke production for many years,[17,18] and they also changed their specifications as a result of changes made by the British Navy. The older specifications on cables, such as MIL-C-915, included physical characteristics such as tensile strength, elongation, and bending endurance. The newer specifications, MIL-C-24640 (1984) and MIL-C-24643 (1986), also include measurements of acid gas production, halogen content, smoke index, and toxicity index. The smoke index and toxicity index are related to Naval Engineering Standards borrowed from the British Navy. The smoke index measures the optical density of smoke, while the toxicity index measures the amount of toxic gases produced by burning cables. Halogens are no longer allowed in the cable jacket, which is the outermost layer of a cable. Research funded by the U. S. Navy includes an assessment of the toxicity and the optical density of smoke from shipboard materials.[19] Work performed after 1985 includes studies on smoke damage to structural materials such as steel that may be used in bulkheads.[20] These studies included smoke corrosivity tests from different types of cables. Current studies include an investigation of potential damage to electrical equipment from Halon and its replacement fire suppressants.[21]

Other Fire Events

Factory Mutual is the leading insurance company organization doing research on fire and smoke damage. FMRC claims that the effects of fire on a computer system, even a small smoldering fire, can be extensive over a period of time, even if the fire is not located in the same room. According to FMRC, computer rooms have been damaged more often by fires originating outside the rooms than by fires originating within the room.[22] Unfortunately, the bulk of FMRC data related to these findings is proprietary, and hence, was unavailable.

Smoke Exposure Testing

This section discusses failure modes of electrical equipment in a smoke environment, equipment survivability tests, and smoke corrosivity tests. Smoke-generated failures are specific to the equipment exposed, and while some failure modes are very quick, others, such as corrosion, are slower. Equipment survivability tests in this context are tests of the reliability or performance of equipment in a smoke-filled atmosphere. Equipment survivability tests have generally been performed during full-scale fires and using equipment that is typical of systems that will be exposed to smoke. No standard tests exist for equipment survivability in a smoke-filled environment. In contrast, smoke corrosivity tests are small-scale material tests that measure how corrosive the smoke from a particular material is to a specified metal target. Manufacturers of cable and building materials developed these tests to prove that smoke from their cables is benign. These tests provide only a relative measure of the corrosivity of combustion products under very specific test conditions and the results cannot be used directly to predict equipment damage.

Failure Modes

Most smoke failure modes are similar to failures caused by environmental pollution, but they take place more quickly. In atmospheric pollution, dust and small particles can coat equipment over periods of years and cause damage and failure. This damage occurs because of corrosion of metal contacts, bridging of conductor circuits, and formation of nonconducting surfaces on electrical contacts. Dust can damage moving parts, such as in mechanical timers and relays, interfering with movement. Pollutants can also obscure optical equipment. The deposition of smoke from a fire can be the equivalent of decades of dust in a normal environment. During a fire, the environment is not only very polluted by smoke, but often the addition of humidity and fire suppressant chemicals produces harmful synergistic effects. These conditions can produce catastrophic failures for electrical equipment over relatively short periods (minutes to hours).

Smoke produces many problems for humans; it is toxic and obscures vision. For electronic equipment, these qualities are not usually important, except in the case of optical equipment. Because these qualities are very important for humans, however, standard tests have been developed for measuring both smoke obscuration[23] and toxicity. These tests are material tests, that is, the various materials that will be the fuel are tested rather than any equipment. No studies have been published on the effect of smoke on optical equipment.

Smoke damage to electrical equipment through corrosion of metal, especially from plastics such as PVC, has been known for several decades.[24] The development of standards to test materials for smoke corrosivity has only been actively pursued since the mid-1980s. Present and proposed smoke corrosivity tests concentrate on measuring the loss of metal through corrosion, although corrosion is not the only failure mode for electrical equipment in a smoke environment.

Recently, several investigators in the field of smoke damage (including SNL) have proposed experiments[25] that will also measure insulation resistance between contacts on a printed circuit board. Soot deposits can reduce the insulation resistance by providing a conductive path between contacts or circuit traces. Loss of insulation resistance can lead to undesired current paths (leakage currents) or circuit bridging. Circuit bridging as a failure mode can be as destructive as corrosion, but will occur on a much shorter time scale. No standards have been developed to measure this effect.

The formation of nonconducting deposits on contacts can also lead to circuit failure. For mechanical relays and switches, this can be an important failure mode. No standard test for the effect of smoke from different materials has been developed to investigate this failure mode; however, tests on switchgear[16] and sockets[11] show that smoke has a significant effect on contact resistance. This particular failure mode is not considered relevant to digital circuits because these circuits do not generally use open contact pairs as switching devices.

Failures due to circuit bridging, changes in contact resistance, loss of mechanical motion, and optical obscuration can occur immediately from smoke exposure, while metal loss failures will take place slowly over a period of weeks to months following the fire. Delayed failures are a problem that may be overlooked by plant operators and that can seriously affect reliability and plant safety. The most important failure mode is highly dependent on the type of electrical equipment that is exposed to smoke. Studies of the reliability of electrical equipment in a smoke environment must include equipment that is typical of the equipment under study and a smoke environment that is characteristic of the type of environment that can occur in a fire. Some failures, such as a change in contact resistance and inhibition of motion, are not considered relevant to digital equipment. Material tests such as those published by the ASTM are important to qualify material for use in a plant, but are no substitute for testing electrical equipment in the smoke environment.

Smoke Exposure to Electrical Equipment

In 1986 Jacobus[26] performed full-scale fire tests and smoke exposures on electrical equipment. The test articles (equipment considered to be typical of that used in nuclear power plants) were tested in a room that contained a burning electrical cabinet. Jacobus tested twenty-four switches, thirteen meters, five relays, two strip chart recorders, two electronic counters, one power supply, one power amplifier, and one oscilloscope amplifier. Some of the equipment was tested with protective covers on, while other equipment was tested with the covers off. The protective covers significantly reduced particulate accumulation. The components that were most strongly affected were those with mechanical moving parts, such as chart recorders. Circuit boards on the electronic counter also failed because of leakage currents. Switches and relays experienced problems due to high contact resistance at low voltage levels. Nuclear-qualified cables and PVC cables provided the fuel for these experiments.

Bridger *et al*[16]performed two full-scale tests on switchgear using standard switchgear wire and new low-emission switchgear wire. The switchgear included pushbuttons, indicator lights, ammeters, relays, and switches. Bridger monitored the equipment before the test, immediately after the exposure, 7 days after the exposure, and 3 weeks after the exposure. The low-emission wire, which contained no halogens, caused less change in contact resistance in the equipment. The residue from the low-emission wire was also easier to clean than that from the standard wire.

DuPont has tested three commercial 386 PCs using smoke from a dynamic combustion instrument called a cone calorimeter.[27] Commercially available utility programs tested the PC for functionality during and after the smoke exposure. Three different cables provided the smoke for these tests. Of the three tests, two PCs failed and one survived. DuPont considers these tests important as far as illustrating the potential for damage from smoke originating from different materials; however, a PC is much too complicated as a test object to reveal the precise causes of failure.

Smoke Corrosivity Testing

Low smoke corrosivity requirements by the telecommunications industry have produced great interest in smoke corrosivity testing. Early tests have been performed using a full-scale fire, that is, the fire is contained in a room about the size of a small office or larger, and the smoke exposure samples are contained in an adjacent comparable room. Since full-scale testing is not very economical, standards committees have concentrated on developing small-scale tests that are supposed to simulate the effects of a real fire. The controversy that develops over use of a small-scale test is: does the small-scale test really produce smoke has the characteristics of a full-scale fire and are the exposure conditions typical of those expected in real fires? Hydrochloric acid gases, which cause corrosion, combine quickly with water. As a result, these gases may not be well distributed throughout a room after a fire.[28,29] In a fire, soot is also not well distributed; the heavier deposits are closer to the fire. The extent to which factors such as these are accounted for in the various standard tests is questionable.

Since the mid-1980s there have been many proposed test standards to measure the corrosivity of smoke from solid materials. These tests measure either smoke acidity or metal loss. Chapin has compiled a list of smoke corrosivity tests that are currently in use or proposed by organizations around the world[30] (see Table 1). These tests only assess one failure mode (corrosion) either directly, as in the last four methods on Table 1 that measure loss of metal by measuring resistance, or indirectly by measuring the acidity of the smoke as in the first eight tests listed in the table. Note that acid gas generation tests consist of percolating smoke through distilled water and then measuring the resulting acidity with a pH meter or by other chemical analysis. Since many halogenated materials produce acidic gases when burnt, and the acidity of the gases is assumed to determine how corrosive they are, the acidity measured by these tests gives some indication of how corrosive the smoke may be.

The early work on smoke corrosivity concentrated on measuring corrosion through the loss of metal from solid metal coupons. The loss of metal was measured in either of two ways: (1) measuring the weight gain as a function of time -- this measures the additional weight of oxygen due to formation of rust (metal oxides),[31,20] or (2) sandblasting off all of the corroded metal and then weighing the metal loss.[12] In either case, the change in weight is very small compared with the weight of the original piece of metal; thus, the measurements must be done very accurately. Other uncertainty is added because for the first technique other materials may add to the weight. With the sandblasting technique, some noncorroded metal may be lost in the sand-blasting process.

Instead of measuring weight changes, metal corrosion can be measured by measuring resistivity. On the basis of this idea, corrosivity probes have been developed which are made up of thin metal traces on printed circuit boards of a standard thickness. Instead of a simple trace, however, a two-legged bridge is formed; one leg is protected by epoxy and the other leg is exposed and allowed to corrode. The change in resistance of the exposed leg determines the metal loss, and hence the rate of corrosion. The reason that two legs of a bridge are needed is that as temperature fluctuates, the resistance of a single trace may fluctuate; however, if a bridge formation is used, temperature effects common to both legs are eliminated. Currently both the ASTM standards developed by the D9 and E5 committees use this corrosion probe (manufactured by Rohrback) as

Detailed Summary of Smoke Corrosivity Test Methods

Category	Standard	Title	Sample	Combustion Chamber	Heat source	Heating Conditions	Carrier gas/atmosphere	Probe	Corrosion Measurement	Expression of Results	Limitations
Acid Gas Generation (dynamic method, stationary furnace)	IEC 754-1, 1994-01	Test on Gases Evolved During Combustion of Materials from Cables, Part 1	Material from cable, 0.5-1.0 g cut into pieces	Silica tube	Tube furnace	Stationary furnace, heat ramped from 23-800C in 40 min then maint. 20 min	dry air 20 ml/mm2/h	2 water traps 220 ml 0.1N NaOH	Titrate with HNO3, AgNO3, FeNH4SO4, NH4SCN	Amount of halogen acid expressed as mg HCl/g sample	Materials containing fluoride or halogen acid > 5 mg/g, not suitable for zero halogen materials
Acid Gas Generation (dynamic method, stationary furnace)	BS 602-1	Test on Gases Evolved During Combustion of Materials from Cables, Part 1	Material from cable, 0.5-1.0 g cut into pieces	Silica tube	Tube furnace	Stationary furnace, heat ramped from 23-800C in 40 min then maint. 20 min	dry air 20 ml/mm2/h	2 water traps 220 ml 0.1N NaOH	Titrate with HNO3, AgNO3, FeNH4SO4, NH4SCN	Amount of halogen acid expressed as mg HCl/g sample	Materials containing fluoride or halogen acid > 5 mg/g, not suitable for zero halogen materials
Acid Gas Generation (dynamic method, stationary furnace)	BS 6245: Part 1	Gases Evolved During Combustion of Materials from Cables, Part 1: Determination of Amount of Halogen Acid Gas Evolved During Combustion of Polymeric Materials Taken from Cables	Material from cable, 0.5-1.0 g cut into pieces	Silica tube	Tube furnace	Stationary furnace, heat ramped from 23-800C in 40 min then maint. 20 min	dry air 20 ml/mm2/h	2 water traps 220 ml 0.1N NaOH	Titrate with HNO3, AgNO3, FeNH4SO4, NH4SCN	Amount of halogen acid expressed as mg HCl/g sample	Materials containing fluoride or halogen acid > 5 mg/g, not suitable for zero halogen materials
Acid Gas Generation (dynamic method, traveling furnace)	CSA C22.2. No. 0.3-M1985-sec 4.31	Test to Determine Acid Gas Evolution	Material from cable, 500 mg, 60 mm long	Silica tube	Tube furnace	800C, 6-1" moves, sample heated 5 min, 10 min to heat deposits	dry air, 100 ml/min	3 water traps, pH 5 7, add 5ml 0.1N NaOH	Titrate with 0.1N NaOH	Percentage of acid gas evolved (based on MW of acid)	Requires ID of acid gas beforehand
Acid Gas Generation (dynamic method, stationary furnace)	SAA AS 1660.5.3	Methods of Test for Electrical Cables, Cords and Conductors, Part 5: Fire Tests - Part 5.3:: Determination of Amount of Halogen Acid Gas Evolved During Combustion of Polymeric Materials Taken from Cables	Material from cable, 500 mg	Silica tube	Tube furnace	800C for 10 minutes	dry air 6 l/h		pH by titration		
Acid Gas Generation and Conductivity (dynamic method, stationary furnace)	IEC 754-2	Test on Gases Evolved During Combustion of Materials from Cables, Part 2	Material from cable, 1000 mg	Silica tube	Tube furnace	preheat > 935C for 30 minutes	dry air, 100 ml/min (15-30 l/h)	1 or 2 wash bottles (vol 1000ml) pH 5-7	pH and conductivity	3 runs; pH, mean, stdev, covar, conductivity; pH>4.3 and cond < 10 microSiemens/mm	
Acid Gas Generation and Conductivity (dynamic method, stationary furnace)	BS 602-2	Test on Gases Evolved During Combustion of Materials from Cables, Part 2	Material from cable, 1000 mg	Silica tube	Tube furnace	preheat > 935C for 30 minutes	dry air, 100 ml/min	1 or 2 wash bottles (vol 1000ml) pH 5-7	pH and conductivity	3 runs; pH, mean, stdev, covar, conductivity; pH>4.3 and cond < 10 microSiemens/mm	
Acid Gas Generation and Conductivity (dynamic method, stationary furnace)	SAS AS 88003 (prop to become AS 1660.5.4)	Methods of Test for Electrical Cables, Cords and Conductors: Determination of Amount of Halogen Acid Gas Evolved During Combustion of Polymeric Materials Taken from Cables									
CNET (static method)	ISO/DIS 11907 Part 2, 8 Jan 1991	Plastics - Smoke Generation - Determination of the Corrosivity of Fire Effluents, Part 2.: Static Method	Material from cable, 600 mg granules mixed with 100 mg PE	20 liter PMMA with seals, heated to 50C with wire wrapped around chamber	Inconel-jacketed nichrome wire	800C for 150 sec	Dry air, injected with water to a specific RH (90 or 40-60%)	PWB 36 tracks 52 mm long, 0.3 mm wide, 17 microns thick; cooled 10C below chamber	Insulation resistance of PWB every 150 s for 1 hour	Percent corrosivity adjusted to 40C, 8 ohms	
DIN 53436 Traveling Tube Furnace (dynamic method)	ISO/DIS 11907 Part 3	Plastics - Smoke Generation - Determination of the Corrosivity of Fire Effluents, Part 3.: Dynamic Method	Material from cable, spgr > 0.4 g/cc 400mm x 15 mm x 2 mm	Silica tube	Tube furnace	600C, motorized drive pass furnace over sample, 20 min duration	air at 100±5 l/h	CNET PWB water cooled at 10C during exposure	Insulation resistance 1, 3 and 24 hrs after exposure at 23C 75±5%RH	% change in resistivity, R_{corr}	
Cone Calorimeter (dynamic method)	ISO/DIS 11907 Part 4, ASTM D5485	Standard Test Method for Determining the Corrosive Effect of Combustion Products Using the Cone Corrosimeter	Intact cable or 1/4" plaques 100mm square, ends sealed, AL wrapped, in frame	11 liter polycarbonate chamber, 105C heated SS transfer tubing	conical heater, variable flux from 10-100 kW/m2	Initial mass loss determination, test to 70% of total mass loss, expose probe to smoke for 60 min	ambient air, sampling rate of 4.5 l/min	Rohrbac Cosasco 45,000A	Measure resistance after 60 min exposure and after 24 hr exposure to 23C, 75±5% RH	Report calorimetry data for mass loss and corrosion runs, calculated metal loss (1 hr and 24 hrs)	
NIBS Smoke Chamber (static method)	ASTM E5.21.70 NBS	Standard Test Method for Measuring the Corrosivt Effects of Smoke from Burning or Thermal Decomposition of Materials and Products	Intact cable or plaques 50 mm square, < 25 mm thick, Al wrapped in frame	NBS Radiant Heat Chamber, 200 liter volume, combustion cell chamber and chimney	Combustion cell with load cell 4 quartz IR lamps at 2000W and 240V, flux 50 kW/m2, spark igniter	15 minutes	60% RH humidified air in chamber	Rohrbac Cosasco CK5 corrosimeter 45,000A and measuring bridge	Close shutter after 15 min heating ends, measure change in resistance for 15 min intervals for 1 hr, remove and expose to 23C and 75±5% RH for 24 hrs and remeasure IR	Plot metal loss for total exposure time and after 24 hours, report calorimetry data; metal loss A = $(R_f-R_o)S/1000$ S is probe span from mfgr	

does the French CNET test. Both ASTM standards suggest using the 2500-Å and the 45,000-Å thick probes, however; Rohrback produces these in different ways. The "thick" and "thin" probes never correlate very well; at times the thin probe will be corroded away, while the thick probe does not show any corrosion at all.

Many workers in this field have compared the various international standards or proposed standards.[32,33,34,35,36] The most frequently compared techniques are the last four on Table 1, the CNET method developed in France, the DIN 53436 method developed in Germany, the cone calorimeter developed in the United States and the National Institute of Building Standards' smoke chamber also developed in the Unites States. Factory Mutual also has their own testing standards and has attempted to correlate large- and small-scale testing.[37]

Two methods of producing smoke for small-scale fire corrosivity tests have been developed: the static method contains all of the air and fuel in an enclosed space, while the dynamic method consists of a continuous air flow that is pumped past the burning material. While the dynamic method ensures a more even burn, the target will not be exposed to all of the smoke. The static method ensures that the target will be exposed to all of the smoke products because they are contained, but the mode of burning is not very even.

The ASTM standard developed by the D9 committee, D5485, uses a cone corrosimeter to burn the material and is a dynamic test.[38] Air is pulled through the burning area with a fan at a prescribed rate. A small amount (0.3%) of the smoke is pulled through a bell jar that contains the corrosion target (Rohrback probe). Gases are pulled through the jar until 70% of the material is burned up. The target remains in the bell jar for 1 hour. After this smoke exposure period, the target is moved to an environmentally controlled chamber (20° C, 75% relative humidity), and tested for 24 hours. One shortcoming of this test is that hydrochloric acid is one of the first combustion by-products to be produced. Since smoke is pulled through the bell jar until a given amount of fuel is burned, the hydrochloric gas may not be allowed to remain in the bell jar with the target. That is, the early release HCl may be "flushed out" of the exposure by the continuous flow of sample gas.

The ASTM standard developed by the E5.21.70 committee uses a radiant heat furnace and an enclosed box.[39] This is a static test in which all combustion products are confined to the exposure chamber. The burning material is exposed to radiant heat for 15 minutes, and all of the smoke is captured in a polycarbonate box that contains the target (Rohrback probe). The target remains in the box with the smoke for a total of 1 hour. After this period, the target is moved to an environmentally controlled chamber (20°C, 75% relative humidity) and tested for 24 hours. One shortcoming of this test is that the fuel combustion process is not well controlled; the quartz lamps provide radiant heat through a clear quartz combustion chamber that may become opaque from soot. The advantage of this method is that all of the combustion products over the full course of the burn are captured.

Material smoke corrosivity measurements are also made by measuring the acidity of gases produced by the fire.[40] The DIN test 57 472 Part 813 Standard is one such test. In this test, one gram of material is burned in a quartz combustion chamber using radiant heat lamps. A continuous bottled air flow is maintained during the combustion and the gaseous burn products are percolated through distilled water. The pH and conductivity of the distilled water are measured with electrode probes. Changes in PH are correlated to the acidity of the combustion products.

General Reliability Testing

Reliability testing for electronics has proceeded along a different path than that for smoke corrosivity. Reliability testing has been performed on actual electronic parts such as connectors, printed circuit boards, and chips, rather than metal blanks and resistive traces. The emphasis in reliability testing has been on both metal loss and circuit bridging in both individual components and assemblies. Although smoke corrosivity can be considered a subset of reliability testing in general, the differences in approach of the two test communities are remarkable.

Accelerated Corrosion Testing

In "accelerated testing" the environments in which the components are tested are more harsh than normal operating environments because the tester wants to accelerate the failure rate. Higher temperature and relative humidity are the bases for most accelerated testing. For example, tests on printed circuit board reliability are conducted at 85°C and 85% relative humidity.[41] Highly accelerated stress tests (HAST) require high pressures, while the temperature and relative humidity are maintained at 140°C and 85% relative humidity.[42]

Ionic contaminants increase the corrosion of electronic components.[9] The ionic contaminants can be added in the form of a mixed gas or salt spray, and these are usually accompanied by elevated temperature and humidity.[43] Bottled gases such as hydrogen sulfide or chlorine are added into the test chamber to increase the corrosion rates. Nueberger[44] developed a detector to measure the HCl distribution in the test chamber. The synergistic effect of humidity and ionic gases has been found to be very important in determining the corrosion rate. Sometimes a "critical" humidity, in the neighborhood of 60-70%, is defined to identify the onset of much faster corrosion.

In general, the failure rate of electronics is dependent on the accumulation and type of deposition, relative humidity, temperature, packaging, connector design, and bias voltage. In smoke corrosion, the deposition rate of the contaminant is much higher than that experienced under normal circumstances. The deposition occurring during a fire in a communications center in Los Angeles, for example, was found to be equivalent to 9 years of deposition under normal circumstances.[9] The bias voltage influences the corrosion process by encouraging dendritic growth of conductors; therefore, it is important to apply typical voltages when testing for reliability.

Special Testing Chips

Most digital electronic devices have high reliability, but fail rapidly and without warning. Emerson has developed "assembly" test chips that are more susceptible to environmental problems and will start to fail earlier and more gradually than production chips.[37] These chips can be used to indicate corrosion in accelerated tests and for tests of printed circuit board assembly lines. They can also be used for highly critical applications to monitor the amount of degradation of an electronic assembly. The assembly test chip may be used to indicate predicted failure rates for critical digital assemblies. This represents a potentially promising approach to nuclear plant applications as these chips might be used in actual components and might provide early warning of impeding failures.

Surface Insulation Resistance

Surface insulation resistance (SIR) is a measurement of the resistance between two parallel circuit traces. In practice SIR can be measured using a board with two interlaced electrodes that form a comb. The resistance between the combs gives a measure of the amount of conductive material that is deposited on top of the comb. These measurements have been used to ascertain the quality of soldering on printed circuit boards. The combs may also be used to indicate circuit bridging effects as a result of surface contamination or dendritic growths between comb materials. The boards can also be used to assess the effectiveness of various coatings to prevent such failures.

Summary

Very little information on the reliability of electronics has been gathered from accidental fires. Most damage information from actual fires is anecdotal and not well documented. In a real fire, no one stops to make careful measurements of the soot deposition or perform a chemical analysis of the soot; instead, the immediate job is to put out the fire and clean up the equipment so it can be salvaged. More information has been found from the study of controlled fires, but few tests of the reliability of electronics in a controlled fire have been performed. The emphasis has instead been on the relative corrosivity of the smoke produced by burning different materials.

Studies of corrosion on electronic equipment are more advanced than tests of the reliability of equipment in a smoky environment. Reliability tests generally use mixed gases, high temperatures, and humidity and hence are easier to reproduce than a consistent smoke environment. The main problem that must be resolved is determining how to relate the corrosive atmosphere to a smoke environment, and then, how to relate a simulated smoke environment to a real fire. It is also important that smoke testing be expanded to include the use of more varied targets in order to assess each of the potential failure mechanisms. To date, smoke exposure testing has focused primarily on direct corrosive attack. Relatively little work on circuit bridging faults has been undertaken.

References

[1] Private conversation with D. Karydas, Factory Mutual Research Corporation, Norwood, MA, March 2, 1995.

[2] Science Applications International Corporation, *Fire Events Database for U.S. Nuclear Power Plants*, NSAC/178L, Revision 1. EPRI licensed material, January 1993.

[3] W. T. Wheelis, "Users' Guide for a Personal-Computer-Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SAND86-0300, August 1986.

[4] "Hinsdale Central Office Fire," Joint Report of Office of the State Fire Marshall and Illinois Commerce Commission Staff, March 1989.

[5] A. Tewarson, "Nonthermal Damage Associated with Wire and Cable Fires," Presentation at the 42nd International Wire and Cable Symposium, St. Louis, MO, Nov. 15-18, 1993.

[6] B. Reagor, "Smoke Corrosivity: Generation, Impact, Detection, and Protection," *Fire Sciences* Vol. 10, pp. 169-179, Mar/Apr 1992.

[7] D. M. Karydas, "Smoke Management Systems for the Telecommunications Industry," *Network Reliability: A Report to the Nation*, Compendium of Technical Papers Presented by the Federal Communications Commission's Network Reliability Council, National Engineering Consortium, Chicago, IL, pp. G15-18, June 1993

[8] R. B. Comizzoli and J. D. Sinclair, Electronic Components and Assemblies: Reliability and Testing, AT&T bell Laboratories, Murray Hill, *Encyclopedia of Applied Physics* Vol. 6. pp. 21-44.

[9] J.D. Sinclair, "Corrosion of Electronics: The Role of Ionic Substances," *Electrochem. Soc.*, Vol. 135, No. 3 pp. 89c-95c, 1988.

[10] R. B. Comizzoli, R. P. Frankenthal, R. E. Lobnig, G. A. Peins, L. A. Psota-Kelty, D. J. Siconolfi and J. D. Sinclair, "Corrosion of Electronic Materials and Devices by Submicron Atmospheric Particles," *Interface*, 1993

[11] R. B. Comizzoli, J. P. Franey, G. W. Kammlott, A. E. Miller, A. J. Muller, G. A. Peins, L. A. Psota-Kelty, J. D. Sinclair, R. C. Wetzel, and E. S. Sproles, Jr., "The Kuwait Environment and its Effects on Electronic Materials and Components," *J. Electrochem. Soc.*, Vol. 139, No. 7, pp. 2058-2066, 1992.

[12] M. M. Hirschler and G. F. Smith, "Corrosive Effects of Smoke on Metal Surfaces." *Fire Safety J.* Vol. 15, pp. 57-93, 1989.

[13] J. A. Pownall, "Cables Designed to Give Reduced Corrosive Products Resulting from Fire on Warships," *Fire Safety J.* Vol. 16, No. 3, pp. 197-211, 1990.

[14] CDR Robert Meyron, Passive Fire Protection Symposium, November 4, 1984, Arlington, VA.

[15] D. Drysdale, *An Introduction to Fire Dynamics*, John Wiley and Sons, New York 1975, pp. 28 and 110-111.

[16] B. Bridger, W. F. Powers, D. W. Cooper, B. L. McClung, "Use of Reduced Emissions Wire in Switchgear Equipment," paper presented at IEEE/IAS/I &CPS Conference, Irvine, CA May 1994.

[17] R. S. Alger, and S. J. Wiersma, "Ship Fire Characteristics: Part 1, Sealed Compartments," Naval Surface Weapons Center, White Oak, Silverspring, MD, Nov., 10, 1976.

[18] R. S. Alger et al, "Fire Characteristics and Fire Protection in High Performance Ships," Final report, Naval Weapons Center, China Lake, CA, NWC Technical Memorandum 3332, Nov. 1977.

[19] "Determination of the Smoke Hazards Resulting from the Burning of Shipboard Materials Utilized by the US Navy," Georgia Institute of Technology, Aug. 31, 1981.

[20] J. S. Patton, "Fire and Smoke Corrosivity of Metals," David Taylor Research Center, Annapolis, MD, *J Fire Sci.*, Vol. 9, No. 2, pp. 149-161, March/April 1991.

[21] Private communication with Lisa O'Connor, Naval Surface Warfare Center, Annapolis, MD, October 1994.

[22] L. P. Sotis, "Post-Halon Computer Protection," *RECORD* Vol. 70, No. 6, pp. 3-9, Nov./Dec. 1993.

[23] ASTM Standard E 622-94a

[24] "Plastics--Fire--Corrosion," SKYDD 69 (Protection 69) Proc. Int. Symp. and 15th. Nordic Fire Protection Day, Stockholm, April 23, 1969, Swedish Fire Protection Assoc., Stockholm, October 1969.

[25] Private Communication with Lauren M. Caudill, DuPont Polymers, Wilmington, DE.

[26] M. J. Jacobus, "Screening Tests of Representative Nuclear Power Plant Components Exposed to Secondary environments Created by Fires," NUREG/CR-4596, Sandia National Laboratories, June 1986.

[27] Private communication with Robert Backstrom of Underwriters Laboratory, Northbrook, IL, March 13, 1995.

[28] G. M. Galloway, and M. M. Hirschler, "Transport and Decay of Hydrogen Chloride: Use of a Model to Predict Hydrogen Chloride Concatenation in Fires Involving a Room-Corridor-Room Arrangement," *Fire Safety J.* Vol. 16, pp. 33-52, 1990.

[29] J. J. Beitel, C. A. Bertelo, W. F. Carroll, Jr., "Hydrogen Chloride Transport and Decay in a Large Apparatus. Part 2. Variables Affecting Hydrogen Chloride Decay," *J. Fire Sci.* Vol. 5, No. 2, pp. 105-145, Mar/Apr 1987.

[30] T. Chapin, "Detailed Summary of Smoke Corrosivity Test Methods," Presented at meeting April 27, 1995 at AT&T Bell Laboratories at Murray Hill, NJ.

[31] E. A. Powell, and B. T. Zinn, "Corrosion of Metals Exposed to Combustion Products Generated During Shipboard Fires," Final Report, April 13, 1988, Naval Research Laboratory, Washington D.C. 9105; 47 p.

[32] S. L. Kessel, C. E. Rogers, and J. G. Bennett, Jr., "Corrosivity Test Methods for Polymeric Materials, Part 5A Comparison of Four Test Methods," *J. Fire Sci.* Vol. 12, No 2, pp. 196-233, Mar/Apr 1994.

[33] P. J. Briggs, "Corrosivity of Fire Effluents: International Development in Performance-Related Test Procedures," *Recent Advances in Flame Retardancy of Polymeric Materials: Materials, Applications, Industry Developments, Markets*, Business Communications Co. Inc. (BCC), Norwalk, CT, Vol. 2, pp. 121-130, May 14-16, 1991.

[34] L. M. Caudill, "International Testing for the Corrosive Effects of Combustion Products," Intl. Conf. on Fire Safety--Fire Retardant Technology and Marketing, March 25-28, 1990 New Orleans, LA, Fire Retardant Chemicals Assoc., Lancaster, PA, pp. 223-225, 1990.

[35] S. J. Grayson, and M. M. Hirschler, "Testing for Corrosivity of Smoke in Materials and Products," *1st Fire and Materials International Conference*, September 24-25, 1992, Arlington, VA, pp. 201-212, Interscience Communications Ltd., London, Eng., 1992.

[36] M. M. Hirshler, "Discussion of Smoke Corrosivity Test Methods: Analysis of Existing Tests and of their Risks," *Fire and Materials*, Vol. 17, No. 5, 231-247, Sept/Oct 1993.

[37] A. Tewarson, "Nonthermal Fire Damage," *J. Fire Sci.*, Vol. 10, No. 3, pp. 188-242, May/June 1992.

[38] J. G. Bennett, Jr., S. L. Kessel, C. E. Rogers, "Corrosivity Test Methods for Polymeric Materials. Part 4. Cone Corrosimeter Test Method," *J. Fire Sci.* Vol 12, No. 2, pp. 175-195, Mar/Apr 1994.

[39] S. L. Kessel, J. G. Bennett, Jr., C. E. Rogers, "Corrosivity Test Methods for Polymeric Materials. Part 1. Radiant Furnace Test Method," *J. Fire Sci.*, Vol. 12, No. 2, pp 109-133, Mar/Apr 1994.

[40] G. C. Stevens, M. R. Dickson, M. G. Weller, "Acid Gas Emissions from Electrical Insulation and Their Influence on Electronic Components," in *IEEE Dielectric Materials, Measurements and Applications*. 5th Int. Conf. IEEE Conf. Publication 289. June 27-30, 1988, London, England, pp. 51-54.

[41] D. Pauls, "IPC Cleaning and Cleanliness Test Program: Phase 3 Water Soluble Fluxes Part 1," Institute for Interconnecting and Packaging Electronic Circuits (IPC), IPC 1992 Fall Meeting, Published by IPC, Lincolnwood, IL, Oct 12-15, 1992.

[42] J. A. Emerson, D. W. Peterson, and J. N. Sweet, "HAST Evaluation of Organic Liquid IC Encapsulants Using Sandia's Assembly Test Chips," *IEEE Proceedings of 42nd Electronic Components & Technology Conference*, 1992, pp. 951-956.

[43] W. H. Abbott, "Comparison of Electronic Components Degradation in Field and Laboratory Environments," *Materials Performance*, Vol. 30, No. 6, pp. 55-58, 1991.

[44] G. G. Neuburger, "Detection of Ambient Hydrogen Chloride with Zinc-Coated Piezoelectric Crystal Resonator Operating in a Frequency-Time Differential Mode," *Anal. Chem*, Vol. 61, p. 1559, 1989.

Appendix C
Preliminary Tests of the Impact of Smoke on Digital I&C Equipment

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Abstract

This report presents the results of three preliminary smoke exposure tests on active digital equipment. The smoke from three different types of cable was used to generate the test environments. These tests show that intermittent failures of digital equipment can occur within minutes of exposure to smoke. These failures are most likely caused by bridging of circuits by soot. Although loss of metal due to corrosion is highly correlated to the failures exhibited in these tests, it is not a likely short-term failure mode. Measurements such as temperature, humidity, soot deposition, and chemical analysis of the soot and gases are also presented; however, these measurements do not correlate well to the failures that occurred.

Introduction

Objective

Sandia National Laboratories (SNL) has been tasked by the USNRC to investigate the impact of smoke on the performance and reliability of digital instrumentation and control (I&C) equipment which may be used in nuclear power plants. Studies on the failure of digital equipment in a smoke atmosphere are rare, at least in part because smoke environments are not easy to quantify and reproduce. Standardized tests have been developed by professional groups such as the American Society for Testing and Materials (ASTM) and the National Institute of Standards and Technology. However, at most, these tests have been developed to measure the relative corrosivity of the smoke from various materials or to characterize the smoke output of materials. These tests do not directly address the problems of electrical equipment operation which is the subject of this effort. Because of the lack of a standard test method, SNL has adopted an approach to testing that includes features from standardized smoke corrosivity tests that are currently being developed by the American Society for Testing and Materials. This report provides a description of preliminary experiments performed by SNL. The objective of these preliminary smoke exposure tests was to explore and demonstrate a procedure for investigating *the impact of smoke on digital I&C equipment.*

Scope

Three multiplexer units were exposed to three different smoke atmospheres. One unit failed, while the other two performed without problems. This report describes the exposure method and results of these tests. These tests were only preliminary in nature and a much broader follow-on study is currently underway.

Smoke Exposure method

Smoke Exposure Environment

Smoke is a known hazard for electronic equipment; however, very few tests have been performed to determine the reliability of electronic equipment in a smoke atmosphere. Smoke composition can vary depending upon fire characteristics such as burn temperature, oxygen availability, material burned, and whether the fire is smoldering or openly flaming. In order to produce smoke in a standard and reproducible way for the purpose of these preliminary tests, the ASTM draft corrosivity test standard produced by the E5.21.70 Subtask group was followed. This draft standard was based on a standard toxicity test that has been in use for many years. The primary measurement of this draft standard is the loss of metal from a corrosion probe as a function of the material burned. Although the objective of this ASTM test (relative corrosivity) is different from our objective of testing electronic equipment reliability in a smoke environment, the methods of smoke production and the time of exposure to the smoke were adopted as the fundamental basis for producing a "standard" smoke environment and exposure scenario.

The fuel was burned using radiant heat from a tungsten-quartz lamp aided by spark ignition inside a cylindrical quartz combustion chamber. The smoke production and exposure equipment is illustrated in Figure 1. The radiant heat lamps are adjusted so that a fixed heat flux level of 50 kW/m^2 is produced at the fuel surface. The heat flux was measured with a Schmidt-Boelter (thermopile) heat flux meter before each test to determine the amount of heat that is incident on the fuel at the beginning of the test. Small variations in the positions of the lamps can affect the heat flux that is incident on the sample. As smoke is produced, the quartz chamber becomes coated with some soot and so the heat flux is reduced. No attempts were made to compensate for this effect.

Nowlen[1] reported on the types of fires that take place at nuclear power plants and their typical fuel load, where the fuel load is defined as the ratio of the weight of fuel consumed to volume of air. The highest fuel load occurs in cabinet fires because of the limited volume of air in the cabinet. Of course, if the fire is very large it will burn up all of the equipment in the cabinet, but for a moderate fire, the equipment may survive the heat and flames but not the smoke. For these preliminary smoke exposures, the fuel load was selected to simulate this high fuel load condition. A fuel load between 26 g/m^3 and 560 g/m^3 corresponds to a small cabinet fire; therefore, a fuel load of 75 g/m^3 was chosen for these tests.

The volume of the exposure chamber was 0.2 m^3, so 75g/m^3 requires 15 g of burnable fuel. Since the most abundant fuel in a nuclear power plant is cable insulation and jacketing material, cables were used to produce the smoke. The amount of cable material burned was determined by stripping the insulation material from a sample cable piece and weighing the fraction of the total cable weight that is made up of insulation. Typically, the insulation and jacketing materials comprised 50 to 75% of the total mass of the cable. Lengths of cable which corresponded to 15 g of insulation were loaded into the combustion cell on aluminum trays. The loaded trays were weighed before and after the burn.

We expect that the type of fuel determines how destructive the smoke will be. In a power plant there are several different types of cables used for instrumentation, power and control. In addition, there are cables with insulation types that are no longer used for new applications, such as as polyethylene and polyvinyl chloride (PVC), but which remain in place at the plants. For these smoke exposures, three types of cable were burned, one type in each test. Test 1 used Brand Rex cable made with cross-linked polyethylene (XLPE) insulation with a chlorosulfonated polyethylene (CSPE) jacket. Brand Rex cable is the third most utilized cable supplier for nuclear power containment.[2] Test 2 used Anaconda Flameguard cable made with ethylene propylene rubber (EPR) insulation and CSPE jacket. This is the most common combination of materials used for insulation in containment.[2] Test 3 used a Belden, non-nuclear qualified PVC jacketed and insulated cable. Although PVC cables are no longer widely used in nuclear power applications, they are still present in power plants and represent one of the most corrosive of cable insulation materials. The weights of the fuel loaded in the trays are presented in Table 1.

Table 1. Table of Cable Materials used in Smoke Exposures

Test	Cable	Weight/in	% plastic	Sample weight	Plastic weight
1	XLPE/CSPE	4.93 g/in	54.6	27.54g	15.04g
2	EPR/CSPE	6.07g/in	76.0	20.25g	15.4g
3	PVC/PVC	6.41g/in	57.4	26.42g	15.17g

As the radiant heat lamps were turned on and the fuel heated, hot gases and smoke rose up the 30-cm long stainless steel chimney to the Lexan exposure chamber. The lamps exposed the fuel material for 15 minutes as specified in the ASTM draft standard. During the entire 15-minute period, a sparker, located 2.5 cm above the fuel, continuously sparked to provide an ignition source for hot gases produced by the radiant heat lamps. After the 15-minute period, the lamps were shut off, the chimney damper was closed, and a small mixed the smoke vapors. Since this was a static smoke exposure, the smoke was not allowed to leave the exposure chamber for the first hour of the test. The smoke chamber was sealed as well as possible to prevent smoke leaks. To allow for the expansion of air and smoke vapors due to the initial heating and subsequent cooling of the contained air volume, an empty plastic bag was placed over one of the ports. After a total of one hour from the beginning of the test, the smoke was vented.

After the smoke exposure, the ASTM draft standard recommends that the target material (the corrosion probe in the case of the standard) be placed in a controlled environment at 75% humidity and 23°C for a 24-hour period after which the target is retested. This step simulates the environment of a water suppressed fire. This would normally take place in an environmental chamber; however, our environmental chamber was not completed at the time of these tests. Hence, a variety of interim methods were attempted to control humidity with differing levels of success.

In Test 1 we did not add any humidity for the first 24 hours so that the equipment remained at the normal humidity for Albuquerque in the winter, below 20% relative humidity (RH). Since the draft standard recommends holding the RH at 75%, we attempted to do this after the preliminary 24 hours by setting a beaker of hot water in the exposure chamber. However, this added too much humidity. The test unit was left in the humid environment for three days. In Test 2 we added humidity right after venting the smoke, using a portable hot steam humidifier. The humidity was adjusted by opening doors and running fans, but there was no control over the humidity overnight. In Test 3 we added humidity right after venting the smoke. This humidity was added using a portable hot steam humidifier, but it in a more controlled way than for Tests 1 or 2.

According to the draft standard, the RH of the sample should be maintained at 60% prior to the test. The humidity inside of the box was measured before the lamps were turned on, but the humidity sensor was removed after the initial reading to prevent damage to the sensor. The humidity sensor was reintroduced to the smoke exposure chamber after the chamber was vented. Due to the nature of the ambient environment prevailing at the time of the tests, a 60% RH was not achieved in these tests.

Smoke Environment Measurements

The measurement of metal loss, while important in determining the relative corrosivity of the smoke, is not the only parameter of interest in the smoke environment. Other standard measurements of smoke, such as optical density, rate of fuel combustion, and time of ignition and extinguishment, have been specified by the ASTM. We attempted to characterize the smoke environment by making these measurements, along with others such as temperature, smoke deposition, and chemical analyses of gases and soot.

Corrosion Probe

The metal loss measurement is made with Rohrback/Cosasco probes that measure metal loss via changes in resistance of a copper trace deposited on a printed circuit board. In the SNL tests resistance was monitored with a high precision LCR (inductance, capacitance and resistance) meter. The probe contains two copper traces of the same thickness and width: an uncoated trace that is allowed to corrode and a reference epoxy-coated trace. The purpose of the two traces is to separate the changes in resistance due to metal loss from changes due to temperature fluctuations. Since the original intent of these probes was to measure atmospheric corrosion, the copper probes normally sold by Rohrback/Cosasco (250 nm thick) are too sensitive (thin) and were found to corrode away too quickly. The ASTM draft standard suggests using a thicker probe (4500 nm) for greater longevity. The process used to deposit the copper traces on the thicker probes differs from that used on the thin probes. For these tests both probe thicknesses were used. Since changes in these measurements were expected to occur relatively slowly, the measurements were made at one minute intervals during the first hour of the test, and at 10-minute intervals during the rest of the test.

Load Cell

A commercial load cell (Single Point I, Interface Inc.) measured the loss of mass of the fuel as it burned. The load cell was mounted under the quartz combustion cell as shown in Figure 1. The fuel tray was mounted to the load cell through a hole in the combustion cell. The load cell converts force by means of a strain gage into voltage and can measure weights up to three pounds. Load cell output was recorded at five second intervals during the first 15-minute period to determine how quickly the fuel was consumed. This measurement is included in the ASTM draft standard.

Thermocouples

Temperature measurements were made throughout the test, in seven locations in the smoke exposure chamber. Five Chromel-Alumel (type K) thermocouples housed in stainless steel sheaths penetrated the walls and floors of the smoke chamber, (Figure 1). Two non-sheathed type K thermocouples were welded to the surface of the quartz crystal microbalance cases (see discussion in Section 0.) Although the temperature of the chamber was not controlled, temperatures were measured to determine if any failures could have resulted from heat rather than smoke. Temperatures were logged at five-second intervals while the lamps were on and at one-minute intervals for the remaining time that the smoke was in the chamber. After the smoke exposure chamber was vented, the temperatures were logged at 10-minute intervals.

Turbidimeter

A turbidimeter measures the optical density of smoke by passing light through the smoke and determining the loss of light intensity. Light from a high intensity bulb (white light) is focused with a lens and then passed through a glass slide into the smoke exposure area. After crossing a 3.2 cm-section of the smoke chamber, the light passes through a second glass slide and into another lens. The purpose of the glass slides is to keep smoke from fouling the optical components of the turbidimeter. Beyond the second lens, a combination of prisms and filters divide the light into three colors: red, blue, and infra-red. The optical throughput of each color is then converted by photodiodes into an electrical signal. The voltage from the photodiodes was recorded at five-second intervals while the radiant lamps were on, 1-minute intervals for the rest of the first hour, and at 10-minute intervals after the smoke was vented.

The glass slides collected a coating of soot which should not be included in the smoke density measurements since the measurement should only include the smoke that is suspended in the air. The optical density of the smoke can be estimated from the difference in the turbidimeter output before and after the smoke is vented.

Gas analysis

Gases for the analysis of the smoke were captured in two ways. A vacuum grab system captured a 10 ml filtered sample of gas in a stainless steel bottle. For fuel samples that ignited (flaming rather than smoldering), the gas sample was taken within a minute of the flame extinguishment. If there were no flames, a grab sample was taken after the quartz lamps were turned off (15 minutes into the test). The samples were analyzed by a Tracor gas chromatograph. These measurements provided the percentage of methane, carbon monoxide, nitrogen, carbon dioxide and oxygen present in the sample. The amount of heat releasedwas estimated from the amount of carbon dioxide and carbon monoxide in the air, or the amount of oxygen remaining in the air.

Samples of acids contained in the smoke were collected in a silica-gel-filled sorption tube. A sampling pump pulled 20 ml per minute of smoke through the sorption tube during the entire burn time (15 minutes). Analysis of the tube contents provided information on the relative amount of chlorine present in the chamber. The materials that remained in the sorption tubes were analyzed using ion chromatography following the procedure contained in NIOSH 7903.

Soot Deposition Measurement

Quartz crystal microbalances (QCMs) measured the mass deposition of the smoke as a function of time. The purpose of this measurement was to determine the amount of soot deposited on electronic equipment. Quartz is a piezoelectric material that undergoes shear deformation when subjected to an electrical field. Conversely, if it is strained, it will generate an electrical field. The QCM consists of a quartz crystal with electrodes to connect it to an electrical oscillator that is tuned to the fundamental frequency of oscillation of the crystal. When material such as soot is deposited on the surface of the crystal, the oscillation frequency decreases. The change in frequency can be related to the additional mass on the quartz crystal. The frequency of oscillation is also dependent on the temperature of the crystal, so thermocouples were attached to the QCM case to determine the temperature around the crystal (as noted in Section 0 above).

Two QCMs were used to measure the deposition, one in a horizontal face-up orientation and one in a vertical orientation. The oscillation frequency was recorded at intervals of five seconds while the heat lamps were on, and at one-minute intervals for the remaining first hour. After the smoke was vented, the frequency was recorded at 10-minute intervals.

Soot Analysis

Ashless filter papers were used as a substrate to collect soot samples for chemical analysis. Two filters were placed at the bottom of the smoke exposure chamber for each test to gather samples of soot. These samples were submitted for chlorine analysis by ion chromatography and for trace metals analysis by plasma-excited atomic emission spectroscopy (IPC). Ashless filters are used because the analysis involves burning up the filter paper. Soot samples were also scraped from a stainless steel sheet placed on the bottom of the smoke exposure chamber. The soot was analyzed for total organic carbon.

Digital Equipment Description

The first component smoke tests at SNL have evaluated the affect of smoke deposited on the Analog Devices® modules and backplanes. These components were selected by Oak Ridge National Laboratory for testing because they incorporated operations needed for a reactor trip system in a commercially available product.

Hardware

Analog Devices sells a series of plastic encased modules that can perform different functions: measure voltage, measure thermocouple or resistive temperature device (RTD) output, and then output current or voltage. All of these modules plug into a printed-circuit type board called a backplane. The backplanes are powered with a 5 volt DC power supply. For these tests we bought a 6BP04-2 backplane that can support up to four modules at one time. The backplane has ports for an RS232 communication and an RS485 connection. The communication ports allow the backplane to send and receive information from a computer to the various modules using ASCII characters.

The modules are sold with a computer program that can configure and calibrate the modules. Configuring the module includes determining the address of the module, the mode of function of the module, and defining which port of the computer the module is located. The program can also be used in conjunction with other calibrated equipment to calibrate the modules.

The Analog Output Module, model 6B21, can output a current between 0-20 mA or between 4-20 mA. We configured it to output 0 - 20 mA. The module was set to use engineering units for the output which means that the units are in milliamps (as opposed to a percent of span or a hexadecimal output.) When assembled the module produced a current through a load resistor attached to the adjoining terminal strip on the backplane. The address of the output module was configured to be 02.

To act as test equipment, three 6B12 input modules were configured to measure between -20 to +20 mA. The input modules were also configured to present the data in engineering units (milliamps.) Since the module actually reads voltage rather than current, a precision load from Analog Devices was placed across the terminal strip to act as the load for the output module. The input modules were configured to be at address 01.

In order to allow the physical separation of the input and output modules needed for this test, two separate backplanes were used, each requiring its own serial port. We used a Hauppage 386 personal computer with an additional IO board to provide the serial ports (RS232). Thus the input module was plugged into a backplane connected to the RS232 port called COM1 and the output module was plugged into a separate backplane that was connected to the RS 232 port COM2. The mode of communications was 9600 baud, eight data bits, no parity, and one stop bit.

A diagram of the hardware wiring is shown in Figure 2. The current from the output module was determined by measuring the voltage (using the input module) across a precision resistor. The input module was placed inside of the smoke chamber and the output module was placed outside of the smoke chamber. During the smoke exposure the input module measurements were compared to the output module readings. Ideally the measurements should match exactly.

Software

The software for assessing the performance of the test modules was developed by Kofi Korsah at Oak Ridge National Laboratory in the form of a Turbo Basic program,. It has several menu items to test the modules singly or to test the system as wired above. There are also options to print out the data files to the screen or to a printer.

For the system test, the computer directs the output module to feed a known current to the input module. The computer reads the actual output module current and reads the input module measurements at one-second intervals. The computer then changes the output current and repeats the readings. The current output starts at 0 and is incremented by +0.1 mA steps up to 20 mA. After the current output reaches 20 mA, the data from the previous 1400 readings are recorded in a data file. The process is then repeated. Because the program only stores data after 1400 readings (approximately 20 minutes of data measurements), system failures can cause significant loss of data.

Test Results

General Observations

Before each smoke exposure, the test units were assembled and tested to verify functionality. The test program, MUXTEST5 was then run continuously throughout the smoke exposure and post-exposure periods. The results of the multiplexer board exposures are listed in Table 2. The XLPE/CSPE cable (Brand Rex) and PVC cable (Belden) both caught fire while the EPR/CSPE cable (Anaconda Flameguard) only smoldered. In fact, the PVC cable caught fire at 1:39 (min:sec), extinguished at 4:02, and reignited at about 5:00 and extinguished at approximately 8:00. The XLPE/CSPE cable ignited at 3:18 into the test and extinguished at 5:18.

Table 2. General Results of Smoke Exposure

Test	Cable	Equipment performance
1	XLPE/CSPE	No change
2	EPR/CSPE	No change
3	PVC/PVC	Intermittent failures

The smoke affected the equipment by halting MUXTEST5 rather than affecting the output data values. Intermittent failures during Test 3 occurred three times. The first malfunction occurred at 8:40 after the start of the test, while the radiant heat lamps were on and resulted in stopping MUXTEST5. The computer indicated an error code and returned to the disk operating system (DOS) prompt, indicating that MUXTEST5 had stopped. MUXTEST5 was restarted and the data was normal. The next malfunction occurred at about 1:00:00 (one hour) when the chamber was beginning to be vented. This malfunction did not stop the program, however the numbers in the data file were unusual and the printout on the screen was shifted. At 1:20:00 humidity was added to the environment. The next malfunction at 1:29:00 stopped MUXTEST5 and returned the DOS prompt with the same error code as the first malfunction. Again, the program could be restarted and the data was normal. The first and third failures are believed to be a communications error, but since the there was no error trapping in the program to accommodate these problems, the true nature of the failures are unknown. MUXTEST5 stopped again around midnight, but that failure was probably due to problems in accessing the timer during the change from one day to another.

The smoke-exposed equipment from Tests 1 and 2 both operated normally throughout and after the smoke exposures. Although the equipment showed some visible soiling, this did not affect the performance of the equipment. Steel parts that were exposed to Test 3 are especially corroded after exposure.

To further explore failures in the equipment exposed during Test 3, the equipment was periodically tested for one month after the smoke exposure. The equipment continued to operate normally until humidity was added in the form of mist from a cool water mister. The mist condensed on the backplane and caused the backplane to short. When the backplane began to short, MUXTEST5 stopped again and produced the same error message as at 8:40 and 1:29:00 into the smoke exposure. This time, however, the equipment was permanently damaged and would not restart.

Comparison of Measured Values

Physical Measurements

Physical measurements of the smoke environment include the temperature, humidity, optical density of smoke, mass deposition of soot, and loss of mass from the burning fuel. These qualities help to identify the environment of the smoke exposure chamber.

The temperature was measured in seven locations in the smoke enclosure. The temperatures in the exposure chamber varied depending on the position in the chamber. The heat in the chamber was created by two sources, the radiant heat of the lamps and the heat from burning fuel. The highest temperature was measured in the chimney. The second highest temperatures were recorded at the top of the exposure chamber above the chimney. Temperatures in the middle of the chamber, where the test equipment was located, were very close in value to temperatures at the top of the chamber in the corner away from the chimney. The lowest temperatures were located along the floor in the corner away from the chimney. These temperatures are presented in Figure 3 for Test 1. Tests 2 and 3 had similar differences in temperature within the chamber. After the first hour, when the chamber is vented to the atmosphere, there is little variation in the temperature from location to location.

Temperatures in the exposure chamber were increased by addition of heat from both the radiant heat lamps and the burning fuel. The heat from the burning fuel is a significant contributor to the temperature of the chamber as shown by the Figure 4. Here both the PVC and XLPE/CSPE cables, which were openly flaming, have higher temperatures than the EPR/CSPE cables which only smoldered. The XLPE/CSPE cable showed an especially prominent peak at approximately 0.09 hours into the test. Since the PVC cable flame extinguished and then reignited, the peak in temperature is not as evident. This peak is more prominent for temperatures measured nearer the chimney than for those located away from the chimney as shown in Figure 3. For the locations farther away from the chimney, the heat is more dispersed and does not have such a sharp peak in time while the fuel was flaming.

The load cell information (Figure 5) shows the change in mass of the fuel as it is consumed. The smoldering EPR/CSPE fire consumed less fuel than the two flaming fires. The rate of mass loss is much higher while flaming than after the flames are extinguished.

The humidity measurements in the smoke exposure chamber were only valid after the smoke was evacuated from the exposure chamber, about one hour and 20 minutes after the start of the smoke exposure. As can be seen in Figures 6, 7 and 8, humidity was added to the smoke exposure chamber after the first 24 hours for Test 1 and after the first hour and 20 minutes for Tests 2 and 3. Since one of the intermittent failures during Test 3 occurred nine minutes after the humidity was first introduced, we can conclude that humidity was a contributor to the failure.

The optical density of the smoke includes the optical density of the deposit on the surface of glass slides which protected the optical parts of the turbidimeter. The maximum optical density for all of the tests was between 0.33 and 0.40/cm^2. However, the quality of smoke from Test 2 was very different from those from 1 and 3. Smoke from flaming fires tend to be very black while the smoke from smoldering fires is white. The soot from flaming fires is black while the soot from smoldering fires is brown. While optical density is a standard measurement endorsed by the ASTM, it did not seem to be particularly significant for these tests. Typically the smoke was the most dense after the first five minutes of the burn, and then tended to clear up as the soot settled out of the air. Figure 9 shows a typical output from the turbidimeter.

The soot deposition varied as a function of time, and as expected, the horizontally oriented probe collected more soot than the vertical orientation as shown in Figures 10 through 12. The mass deposition measurements were not continuous because of problems with shorting of the quartz crystal oscillator circuit during some of the tests. Because the quartz crystal oscillator frequency will change as the temperature changes, one thermocouple was attached to the case of each oscillator. The temperature of these thermocouples never varied as much as the thermocouple that was suspended in the middle of the exposure chamber, although they were placed very close together. The temperature of the air fluctuates more rapidly than that of a stainless steel case due to the differences in material thermal capacity; which accounts for the differences. The temperature for which the oscillator circuit should actually be compensated is that of the quartz crystal itself; however, these measurements were not made. The values of deposition in Table 3 were measured after the smoke exposure chamber was vented.

Table 3. QCM results

Test	Vertical Deposition	Horizontal Deposition
1	29 $\mu g/cm^2$	42 $\mu g/cm^2$
2	17 $\mu g/cm^2$	182 $\mu g/cm^2$
3	17 $\mu g/cm^2$	47 $\mu g/cm^2$

The deposition in the horizontal orientation was much higher for Test 2 than for Tests 1 and 3, although the deposition in the vertical orientation was not significantly different from Test 3. The soot was also much more tacky and black in the cases of Tests 1 and 2.

Chemical Measurements

The chemical measurements of the gases and material were performed at SNL. Ion chromatography analysis of the filter paper and sorption tubes as well as the total carbon in a sample of soot are included in Table 4. Analysis of metals from the filter paper is presented in Table 5. The analyses of the vacuum grab samples by gas chromatography is presented in Table 6.

Table 4. Cl and C Chemical Analysis

Test	Cable	Filter Paper Total Cl (14 cm^2)	Sorption Tube Total Cl	% Carbon (wt)
1	XLPE/CSPE	0.45 mg	0.24 mg	13.4
2	EPR/CSPE	1.13 mg	0.07 mg	37.6

3	PVC/PVC	0.35 mg	0.23 mg	9.05

A surprising result of these analyses was that the amount of Cl from Test 2 was significantly higher than for Test 3; however, the much higher proportion of horizontal deposition as shown in Table 3 may account for the large amount of Cl deposited on the filter. The amount of Cl on the filter paper is 207 μg/in^2 for Test 1, 520 μg/in^2 for Test 2 and 161 μg/in^2 for Test 3. Reagor[3] has determined that the ability to salvage electrical equipment after a fire, as well as long-term failure rates, are dependent on the amount of Cl contamination that is present. All of these values of Cl deposition are within the range of salvageable equipment according to Reagor (200 to 600 μg/in^2.)

Table 5. Particulate Analysis (μg/14cm^2)*

Test	Zn	Cu	Ag	Fe	B	P	Pb	Sb	Sn
1	1.3	131	ND	3	8	ND	87	222	ND
2	0.5	29	ND	1	5	ND	1180	6	ND
3	0.7	119	6	3	ND	24	146	60	23

* ND means that the amount of metal was below the detectable limit of the analysis. The detection limit is 1 μg/filter.

The analysis of the particulate shows that some metals are deposited along with the soot.

Table 6. Analysis of Vacuum Grab Sample

Test	CH_4	CO	N_2	O_2	CO_2
1	0.3%	1.0%	74.0%	15.0%	3.7%
2	0.1%	0.5%	73.4%	17.8%	2.3%
3	0.0%	0.5%	80.0%	18.3%	1.5%
Stand. Air [4]	0.0%	0.0%	78.084%	20.946%	0.033%

The uncertainty is this measurement is estimated to be ±5% of the reading.

The vacuum grab samples were taken at different times in the test. For Test 1 the sample was taken at 6:03 into the test, after the flames went out. For Test 2, the sample was taken at 15:30, after the lamps were turned off because the fuel never ignited. For Test 3, the sample was taken at 4:28, however, the fire started again at 5:00. Any calculations from the grab sample data from Test 3 would be incomplete because the cable had not completed burning.

Since the fraction of O_2 present after the test is smaller in Test 1 than in Test 2, we can assume that more fuel was burned Test 1. In addition, the fuel mass loss was 12.8 g in Test 1 and 9.54 g in Test 2. The heat released from the fuel may be calculated using the grab sample analysis. This calculation is based on the percentages of O_2, CO and CO_2 before and after the burn as described by Parker.[5] The heat released from this calculation is 0.232 MJ for Test 1 and is 0.134MJ for Test 2.

Corrosion Probe Results

Loss of metal measurement on corrosion probes may be the factor most closely related to the failures of the test unit. Test 3 (PVC) cable was by far the most corrosive smoke and also was the only test to have failures. Because of the intermittent nature of these failures, however, the failures themselves were probably not due to loss of metal, but rather to circuit bridging by soot. Perhaps the increased corrosivity of the smoke (which produces more metal loss) also encourages circuit bridging. Figures 13 through 15 show the loss of metal for the corrosion probes for Tests 1, 2 and 3. The effect of adding humidity to the environment severely affected the corrosivity probes: for both Test 1 and 3 the change in rate of metal loss for the thin probes is significant after the humidity was raised.

There is very little correlation between the loss of metal for the thick and thin probes. The processes for depositing the copper is different for the two types of probes so the structure of the copper on the probes may be different. In general it was found that the thick probes are too insensitive and the thin probes are too sensitive for our purposes. A probe thickness that is in between 250 and 4500nm would be better for corrosivity testing.

Conclusions

Our tests show that smoke can cause failures in digital electrical equipment during the first 24 hours. These failures may be intermittent. These failures may be caused by intermittent shorts from soot that bridges conductors in circuits. One explanation as to why the shorts observed in these tests were intermittent is that when the short occurs, the current flow will cause the soot on the current track to be burned off or to move. The equipment could then be restarted because the current path for the short circuit would no longer exist. Corrosion also occurs, but it takes much longer to cause failures. We conclude that the failures observed were in fact caused by circuit bridging faults.

Humidity is a significant factor in producing failures. Humidity may add to the conductivity of the soot as well as increasing the metal loss of conductors. Unfortunately, the humidity in a smoke environment is difficult to measure since the smoke will damage the sensor and can produce erroneous readings. Humidity control is important for standardizing any smoke exposure tests. Future SNL tests are to be performed under closely controlled humidity conditions.

When the physical and chemical measurements taken during these tests are compared, few show significant differences between those exposures that resulted in equipment failure and those that did not. The loss-of-metal measurement was the strongest indicator of failure for the digital equipment although the suspected failure mode was not loss of metal (corrosion). A better measurement would be to test directly for circuit bridging. One such test would be to measure the insulation resistance loss between conductor traces as smoke is deposited. As insulation resistance is lost, the likelihood of shorting will increase. Such tests are planned as a part of follow-up efforts.

Needed improvements in testing software were identified in these tests. The testing software should be robust enough to recover from intermittent failures. In these tests intermittent failures caused the testing software to stop which resulted in losing data from the computer and interrupting the testing process routine. Determination of the time of failure could only be estimated based on when the operator noticed that the program had failed. The software also should include error trapping features which would allow errors to be detected and recorded, and yet not cause the program to stop because of the smoke-induced equipment malfunctions. It was found that the computer timer is reset at midnight, and since MUXTEST5 accesses the timer, the program always failed at midnight.

In summary, the preliminary smoke exposure tests reported here show that intermittent failures of digital equipment may occur within minutes of exposure to smoke. These failures are most likely caused by bridging of circuits by soot. Although loss of metal due to corrosion is highly correlated to the failures exhibited in these test, it is not a likely failure mode in such a short period of time.

References

1 Nowlen, S. P. Letter report on "Defining Credible Smoke Scenarios" dated September 30, 1994.
2 Bustard, L. and Holzman, P. "Low-Voltage Environmentally Qualified Cable License Renewal Industry Report; Revision 1", TR-103841, Published by Electric Power Research Institute, July 1994.
3 Reagor, B.T., "Smoke Corrosivity: Generation, Impact, Detection, and Protection", *J. Of Fire Sciences*, Vol. 10, March/April 1992.
4 Weast, R.C., *CRC Handbook of Chemistry and Physics*, 69th Edition, p. F-155, 1988-1989.
5 Parker, W. J. "Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications," NBSIR 81-2427-1, March 1982.

Appendix D

Letter Report to the USNRC

Smoke Exposure Conditions for Experimental Digital Trip System

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February 22, 1996

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Smoke Exposure Conditions for Experimental Digital Trip System

Abstract

In collaboration with Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL) performed a series of tests exposing an experimental digital safety system to smoke to determine the reliability of such a digital system in fires in nuclear power plants. ORNL built the experimental digital trip system to serve as a representative safety trip channel in environmental tests. Eight smoke exposures and a high temperature test were performed, as well as a test with CO_2. The smoke environments were specified by the amount and type of fuel burned, the burn temperature, and the humidity level of the environment after the burn. This report documents the physical and chemical measurements of the environment to which the digital safety system was exposed.

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I would like to acknowledge the help of Kofi Korsah, Brian Swail, and Richard Wood from Oak Ridge National Laboratory in providing a test unit, assisting in the exposures, and documenting the test. They are to be especially commended for the excellent cleanup of the smoke exposure unit. I would also like to thank D. Michael Ramirez for his participation in the tests, in both setting up the equipment, helping to run the tests, and being in charge of the cleanup after every test. This work has been sponsored by the USNRC under the technical monitoring of Christina Antonescu.

Table of Contents

ORNL Experimental Digital System Exposures

Introduction

Project Objectives

The objectives of these tests were to expose an experimental digital safety system to credible smoke environemnts. These exposures will help determine the failure modes of a digital safety system in a smoke environment. The results will be added to information from other environmental tests to determine the risk that can be expected from the use of digital equipment.

Scope of Study

Test conditions simulated two generic locations within a nuclear power plant: the control room, where the humidity is low and there are no sprinklers, and general plant areas where the humidity may be higher and sprinklers could be used to suppress a fire. The digital safety channel was exposed to three levels of smoke corresponding to: (1) a small fire in a large room, (2) a small fire in the same cabinet as the safety equipment, or (3) a medium fire in the same room as the safety equipment. These conditions are summarized in Table 1.

Table 1. Simulation Conditions

Smoke Load	Humidity	Suppression	Simulation Scenario
Low: 3 g/m^3	30%	CO_2 or none	Control room - large fire located in separate cabinet from equipment
	80% after fire	Water	General plant area - large fire located in separate cabinet from equipment
Medium: 26 g/m^3	30%	None	Control room-small fire located in the same cabinet as equipment
	80% after fire	Water	General plant area - small fire located in the same cabinet as equipment
High: >200 g/m^3	30%	None	Control room - medium fire located in the same cabinet as equipment

This report presents the physical and chemical environmental measurements for the eight smoke exposures that took place between May 30 and June 15, 1995 under the project "Impact of Smoke on Advanced I&C System Hardware," FIN W6051. Temperature and humidity were also recorded between smoke exposures while the safety system was exercised to determine whether the system was operating correctly (baseline runs). This report only contains information on the smoke conditions, such as temperature, amount of fuel burned, smoke deposition and chemical analysis. Information on the errors of the experimental digital system is included in NUREG/CR 6406 [Korsah et al., to be published].

Experimental Setup and Procedure

This section describes the test equipment, smoke exposure method, measurements, and schedule. The tests were based on the ASTM E05.21.70 draft standard on corrosivity [Kessel, et al., 1994], but we enlarged the smoke exposure volume, and added other types of measurements. The enlarged volume accommodated rack-mounted equipment. In order to produce enough smoke for the larger volume, four combustion cells were used instead of one. Measurements besides those used on the corrosivity draft standard were added so that the environment could be more fully characterized. These additional measurements included chemical analysis of soot and gases, smoke optical density, mass deposition rates, and temperature.

Test Equipment

The experimental digital trip system tested consisted of three main components: the multiplexer and its computer (PRS/MUX), the digital trip computer (DTC), and the fiber optic modules (FOMs). These components were individually exposed to smoke; however, in order to determine the condition of the exposed component, they all needed to operate and communicate with one another during the smoke exposure. Communications between these components were monitored by a separate host computer that was never exposed to smoke.

It is known from previous smoke exposures that in digital equipment communication errors may result in intermittent failures rather than permanent failures (Appendix 3). The software for this system was designed to wait for the correct response for a specified period of time and then to retry the operation rather than halt it when an incorrect response was received. Because of the critical safety issues during a fire, these intermittent failures can be important for a nuclear power plant. The tests were designed to study only short-term failures which would take place within 1 day of the smoke exposure. Long-term failure modes (on the order of several days to weeks), which can also be important, were not pursued because the test schedule did not allow for it. Such a study may be important in the future in terms of what equipment can be reused after a fire.

The equipment was exposed for 1 hour and then the smoke was vented. Equipment was monitored for at least 12 hours after exposure and then cleaned. The cleaned equipment was used for subsequent exposures. To determine if the cleaning process was effective, the baseline operation of the equipment was monitored in a controlled environment for several hours. The PRS/MUX was exposed to smoke four times while the DTC was exposed to smoke three times and once to CO_2. The FOMs were exposed to a smoke environment as well as high-temperature tests since earlier tests showed that they were very sensitive to heat.

Smoke Production

No standard procedure exists to test the reliability of electrical equipment exposed to smoke and smoke is a difficult environment to reproduce consistantly. When fuel burns, it produces many different chemicals whose concentrations are dependent on the burning conditions. Conditions such as the fire temperature, amount of oxygen available for burning, whether the fuel is stacked tightly or spread out, and whether there is a flame or only a smoldering fire can affect the type of smoke that is produced. The amount of damage to the equipment may be affected by the temperature and humidity during and after the fire. The soot that deposits on the equipment will be affected by the distance the smoke travels from the fire to the equipment. In order to test the reliability of a digital safety system, it must be exposed to a known, reproducible environment.

In these tests, the fire scenarios for different areas of a nuclear power plant were specified (Appendix 1) in terms of (1) the ratio of fuel mass available to be burned to the volume of air available defined as the smoke load, (2) the presence of humidity, and (3) addition of fire suppression agents. The scenarios were selected from this set of possible smoke conditions as shown in Table 1.

The smoke was produced in an enclosed volume following the basic protocol (with some modification) of the American Society for Testing and Materials (ASTM) draft standard on smoke corrosivity as developed by subtask group E05.21.70 [Kessel, et al., 1994]. These exposures are small-scale tests. No claims have been made by the ASTM that this test models a true fire; however, the fuel-to-air volume, smoke duration, and humidity levels were modified to simulate nuclear power plant fires.

The type of fuel burned to produce the smoke is a key factor in the amount of damage to the electronic equipment. In a nuclear power plant, there are many sources of fuel for an accidental fire, but the most abundant source is cable insulation. Many different qualified cables are used for instrumentation and control. In addition, there are cables that are no longer in use but are still in place. Because of the wide variety of available cables and the limited scope of these tests, we burned a mixture of cable types rather than testing the effect of individual cables.

The cables were selected from Table 3.4 in "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report; Revision 1" [Bustard and Holzman, 1994], which lists the ten most popular cable types used inside containments and the number of plants that use these cables. From this table, the proportion of plants in which each of the cables were used was determined. Common materials used for insulation and jacketing for these cables include ethylene propylene rubber (EPR), chlorosulfonated polyethylene (CSPE), neoprene, and cross-linked polyethylene (XLPE). The mass of a particular cable's insulation and jacket material in the fuel mixture was proportional to the number of plants that used the cable in containment.

A list of cable materials used in the smoke exposures for each of the tests is presented in Table 2. The amount of fuel for each test corresponds to the conditions that were to be simulated as presented in Table 1. Tests 1 to 4 correspond to a low smoke load, tests 5 and 6 to a medium smoke load, and tests 7 and 8 to a high smoke load. The weight of the cable per length and percentage of plastic was measured by stripping the insulation material from sample pieces. Typically the insulation material weighed 50 to 75% of the total mass of the cable. After determining the length of cable required to obtain the correct amount of fuel, the lengths were measured and cut for the fuel load. Rather than just the insulation, the entire cable was placed in the combustion cell. The fuel was loaded into small aluminum trays for ease of weighing before and after the exposure. These measurements determined how much fuel was burned.

Small amounts of cable are difficult to cut and measure; therefore, for the small smoke loads of 3 g/m^3, a reduced number of cables was used to produce the necessary amount of fuel. The masses for cables of similar composition from the cable mixture were combined and one cable was used to represent this combination. For the larger smoke loadings, polyvinyl chloride (PVC) cable insulation and jacket materials were included. Smoke from PVC contains hydrochloric acid and is very corrosive. Although few plants use PVC cables today, PVC used to be a very popular cable insulation, and power plants may still contain some of this material. Approximately 2% of the mass of the fuel consisted of PVC for these larger smoke loads.

Table 2. Fuel

Cable Name	Insulation	Jacket	% plastic	g/inch	Fuel (grams)			
					Test #1 to 4	Test #5 and 6	Test #7	Test #8
Rockbestos Firewall III	FRXLPE	CSPE	56.7	5.07	1.87	10.49	139.49	40.66
Anaconda Flameguard 1kv	EPR	CSPE	75	6.02	1.24	4.95	48.42	18.52
Brand Rex XLPE	XLPE	CSPE	54.6	4.93		5.26	71.33	20.01
Okonite Okolon	EPR	CSPE	60.9	5.73		4.33	53.41	16.62
Kerite HTK	unknown	unknown	73	11.1	1.42	4.83	44.92	17.52
Rockbestos Coax (le)	unknown	unknown	58	1.38	0.53	3.64	47.66	13.68
Raychem XLPE	XLPE	NA	71	1.23	0.40	2.66	28.02	8.77
Dekoran Dekorad	EPDM	CSPE	54.2	2.74	0.80	3.37	45	8.93
BIW	EPR	CSPE	75.6	3.6		2.16	21.3	8.05
Kerite FR			65.6	2.13		1.81	21.04	6.92
PVC	PVC	PVC	56	6.25		1.34	14.72	4.62

The smoke production and exposure equipment is illustrated in Figure 1. Tungsten-quartz lamps provided the heat for combustion. In order to produce flaming combustion, ignition was aided by either an electrical spark or butane pilot flame. The cables would not ignite without the spark or flame. The cylindrical quartz combustion chamber, 32 cm long x 14 cm in diameter, contained the fuel during smoke production. The heat lamps were placed outside of the combustion chambers, directed toward the fuel.

The heat flux was measured with a Schmidt-Boelter (thermopile) heat flux meter prior to each test to ensure that smoke was produced in a consistent manner. Small variations in the positions of the lamps can affect the heat flux that is incident on the fuel. The measured heat flux included heat from the lamps as well as indirect heating from other surfaces surrounding the test chamber which were heated by the lamps. As the temperature of the surrounding surfaces rises, less power is needed from the radiant heat lamps to obtain the same reading from the meter, thus the power needed to obtain a fixed heat flux on the meter constantly decreases. To obtain a single power setting, a computer controlled the lamps and measured the flux meter output to determine the power setting needed to produce 50 kW/m^2 at the fuel surface after 5 minutes of irradiation. This corresponds to the radiant heat produced by a flaming fire. Although the heat flux incident on the fuel could be reduced during a burn by coating the combustion chamber with soot, the lamp power was not adjusted for this effect since the amount of reduction would vary from test to test. The combustion cell was also cleaned thoroughly after each test.

For small amounts of smoke, only one combustion chamber out of the four was used. For medium or high smoke densities, two to four combustion chambers were used. The smoke from the combustion chamber was conducted to the exposure chamber through stainless steel chimneys. Each chimney had a motor-driven damper so that it can be opened and closed remotely. The dampers were opened while the lamps were on, and then closed when the 15- minute burn time was over. The dampers reduced the amount of soot from one combustion chamber that could coat the surface of another chamber.

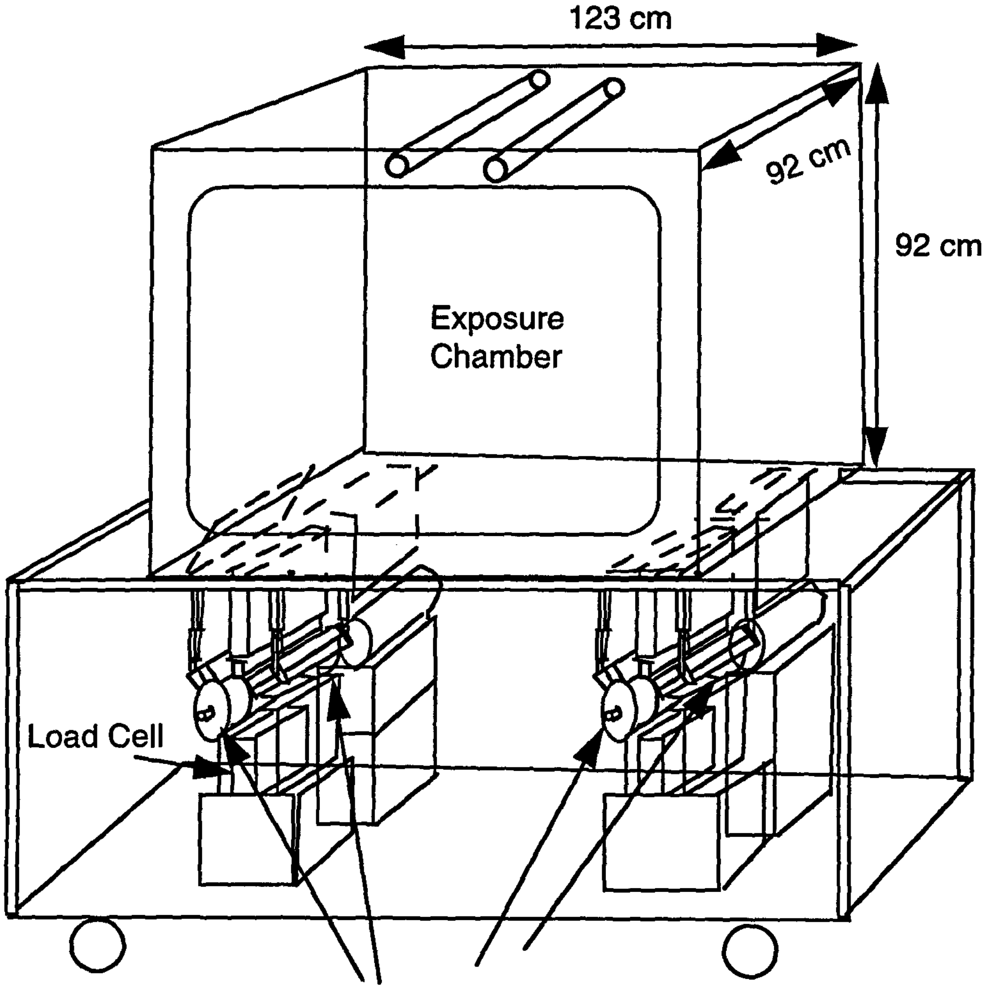


Figure 1. Smoke exposure unit

Exposure of Electronic Equipment

The smoke exposure unit is entirely housed in a walk-in temperature and humidity-controlled environmental chamber. The temperature in the environmental chamber is measured by a type T thermocouple and controlled within about 1 _F. For most of the tests this temperature was 75_ F. The humidity in the environmental chamber is measured using a capacitive humidity sensor. The humidity is produced by an electrical coil submerged in a tank of water within the environmental chamber, and the environmental chamber reduces humidity by running the refrigeration and main heating simultaneously. Because of the lag time in both producing and reducing humidity, the humidity in the chamber is probably only controlled within 5% RH. For these tests the humidity was set for 30% RH.

Although the environmental chamber entirely surrounded the smoke exposure unit, the temperature or humidity within the smoke exposure unit was uncontrolled while the unit was closed up for the smoke exposure. After the smoke exposure, the smoke was vented out of the exposure unit and environmental chamber.

Individual components of the experimental digital safety system were exposed to smoke while the system was operating. In general, the equipment was exposed to smoke for a total of 1 hour, after which the smoke was vented. The exposure time included the time the smoke was being produced. The system was monitored for 24 hours after the beginning of the smoke exposure. Given the limited time of measurements, only short-term failure mechanisms were expected. Potential short-term failures include circuit bridging, contact fouling, or loss of optical transmission. The effects of metal loss due to corrosion would probably not cause failures during these short exposures.

The day after the exposure, the equipment was cleaned using spray degreasing compounds. This process of cleaning the equipment for the next test exposure was important because all the components were necessary to run the system. The intent was to return the component to pre-exposure condition so that it could be reused as either the exposure subject or as an unexposed part of the system during exposures involving other components. The spray degreasing chemicals included Tech Spray Electronics Cleaner/Degreaser and Chemtronics CFC-Free Electrowash 2000. Prior to each exposure, the full system was subjected to baseline monitoring for several hours. This was to determine the pre-exposure state. During the baseline tests, any errors as well as the temperature and humidity of the equipment were logged.

The conditions of each of the eight smoke exposures varied according to the type of environment that was to be simulated as shown in Table 2. The temperature and humidity in a nuclear plant control room are well controlled, but in other areas in a plant the humidity may be high because it is uncontrolled, or the fire may be extinguished with water. For tests simulating conditions outside of the control room, humidity was added during the smoke exposure.

To simulate the high humidity condition, steam was added to the smoke exposure chamber after the fuel was burned. A standard amount of water, 34 g, was converted to steam by heating it for 15 minutes in the combustion chamber. This allowed the digital system to be exposed to smoke and steam at the same time. The amount of water added to the exposure chamber was determined by calculating the volume of water needed to produce 80% RH if the chamber was 80_ F. The amount of water present in the chamber given starting conditions of 30% RH and 75_ F was subtracted from the water needed for the humid condition.

Because of the corrosivity of smoke, an inexpensive humidity sensor with an uncertainty of ±2% RH was placed in the smoke chamber with the equipment rather than using a more expensive sensor with an output signal. This sensor had only a liquid crystal readout, and could not transmit information to the computer. The humidity was recorded manually at intervals during the tests.

Carbon dioxide was added to test 4 after the smoke exposure. The CO_2 was added by means of a fire extinguisher connected to the top of the exposure chamber. While the fire extinguisher was being discharged, the extinguisher was weighed so that approximately 2.5 pounds of CO_2 was added to the chamber. This would correspond to filling the chamber with CO_2 to 60% by volume. The effect was to lower the temperature in the chamber and to remove much of the soot from the air. CO_2 can also induce high static charges.

Smoke Environment Measurements

The measurements presented in the results section of this report include both measurements suggested by the ASTM draft standard and other standard measurements of smoke, such as optical density, rate of fuel combustion, and time of ignition and extinguishment. We have characterized the smoke environment by making these measurements, along with others such as temperature, smoke deposition, and chemical analyses. This section describes how the results were obtained. The measurements performed are listed in Table 3 and procedures are described in this section.

Table 3. Measurements on Smoke Exposure Tests

Measurement	Analysis
Temperature	Baseline temperatures and smoke exposure temperatures were statistically analyzed. The smoke exposure temperatures were plotted.
Humidity	The relative humidity of the environmental chamber was statistically analyzed. Maximum values for the smoke exposure chamber are given if available.
Fuel	Total mass of fuel burned, weight of each cable type in fuel mixture and time for 10 - 90% weight loss.
Smoke Optical Density	Graph of turbidity of smoke for red, blue, and IR wavelengths vs. time.
Soot Deposition	Graph of mass deposition vs. time in horizontal and vertical orientations.
Gas Analysis	Grab sample: Proportion of atmospheric gases in chamber after fire. Sorption tube: analysis of acid gases
Soot Analysis	Filter paper: Chemical analysis of acids deposited on filter paper

Temperature

Temperatures were measured in ten fixed locations in the smoke exposure chamber throughout the test. The locations of the thermocouples are presented in Table 4. Two nonsheathed type K thermocouples (Tq1 and Tq2) were welded to the surface of the quartz crystal microbalance cases. T12 and T13 logged the temperature inside of the experimental digital system that was being exposed to smoke. T17 logged the temperatures near the computers located outside of the environmental chamber, such as the host computer and the parts of the system that were not being tested. T18 and 19 logged the temperatures that were inside the environmental chamber but not in the smoke exposure chamber. Temperatures were logged at 5-second intervals while the lamps were on and at 1-minute intervals for the remaining time that the smoke was in the chamber. After the smoke exposure chamber was vented, the temperatures were logged at 10-minute intervals.

Temperatures were also recorded for the baseline equipment checks. The humidity sensor houses a platinum resistive temperature detector (RTD) for use in calculating relative humidity. This RTD was the only temperature monitored during the baseline runs.

Table 4. Thermocouple locations

T0	Center of floor of smoke exposure chamber
T1	Near lamp 1 in floor of exposure chamber
T2	Near lamp 2 in floor of exposure chamber
T3	Near lamp 3 in floor of exposure chamber
T4	Near lamp 4 in floor of exposure chamber
T5	Top of smoke exposure chamber
T6	Above lamp 1 in smoke exposure chamber ceiling
T7	Above lamp 2 in smoke exposure chamber ceiling
T8	Above lamp 3 in smoke exposure chamber ceiling
T9	Above lamp 4 in smoke exposure chamber ceiling
Tq1	On vertical QCM case
Tq2	On horizontal QCM case
T12	In experimental digital system
T13	In experimental digital system
T17	Laboratory temperature near computers
T18	Floor of environmental chamber
T19	Floor of environmental chamber

Fuel Mass Loss

The fuel mass loss was measured in two ways: aluminum foil trays containing the fuel were weighed before and after each test on a calibrated scale, and load cells measured the loss of fuel mass during the burn at 5-second intervals. The load cells were mounted under the quartz combustion cell as shown in Figure 1. The stainless steel fuel trays were attached to the load cells by a shaft through a hole in the combustion cells. The foil trays containing the fuel were placed on the stainless steel trays for simultaneous burning and weighing. The load cell converts the weight into voltage by means of a strain gage. The active measurement of fuel loss is recommended in the ASTM draft standard. Since the scale used for these measurements was more accurate than the load cell, the final values reported on the amount of fuel burned were determined from scale measurments.

Smoke Opacity

A turbidimeter measured the optical density of smoke by passing light through the smoke and determining the loss of light intensity. The ratio of the initial intensity, I_0, to the transmitted intensity through smoke, *I*, is related to the turbidity (or extinction coefficeint), τ, and pathlength, *l*. The ratios are related by the following equation [Van de Hulst, 1957]:

$$I = I_o \exp(-\tau l).$$

The ideal experiment would only measure the optical density of the smoke in the air, but not that deposited on any surfaces. Because we wished to protect our optical components from the smoke, glass slides were installed. To account for the loss of intensity due to smoke on the protecting glass surfaces, we used two separate turbidimeters with different pathlengths, assuming that the amount of smoke deposited on each glass slide would be equal.

The turbidimeter was arranged as follows: Light from a high-intensity bulb (white light) was focused with a lens and then passed through a glass slide into the smoke exposure area. After crossing an open section of the smoke chamber, the light passed through a second glass slide and into another lens which was isolated from the smoke exposure chamber. The turbidimeter is well collimated A combination of prisms and filters divided the light into three colors: red (0.6328 µ), blue (0.4579 µ), and infrared (1.060 µ). The optical throughput of each color was converted by photodiodes into an electrical signal. The voltage from the photodiodes was recorded at 5-second intervals while the radiant lamps were on, at 1-minute intervals for the rest of the first hour, and at 10-minute intervals after the smoke was vented. One turbidimeter had a pathlength of 1.9 cm and the other had a pathlength of 3.2 cm through the smoke exposure chamber. The resulting turbidity, τ, can be calculated using this formula:

$$-\tau(t) = \frac{\ln\left[\dfrac{I_2(0)\, I_1(t)}{I_1(0)\, I_2(t)}\right]}{l_1 - l_2}$$

where the subscripts 1 and 2 describe the two turbidimeters; *I* is the intensity measured through the turbidimeters at zero time (before the smoke is added) and at any time *t*; and *l* is the respective pathlength for each turbidimeter.

Gas Analysis

Gases were captured in two ways–by a vacuum grab sample bottle and through a sorption tube. A vacuum grab system captured a 10-ml filtered sample of gas in a stainless steel bottle. These samples were analyzed by gas chromatography, which provided the percentage of methane, carbon monoxide, nitrogen, carbon dioxide, and oxygen present in the sample. (For reference, a standard air mixture contains 78% nitrogen, <21% oxygen, <1% carbon dioxide, and <1% argon.)

Samples of acids contained in the smoke were collected in silica gel-filled sorption tubes. A sampling pump pulled 20 ml per minute of air through the sorption tube during the entire burn time (15 minutes). Analysis of the tube contents provided information on the relative amount of acid gases (chlorine, sulfur, and bromine) present in the chamber. The materials that remained in the sorption tubes were analyzed using ion chromatography following the procedure contained in NIOSH 7903. Before the contents of the sorption tube were measured, the instruments were calibrated for chlorine and sulfur only. After all the samples were measured, bromine was found to be a significant contributor for some tests. Since the procedure was not calibrated for bromine, only estimates of the amount of bromine are reported. These estimates are the results of the reported relative sensitivity of the procedure to chlorine and bromine.

Soot Deposition

The purpose of this measurement was to determine the amount of soot deposited on the electronic equipment. Quartz crystal microbalances (QCMs) measured the mass deposition of the smoke as a function of time. Quartz is a piezoelectric material that undergoes shear deformation when subjected to an electrical field. Conversely, if it is strained, it will generate an electrical field. The QCM consists of a quartz crystal with electrodes to connect it to an electrical oscillator that is tuned to the fundamental frequency of oscillation of the crystal. When material such as soot is deposited on the surface of the crystal, the oscillation frequency decreases. The change in frequency can be related to the additional mass on the quartz crystal. The frequency of oscillation is also dependent on the temperature of the crystal, so thermocouples were attached to the QCM case to determine the temperature around the crystal.

Two QCMs were used to measure the deposition–one in a horizontal face-up orientation and one in a vertical orientation. The oscillation frequency was recorded at intervals of 5 seconds while the heat lamps were on, and at 1-minute intervals for the remaining first hour. When the sparkers were used to ignite the fuel, the QCM data were noisier; however, the frequencies recorded at the beginning of the smoke exposure before the sparkers were started and late in the smoke exposure after the sparkers were turned off indicate the amount of soot deposited during the exposure.

Soot Analysis

Previous studies have linked the amount of chlorine in smoke to equipment damage, therefore it is important to determine the acidic compounds deposited on equipment during a fire [Reagor, 1992]. Ashless filter papers were used as a substrate to collect soot samples for chemical analysis. Two filters (4.25 cm diameter) were placed at the bottom of the smoke exposure chamber for each test to gather samples of soot. The samples were analyzed for chlorine, sulfur, and bromine by ion chromatography and for trace metals by plasma-excited atomic emission spectroscopy. As in the sorption tube samples, the procedure was originally calibrated only for chlorine and sulfur, but since a significant amount of bromine was found in the samples, estimates of the amount of bromine are reported using published relative sensitivities between chlorine and bromine. Ashless filters were used because the analysis involves burning the filter paper.

Test Schedule

The smoke exposure schedule is presented in Table 5 and shows the type of exposure, type of equipment (EUT), and conditions such as addition of fire suppression agents. Since the TRP/MUX was most likely to be situated in general plant areas rather than the control room, it is most likely to encounter higher humidity; thus water was added only to exposures of the TRP/MUX. The DTC is most likely to be placed in the control room, so CO_2 was added to a test for the DTC. On June 6, two separate tests were performed–a test to determine the effect of CO_2 alone, and a smoke exposure with the addition of CO_2.

Before each test the equipment to be used was installed in the smoke exposure chamber and the environmental chamber was used to control the temperature and humidity for baseline information. The baseline conditions for each test were recorded with the results of that test.

The last test (8) on the FOMs was performed differently than the others. Because of the anticipated problems due to heat on the FOMs, the environmental chamber was cooled so that when the lamps were on they would not cause the FOMs to fail. Smoke was also produced differently. A low smoke load was burned in lamp 1, and then the smoke was allowed to remain in the chamber for 1 hour. After this, a second lamp with enough fuel to provide for a medium smoke load when combined with the first lamp was burned and the smoke was contained for 1 hour. For the last part of the test, lamps 3 and 4 were burned to bring the total smoke load up to a high level, and then the smoke was contained for 1 hour.

Table 5. Schedule of Smoke Exposures

Date	Activity	Smoke (g/m^3)	EUT	Suppression	Exposure Time
5/30/95	Smoke	2.8	TRP/MUX	none	1 hour
5/31	Clean				
6/1	Smoke	2.8	TRP/MUX	water	add H_20 immed. after burn
6/2	Clean				
6/3	Smoke	2.8	DTC	none	1 hour
6/5	Clean				
6/6	Suppr.	0	DTC	CO_2	add CO_2 only
6/6	Smoke	2.8	DTC	CO_2	add CO_2 immed. after burn
6/7	Clean				
6/8	Smoke	26 w/ PVC	DTC	none	1 hour
6/9	Clean				
6/10	Smoke	26 w/ PVC	TRP/MUX	water	add H_2O immed. after burn
6/12	Clean				
6/13	Smoke	320 w/PVC	TRP/MUX	none	1 hour 20 min.
6/14	Clean				
6/15	Smoke	200 w/PVC	FOM	none	4 hours
6/16	Clean				

Notes:

(1) No PVC in smoke, unless otherwise noted.

(2) Water suppression to TRP/MUX is not a direct spray of water. It is a humidity increase in the area near the unit.

Results of ORNL Exposures

Test 1

Test name: ORNL1
Test date: May 30, 1995
Test time: 16:35:36 EDT

Baseline information: 4.3-hour baseline on May 30, 1995 beginning at 09:36:43 EDT.

Condition	Minimum	Maximum	Mean	SD
Temperature(_C):	19.97	22.37	21.3	0.87
Relative humidity (%):	29.2	42.0	32.1	2.46

Cable Mixture:

Cable name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	2
Anaconda Flameguard 1kv	EPR	CSPE	75	1.23
Kerite HTK	unknown	unknown	73	1.937
Rockbestos Coax (le)	unknown	unknown	58	0.59
Raychem XLPE	XLPE		71	0.53
Dekoran Dekorad	EPDM	CSPE	54.2	0.923

Heat flux: 50 kW/m^2, 1 lamp only
Ignition: Sparkers
Lamp start time: 16:35:53 EDT
Flame start time: 16:37 EDT approx.
Flame off time: 16:38 EDT approx.
Mass loss of cables: 3 g
Time for 10-90% loss of cable mass: 2 min

Suppression: None

Sorption tube time: 1hour
Sorption tube results:

Chloride		Sulfate		Bromide (estimate)	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.023 mg	0.003 mg	0.013 mg	0.003 mg`	0.023 mg	ND

Filter paper results:

Chloride	Sulfate	Bromide*
0.022 mg	0.003 mg	0.009 mg (estimate)

* The bromide values are estimated because the instruments were not calibrated.

Results of Test 1

Grab sample results:

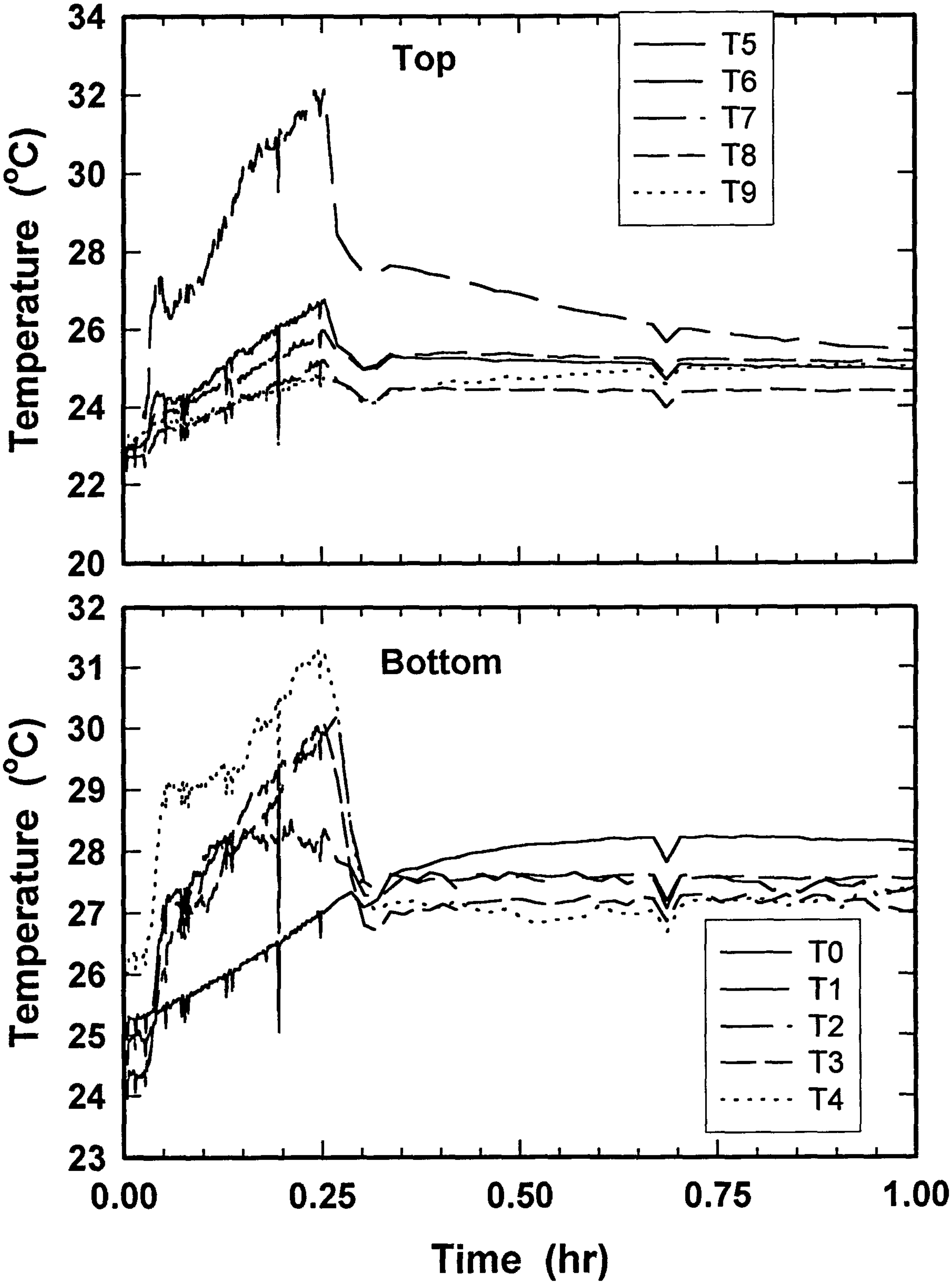
% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
0.8	78.9	20.0	0.0	0.0	0.2	ND

Temperature in chamber (_C):

TC	Minimum	Maximum	Mean	SD
T0	24.93	28.24	26.42	0.95
T1	24.52	30.23	27.74	1.31
T2	23.96	28.51	27.41	1.17
T3	24.01	30.09	27.58	1.61
T4	25.90	31.30	28.85	1.53
T5	22.58	26.78	25.02	0.99
T6	22.55	32.13	28.10	2.51
T7	22.63	25.98	24.68	0.81
T8	22.36	25.20	24.03	0.68
T9	22.92	25.08	24.16	0.55
Tq1	24.37	28.97	26.67	1.32
Tq2	24.50	28.89	26.67	1.26
T18	20.68	22.94	21.90	0.49
T19	20.61	23.04	21.90	0.51

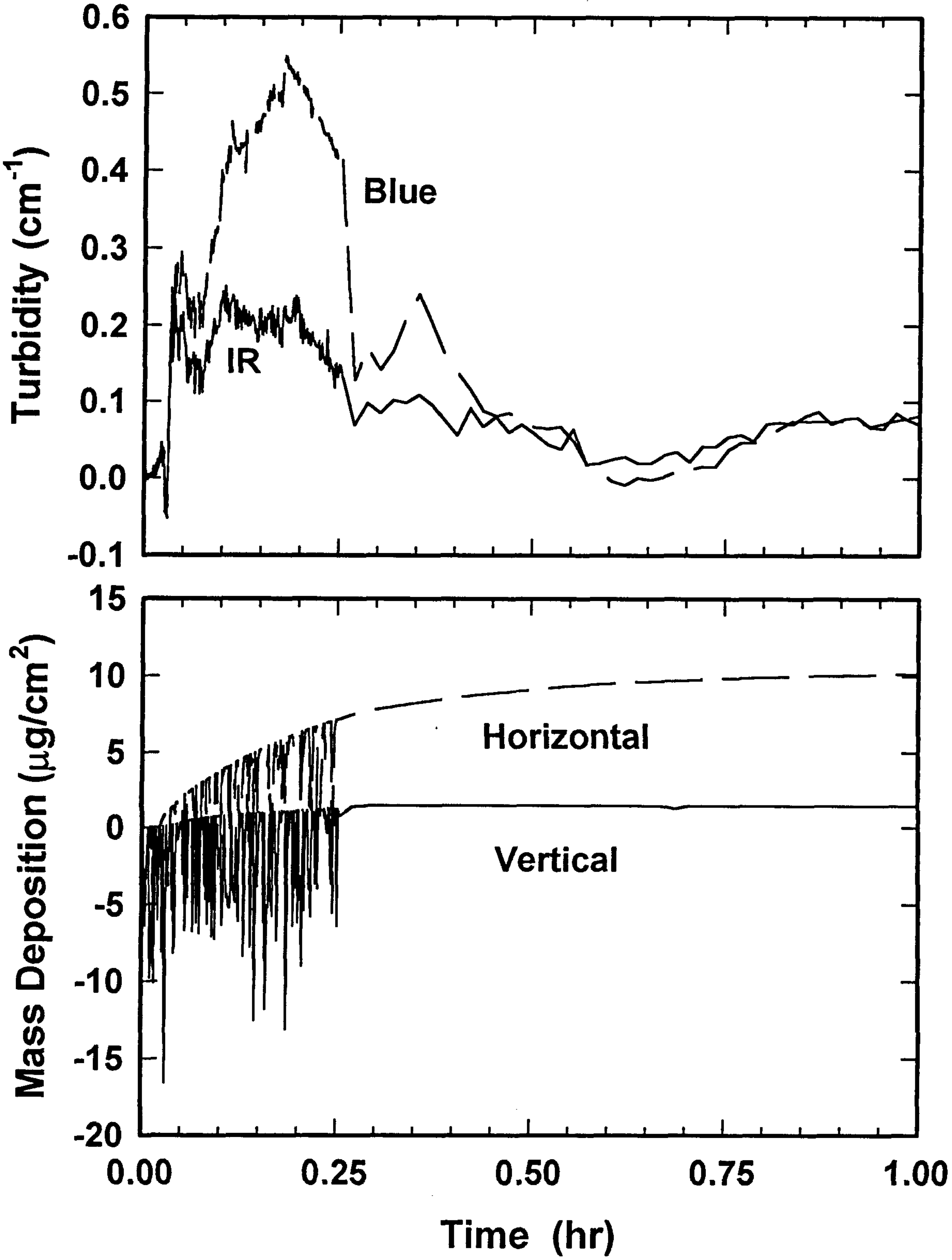
Chamber Temperature (°C)

Test 1



Smoke Optical Density and Accumulation

Test 1



Test 2

Test name: ORNL2
Test date: June 1, 1995
Test time: 11:48:49 EDT

Baseline information: 16 hour baseline run on May 31, 1995, starting at 18:42:06 EDT

Condition	Minimum	Maximum	Mean	SD
Temperature(_C):	22.5	23.2	22.9	0.16
Relative humidity (%):	20.4	31.7	24.1	4.0

Cable Mixture:

Cable Name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	1.922
Anaconda Flameguard 1kv	EPR	CSPE	75	1.336
Kerite HTK	Unknown	Unknown	73	1.159
Rockbestos Coax (le)	Unkown	Unknown	58	0.58
Raychem XLPE	XLPE	NA	71	0.384
Dekoran Dekorad	EPDM	CSPE	54.2	0.601

Heat Flux: 50kW/m^2, 2 lamps (one for water)
Ignition: Sparkers
Length of flame: 2 minutes
Mass loss of cables: 2.8 g
Time for 10-90% loss of cable mass: 2 minutes

Suppression system: Water, 34 g boiled off after first 15 min cable burn

Maximum relative humidity in sensor inside chamber: 84%

Filter paper results:

Chloride	Sulfate	Bromide
0.029 mg	0.004 mg	0.007 mg Estimated

Grab sample results

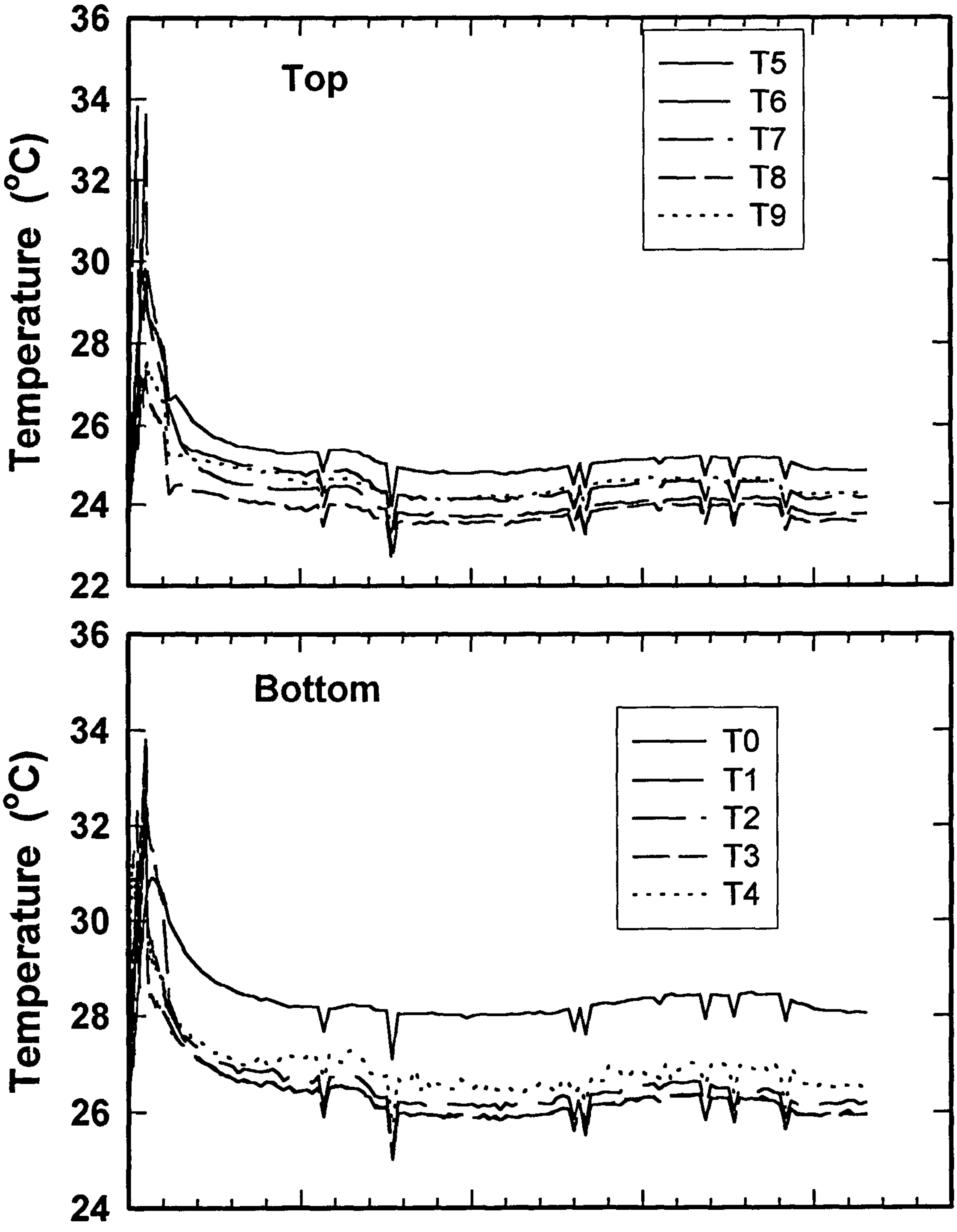
% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
0.8	79.0	20.0	0.0	0.0	0.2	0.0

Results of Test 2

Temperature in chamber(_C):

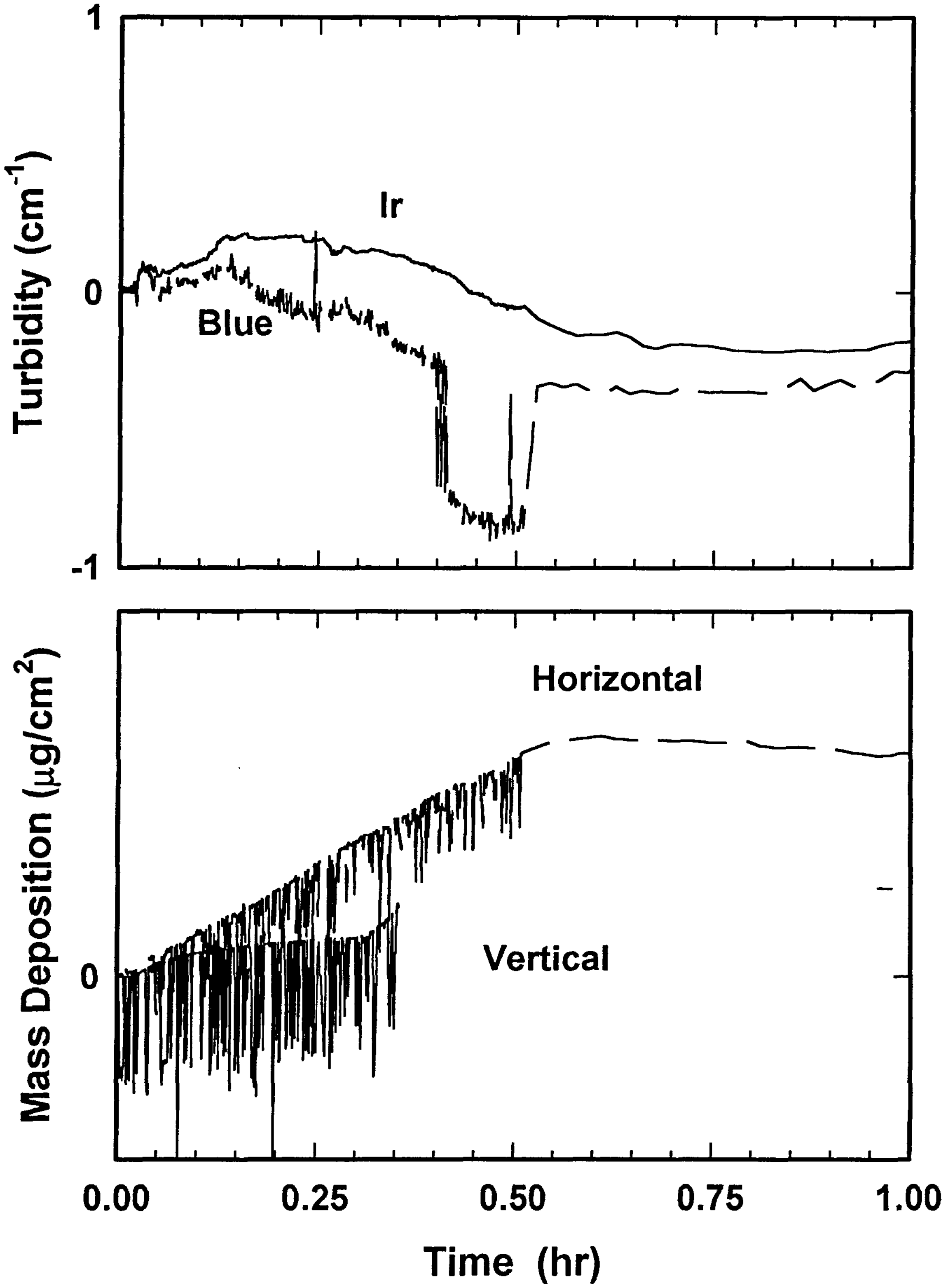
Variable	Minimum	Maximum	Mean	SD
T0	26.42	30.91	28.48	1.22
T1	25.22	32.37	29.09	2.0
T2	24.88	33.69	29.27	2.56
T3	24.93	32.64	28.49	2.04
T4	25.73	33.81	29.78	2.11
T5	23.67	29.55	26.87	1.65
T6	23.31	33.81	28.40	2.76
T7	22.89	33.61	26.97	2.91
T8	22.63	27.22	25.22	1.24
T9	23.26	27.56	25.59	1.14
T10	25.81	31.91	29.05	1.65
Tq1	25.71	31.72	28.92	1.64
Tq2	31.38	39.66	35.52	1.65
T13	30.60	37.32	34.55	1.58
T18	21.19	23.65	22.71	0.35
T19	21.02	24.08	22.51	0.48

Chamber Temperature (°C)
Test 2



Smoke Optical Density and Accumulation

Test 2



Test 3

Test name: ORNL3
Test date: June 3, 1995
Test time: 11:15:46 EDT

Baseline Information: 16 hour baseline run on June 2, 1995, starting at 19:28:32 EDT.

Condition:	Minimum	Maximum	Mean	SD
Temperature (_C):	22.2	31.4	25.91	4.1
Relative humidity (%):	26.0	34.4	30.2	1.1

Cable Mixture:

Cable Name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	1.726
Anaconda Flameguard 1kv	EPR	CSPE	75	1.054
Kerite HTK	Unknown	Unkown	73	1.219
Rockbestos Coax (le)	Unknown	Unknown	58	0.47
Raychem XLPE	XLPE	NA	71	0.396
Dekoran Dekorad	EPDM	CSPE	54.2	0.91

Heat flux: 50 kW/m^2, 1 lamp
Ignition: Sparkers
Mass loss of cables: 2.63 g
Time for 10-90% loss of cable mass: 2.5 min

Suppression system: None

Sorption tube time: 15 min.

Sorption tube results:

Chloride		Sulfate		Bromide	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.012 mg	0.002 mg	0.007 mg	0.004 mg	0.009 mg Est.	ND

Filter paper results:

Chloride	Sulfate	Bromide
0.030 mg	0.003 mg	0.009 (Est)

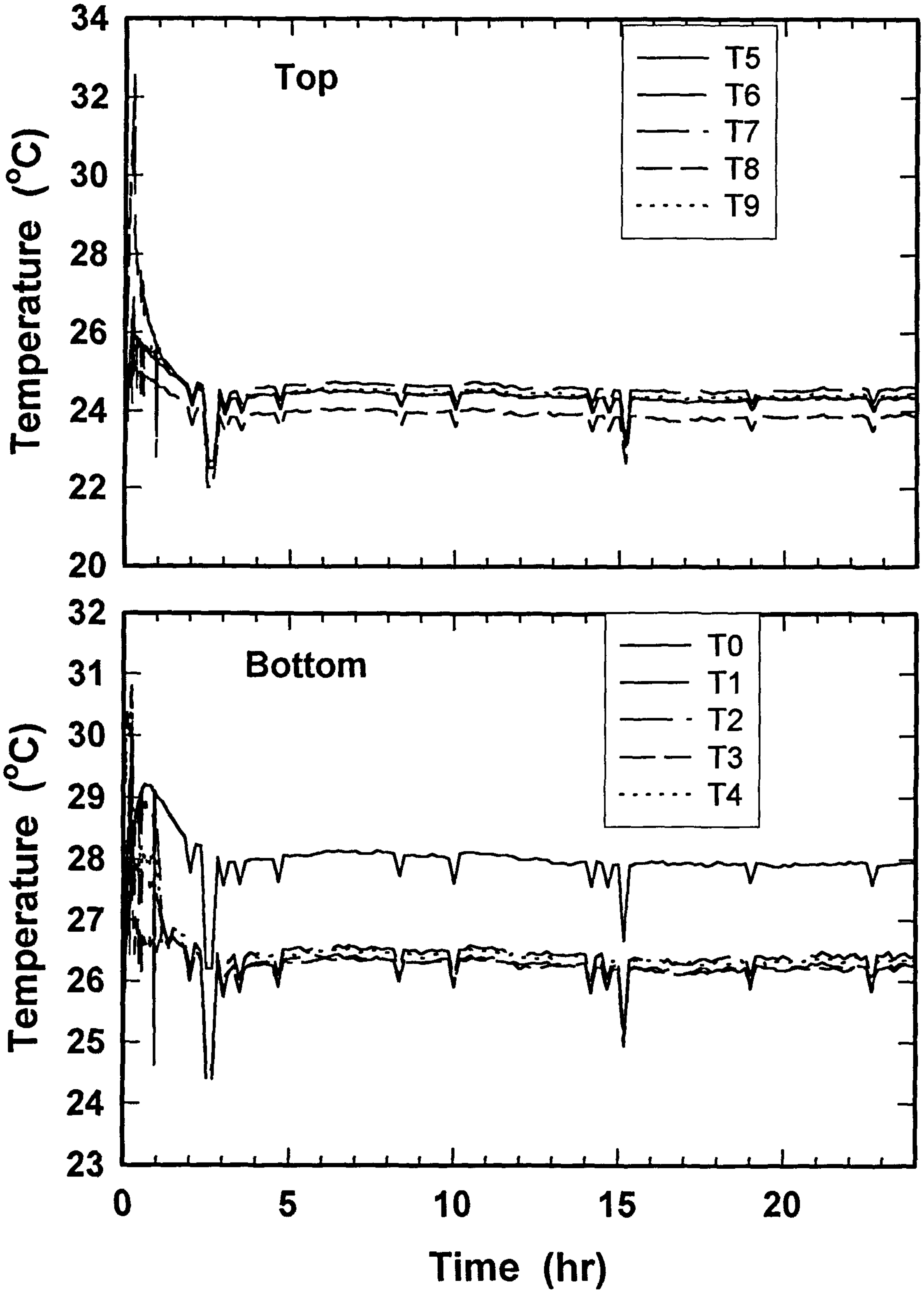
Grab sample results:

% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
0.8	79.0	20.0	0.0	0.0	0.2	0.0

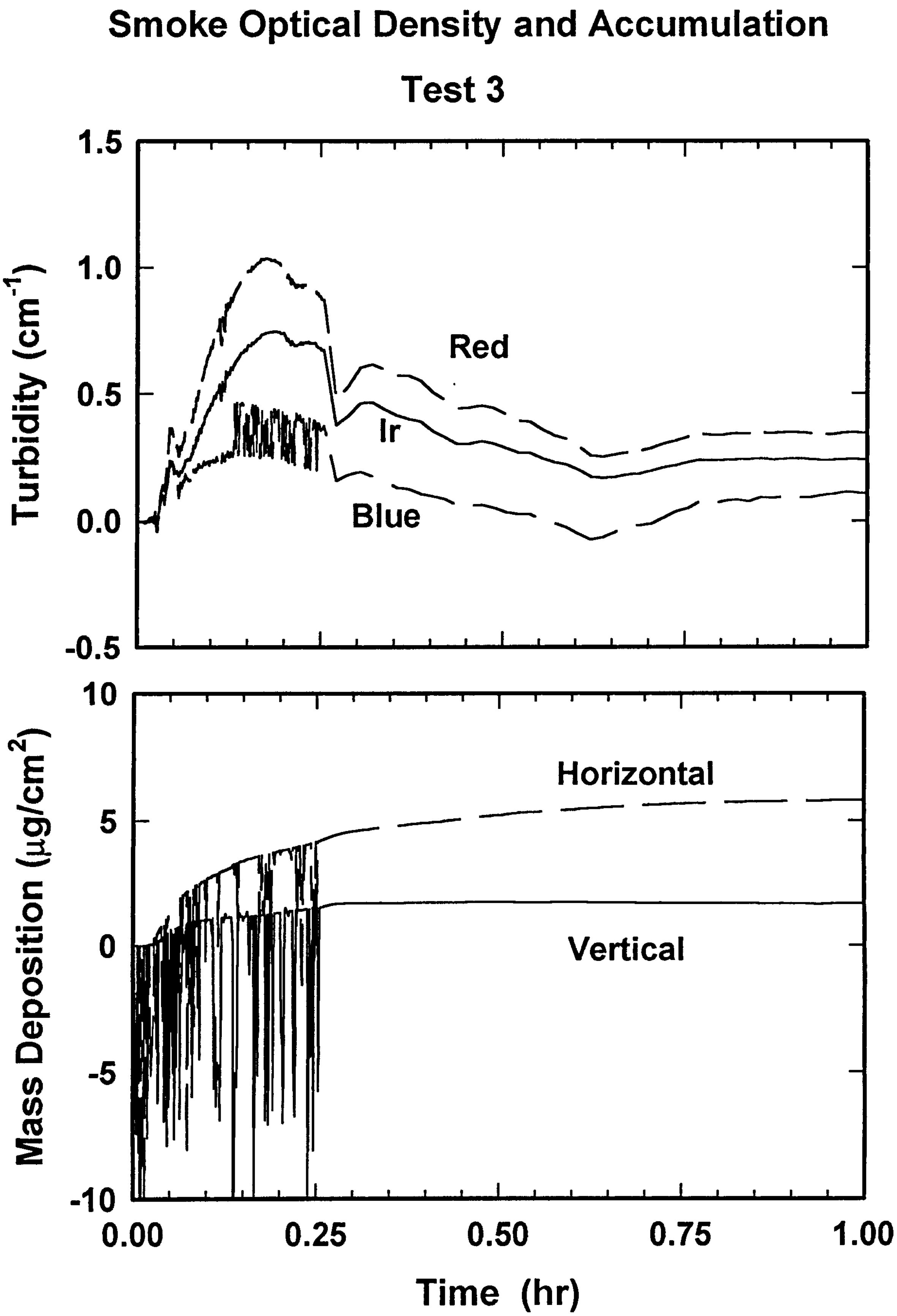
Results of Test 3

Temperature in chamber (_C):

TC	Minimum	Maximum	Mean	SD
T0	25.49	29.21	27.73	0.84
T1	23.69	30.28	27.12	1.33
T2	23.91	29.92	27.07	1.24
T3	24.37	29.33	26.68	0.89
T4	24.52	30.84	27.76	1.72
T5	22.50	26.88	24.81	0.80
T6	22.67	32.54	26.26	2.45
T7	22.50	26.76	24.78	0.75
T8	22.02	25.90	24.25	0.60
T9	22.53	25.76	24.62	0.47
T10	25.42	29.14	27.94	0.83
Tq1	25.39	29.04	28.05	0.90
Tq2	34.08	39.75	37.72	1.03
T13	28.46	32.64	30.88	0.80
T18	20.03	23.16	22.38	0.42
T19	19.76	22.97	22.18	0.44



Chamber Temperature (°C)
Test 3


Smoke Optical Density and Accumulation
Test 3
Turbidity (cm^{-1})
1.5
1.0
0.5
0.0
-0.5
Red
Ir
Blue
Mass Deposition (μg/cm^2)
10
5
0
-5
-10
Horizontal
Vertical
0.00
0.25
0.50
0.75
1.00
Time (hr)

Test 4

Test name: ORNL4
Test date: June 6, 1995
Test time: Two start times, 12:33:13 and 13:25:19 EDT

The first start was aborted after 1 minute because of failures in experimental system due to EMI from sparkers. As a result sparkers were removed and test proceeded without ignition.

Baseline information: 16.9 hour run on June 5, 1995 begining at 17:55:56 EDT.

Condition	Minimum	Maximum	Mean	SD
Temperature(_C):	22.14	22.91	22.60	0.18
Relative humidity (%):	29.79	32.74	31.19	0.79

CO_2 only: This was a test to determine the effect of CO_2 on system.
2.6 lb of CO_2 were added to exposure chamber.
Temperatures in exposure chamber (_C)

TC	Minimum	Maximum	Mean	SD
T0	24.11	25.76	24.68	0.63
T1	-10.56	23.89	18.40	8.7
T2	-11.25	23.57	18.44	8.9
T3	-10.24	23.89	19.24	8.6
T4	-3.30	26.17	21.75	6.8
T5	18.60	22.65	21.52	0.85
T6	17.31	22.87	21.71	1.2
T7	17.36	23.01	21.80	1.2
T8	17.14	22.72	21.62	1.2
T9	16.58	23.28	21.74	1.4
T12	21.80	29.16	24.71	2.3
T13	21.63	28.78	25.53	2.0
T18	21.90	22.77	22.26	0.26
T19	21.75	22.94	22.25	0.36

The following information refers to the smoke exposure portion of the test.

Results of Test 4

Cable Mixture:

Cable Name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	1.803
Anaconda Flameguard 1kv	EPR	CSPE	75	1.351
Kerite HTK			73	1.385
Rockbestos Coax (le)			58	0.497
Raychem XLPE	XLPE		71	0.313
Dekoran Dekorad	EPDM	CSPE	54.2	0.777

Heat Flux: 50kW/m^2, 1 lamp

Igniter: None.

Note: No flames, only smouldering on this test. Igniter of some type necessary for flames.

Mass loss of cables: 2.8 g

Time for 10-90% loss of cable mass: 2 minutes

Suppression system: 2.48 lb. CO_2added after lamps turned off (15 minutes after second start of test)

Sorption tube time: 16 min

Sorption tube results:

Chloride		Sulfate		Bromide	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.018 mg	0.002 mg	0.007 mg	0.004 mg	0.008 (Est)	ND

Filter paper results: None, filter paper was blown away.

Grab sample results:

% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
0.5	51.0	12.1	0.0	0.0	36.4	ND

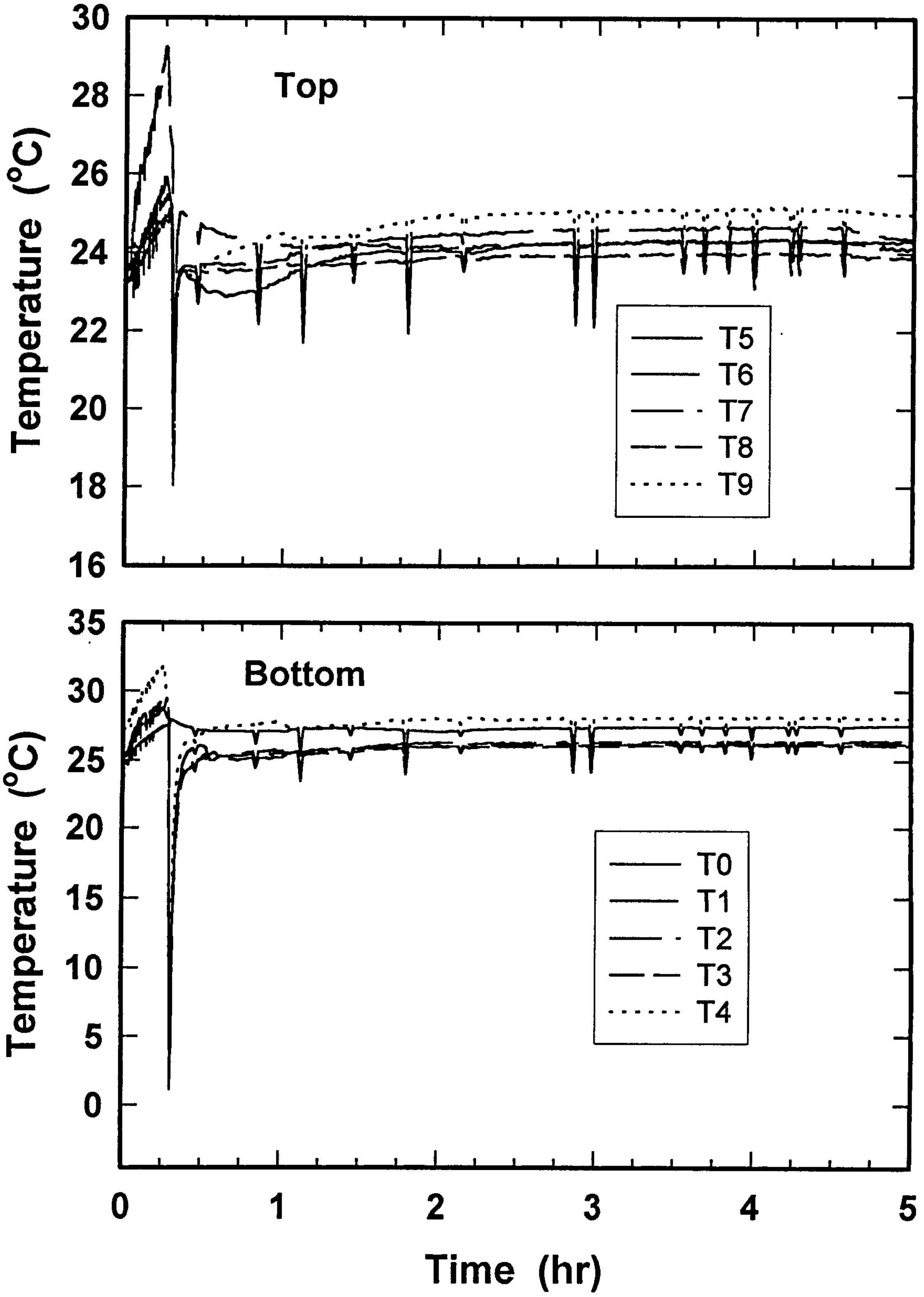
Temperature in chamber (_C)

TC	Minimum	Maximum	Mean	SD
T0	24.93	27.92	27.18	0.49
T1	1.169	29.36	26.25	1.06
T2	1.144	28.75	25.99	1.02
T3	1.531	29.43	25.91	1.04
T4	4.044	31.84	27.99	1.11
T5	19.88	25.90	24.09	0.48
T6	19.74	29.28	24.39	1.09
T7	18.16	25.47	23.84	0.48
T8	18.57	25.10	23.66	0.40
T9	17.97	25.18	24.62	0.41
Tq1	24.88	28.43	27.84	0.55
Tq2	24.79	28.36	27.76	0.56

T12	26.61	32.54	31.43	0.64
T13	29.19	36.83	35.76	1.01
T18	20.08	23.16	22.39	0.39
T19	20.00	28.07	22.35	0.55

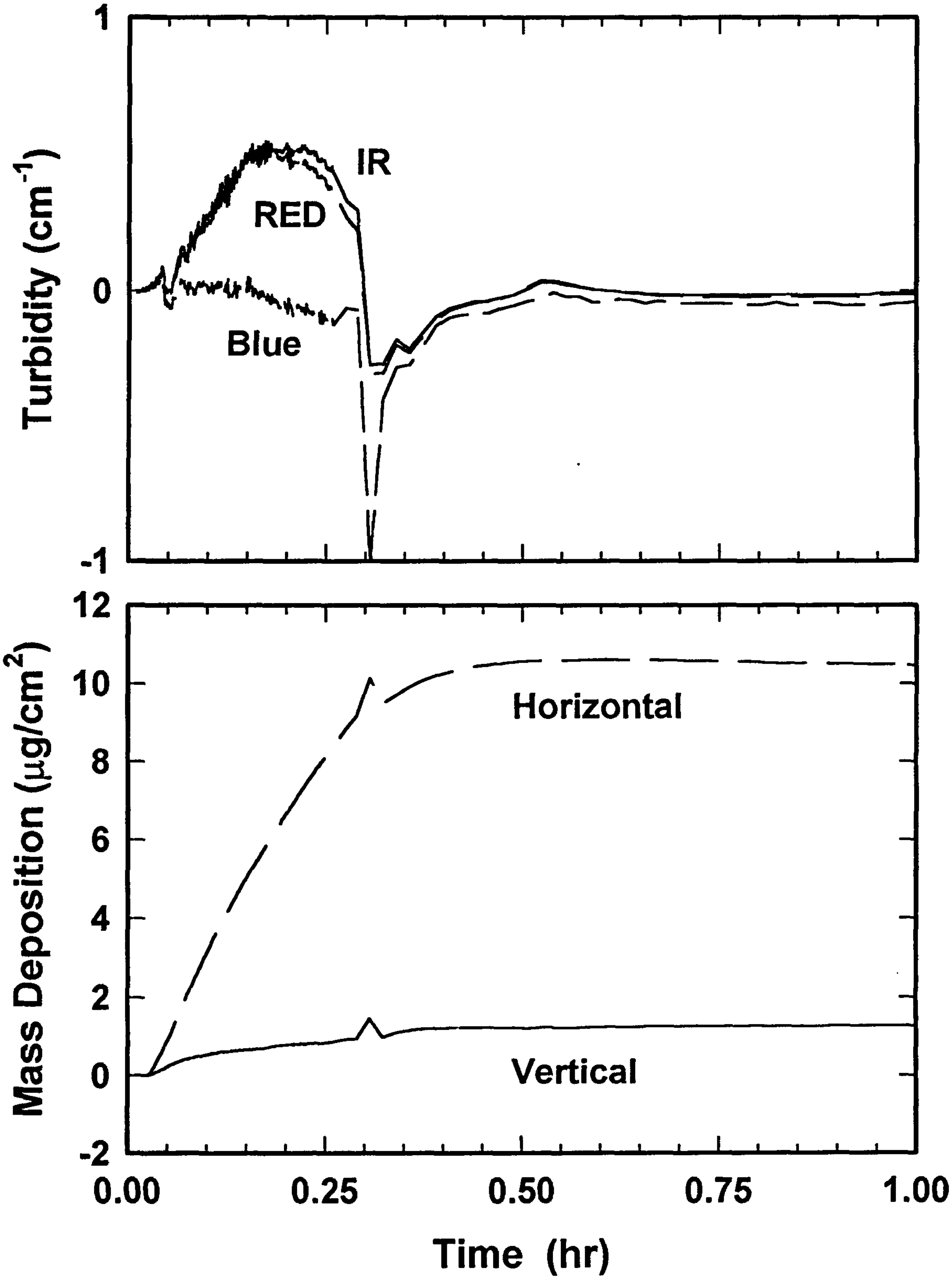
Chamber Temperature (°C)

Test 4



Smoke Optical Density and Accumulation

Test 4



Test 5

Test name: ORNL5
Test date: 8 June 1995
Test time: 13:09:27 and 12:26:50 EDT, problem with program and restarted after 15.5 minutes (after burning Lamp 1)

Baseline Information: 16-hour baseline run on June 7 1995 starting at 19:09:27 EDT.

Condition:	Minimum	Maximum	Mean	SD
Temperature (_C):	22.25	23.11	22.62	0.15
Relative humidity (%):	27.32	35.09	30.15	0.81

Cable Mixture:

Cable name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	10.64
Anaconda Flameguard 1kv	EPR	CSPE	75	4.96
Brand Rex XLPE	XLPE	CSPE	54.6	5.27
Okonite Okolon	EPR	CSPE	60.9	4.23
Kerite HTK			73	4.75
Rockbestos Coax (le)			58	3.69
Raychem XLPE	XLPE		71	2.7
Dekoran Dekorad	EPDM	CSPE	54.2	3.54
BIW	EPR	CSPE	75.6	2.1
Kerite FR			65.6	1.81
PVC	PVC	PVC	56	1.4
Total				45.09

Heat flux: 50 kW/m2, 2 lamps, 1 and 3
Ignition: Sparkers plugged in individually; problems with program, had to restart BIGTEST (the program to run smoke system)
Mass loss of cables: 10.38 g from tray 1, 10.01 g from tray 3

Suppression system: none

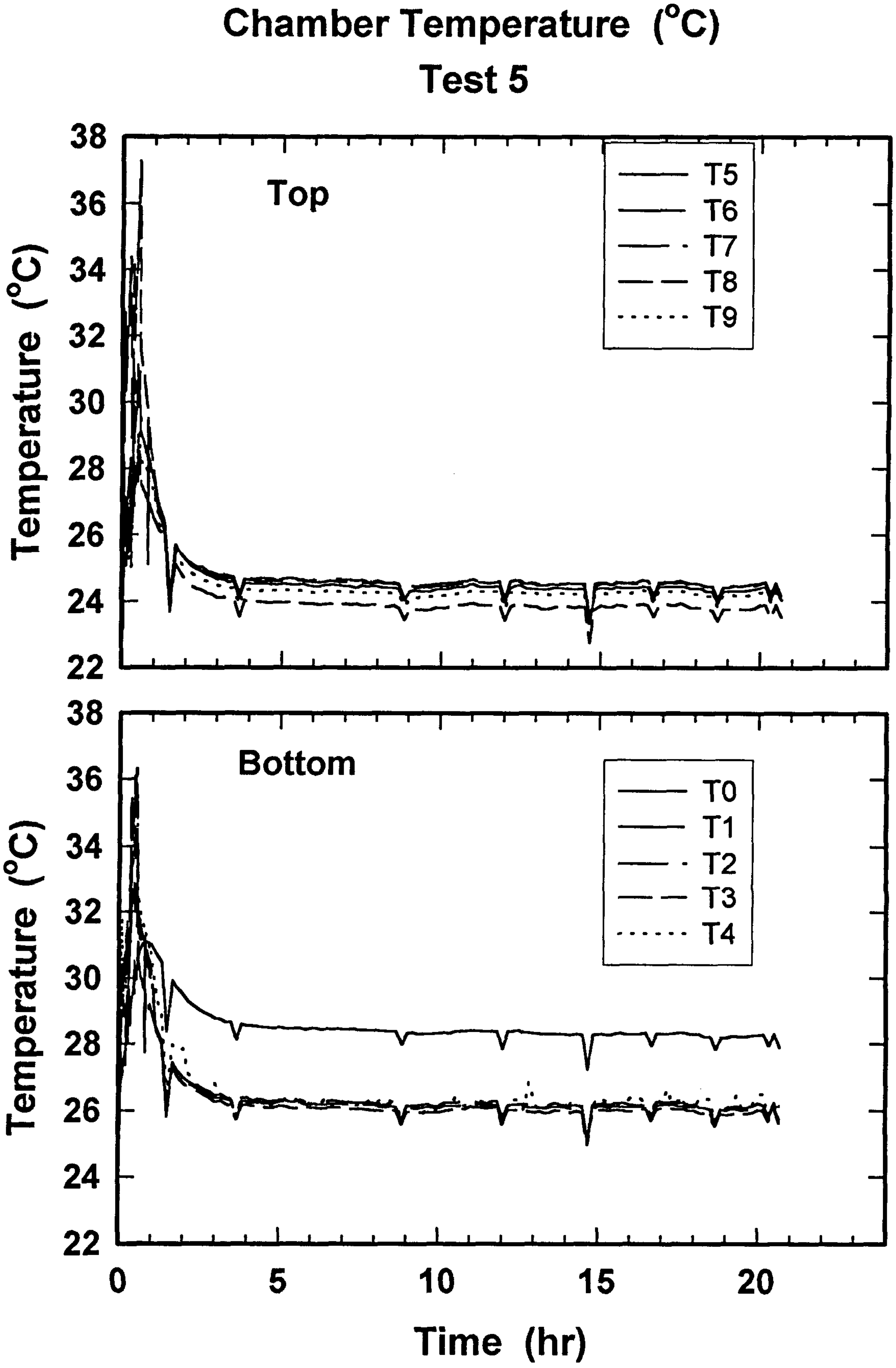
Filter paper results: None.

Grab sample results:

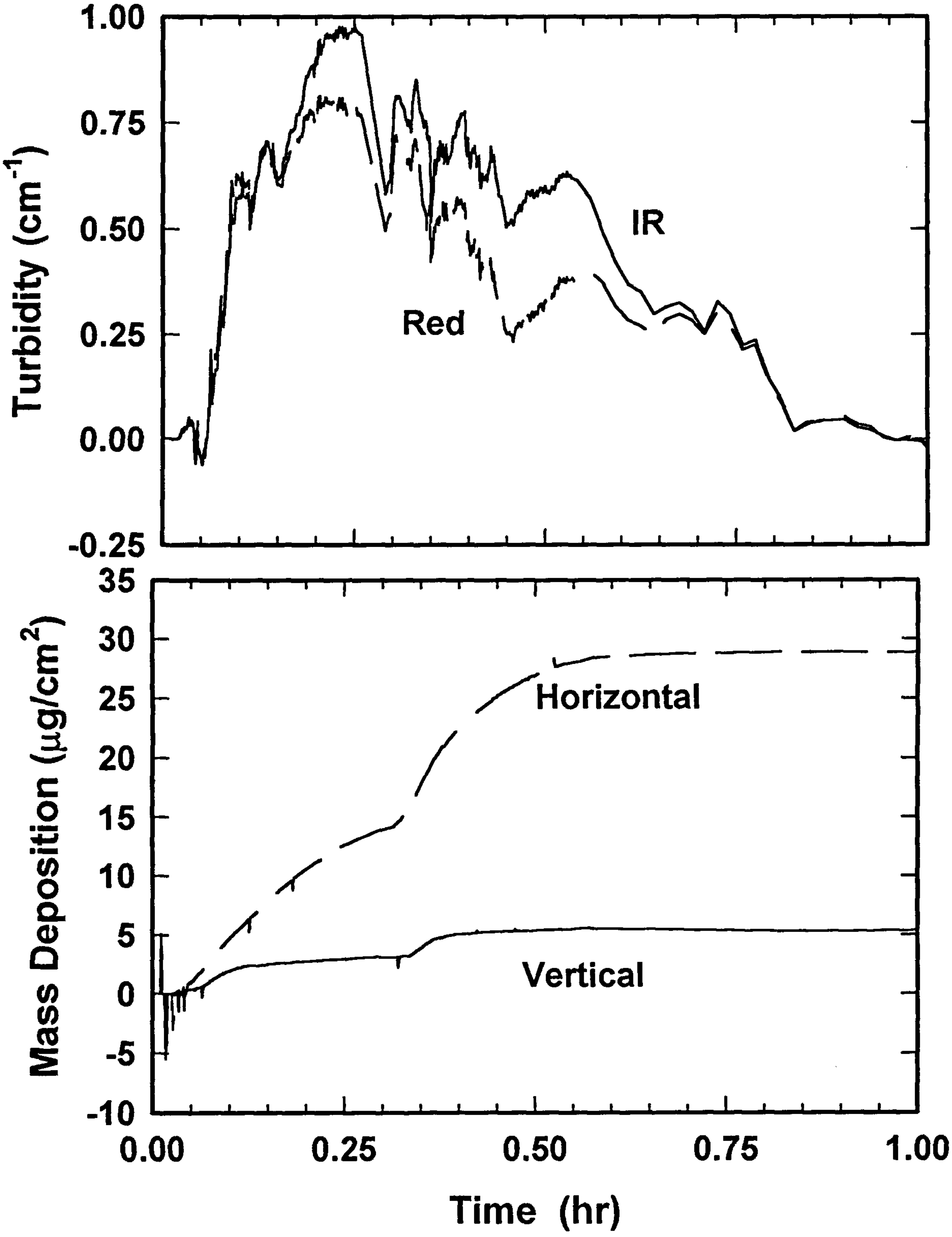
% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
1.1	78.5	18.6	0.0	0.0	2.0	0.5

Temperature in chamber (_C):

TC	Mean	Minimum	Maximum	SD
T0	28.52	25.95	31.11	0.59
T1	30.05	24.45	34.56	2.26
T2	29.38	24.33	32.88	2.08
T3	29.99	24.28	36.32	1.58
T4	30.57	25.01	35.88	1.26
T5	27.12	22.87	30.91	1.52
T6	28.98	23.01	34.37	3.25
T7	26.13	22.94	28.58	1.17
T8	27.83	22.77	37.27	0.94
T9	26.06	23.18	29.14	0.65
T12	35.25	26.95	42.17	1.96
T13	32.99	27.83	36.95	1.43
T18	21.85	19.40	22.80	0.29
T19	21.64	19.11	22.87	0.41


Chamber Temperature (°C)
Test 5
Top
T5
T6
T7
T8
T9
Bottom
T0
T1
T2
T3
T4
Temperature (°C)
38
36
34
32
30
28
26
24
22
0
5
10
15
20
Time (hr)

Smoke Optical Density and Accumulation
Test 5



Test 6

Test name: ORNL6
Test date: June 10, 1995
Test time: 12:38:01 EDT

Baseline information: 17.25-hour run on June 9, 1995 starting at 19:04:25 EDT.

Condition:	Minimum	Maximum	Mean	SD
Temperature (_C):	22.58	23.77	22.91	0.20
Relative humidity (%):	16.87	31.11	26.45	3.7

Cable Mixture:

Cable Name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	10.34
Anaconda Flameguard 1kv	EPR	CSPE	75	4.94
Brand Rex XLPE	XLPE	CSPE	54.6	5.24
Okonite Okolon	EPR	CSPE	60.9	4.42
Kerite HTK	Unknown	Unknown	73	4.92
Rockbestos Coax (le)	Unknown	Unknown	58	3.58
Raychem XLPE	XLPE	NA	71	2.63
Dekoran Dekorad	EPDM	CSPE	54.2	3.2
BIW	EPR	CSPE	75.6	2.22
Kerite FR			65.6	1.79
PVC	PVC	PVC	56	1.27
Total				44.55

Heat flux: 50 kW/m^2, three lamps, 1 and 3 for fuel and 2 for water
Mass loss of cables: 9.93 g from lamp 1 and 10.04 g from lamp 3
Time for 10-90% loss of cable mass: Lamp 1, 4.3 min; lamp 3, 6.0 min.

Suppression system: 34 g water boiled off on lamp 2

Sorption tube time: 1 hour

Sorption tube results:

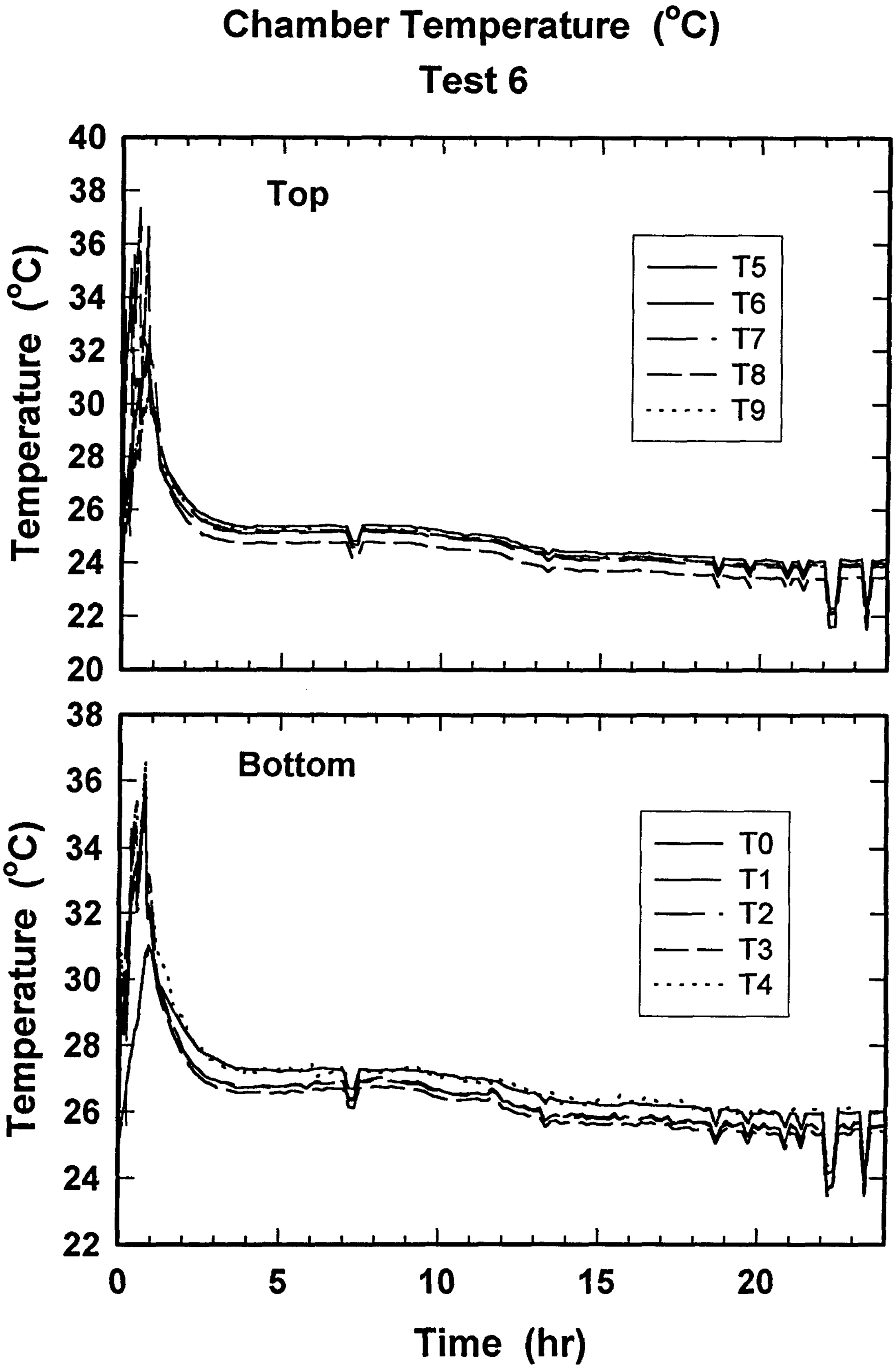
Chloride		Sulfate		Bromide	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.514 mg	0.006 mg	0.152 mg	0.039 mg	0.270 mg Est.	ND

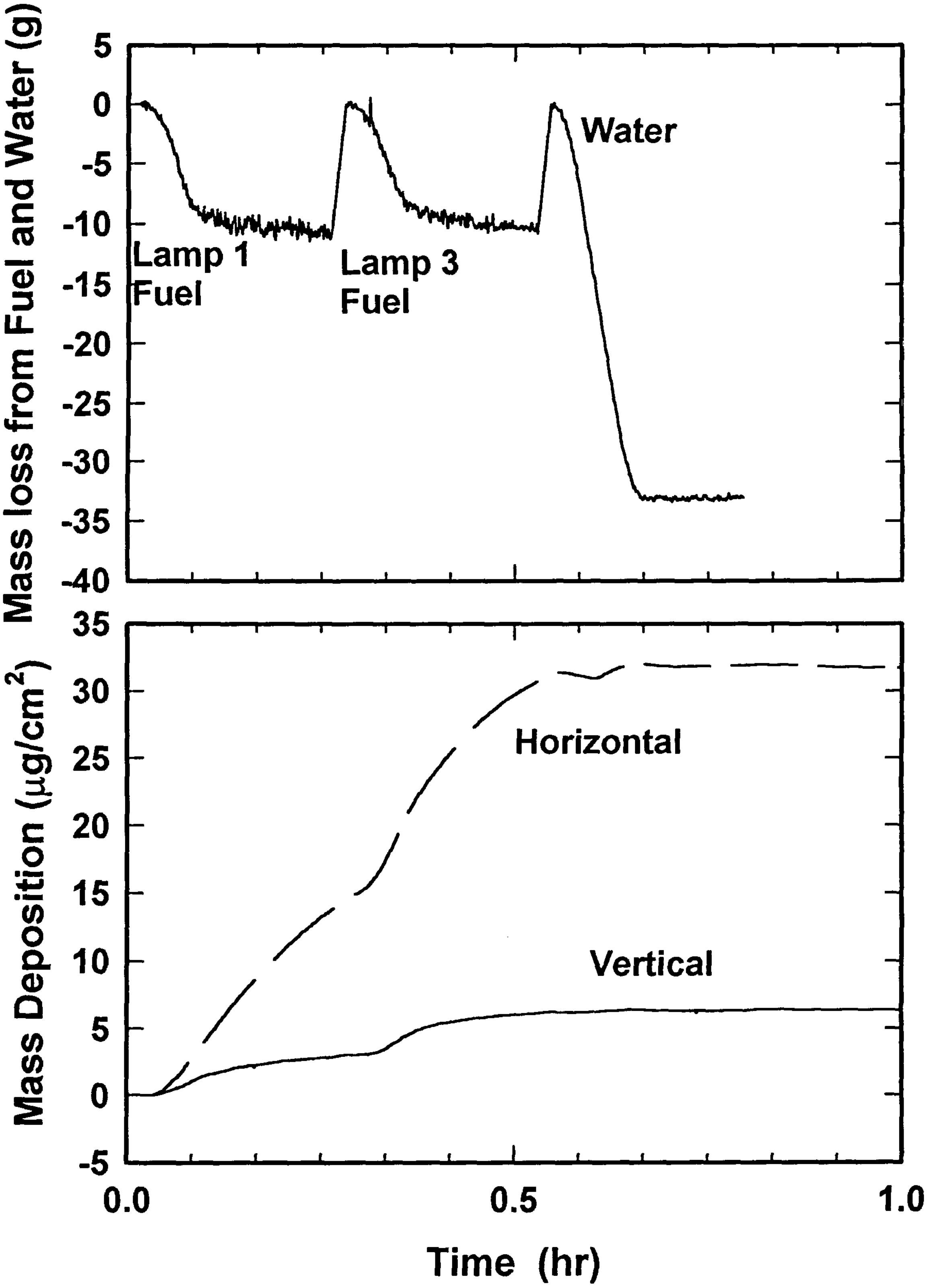
Filter paper results:

Chloride	Sulfate	Bromide
0.057 mg	0.004 mg	0.062 mg Estimate

Temperature in chamber (_ C):

TC	Minimum	Maximum	Mean	SD
T0	24.06	31.01	27.32	1.5
T1	23.65	35.25	29.87	3.3
T2	23.62	35.88	29.76	3.5
T3	23.48	35.98	29.94	3.8
T4	24.18	36.61	30.56	3.5
T5	22.26	32.08	27.51	2.8
T6	21.99	35.05	28.67	3.5
T7	22.09	36.61	27.42	3.5
T8	21.53	37.44	28.22	4.5
T9	22.04	30.38	26.55	2.2
T10	25.25	35.78	30.27	3.0
Tq1	24.79	35.81	30.06	3.1
Tq2	31.11	44.90	38.70	3.5
T13	32.37	51.05	41.55	4.3
T18	20.17	24.18	22.81	0.57
T19	20.00	24.54	22.57	0.72


Chamber Temperature (°C)
Test 6
Top
T5
T6
T7
T8
T9
Temperature (°C)
40
38
36
34
32
30
28
26
24
22
20
Bottom
T0
T1
T2
T3
T4
Temperature (°C)
38
36
34
32
30
28
26
24
22
0
5
10
15
20
Time (hr)



Mass Loss and Accumulation

Test 6

Test 7

Test name: ORNL7
Test date: June 13, 1995
Test time: 11:59:59 EDT

Baseline Information: 15-hour baseline run on June 12, 1995 starting at 19:09:27 EDT. No temperature and humidity information available

Cable mixture:

Cable Name	Insulation	Jacket	% plastic	Total g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	139.49
Anaconda Flameguard 1kv	EPR	CSPE	75	48.42
Brand Rex XLPE	XLPE	CSPE	54.6	71.33
Okonite Okolon	EPR	CSPE	60.9	53.41
Kerite HTK	unknown	unknown	73	44.92
Rockbestos Coax (le)	unknown	unkown	58	47.66
Raychem XLPE	XLPE	NA	71	28.02
Dekoran Dekorad	EPDM	CSPE	54.2	45
BIW	EPR	CSPE	75.6	21.3
Kerite FR			65.6	21.04
PVC	PVC	PVC	56	14.72

Heat flux: 50 kW/m^2, all 4 lamps (overloaded trays)
Mass loss of cables: Tray 1, 45.37 g (flaming); Tray 2, 52.66 g (flaming); Tray 3, 29.01 g (smoldering only); Tray 4, 33.09 g (smoldering only).
Time for 10-90% loss of cable mass: Lamp 1, 9:10 min; Lamp 2, 6:15 min; Lamp3, 8:02 min; Lamp 4, 9:09 min.

Suppression system: None

Sorption tube time: 1 hour, 20 minutes/

Sorption tube results:

Chloride		Sulfate		Bromide	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.752 mg	0.007 mg	0.149 mg	0.042 mg	0.233 Est.	ND

Filter paper results:

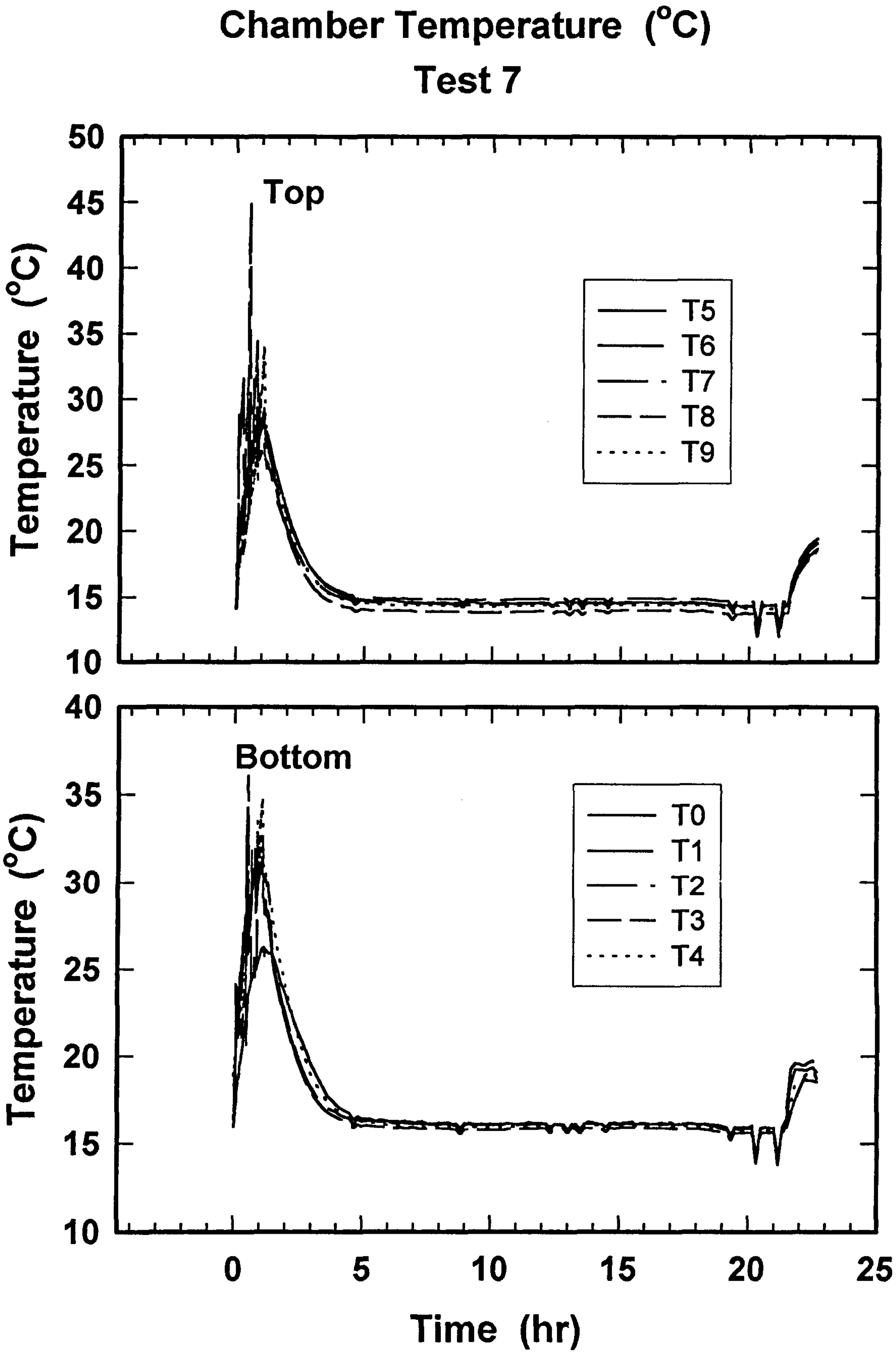
Chloride	Sulfate	Bromide
0.742 mg	0.005 mg	0.547 mg Estimate

Grab sample results

% Argon	% N_2	% O_2	% H_2	% CH_4	% CO_2	% CO
1.0	80.0	13.6	0.6	0.0	5.2	1.5

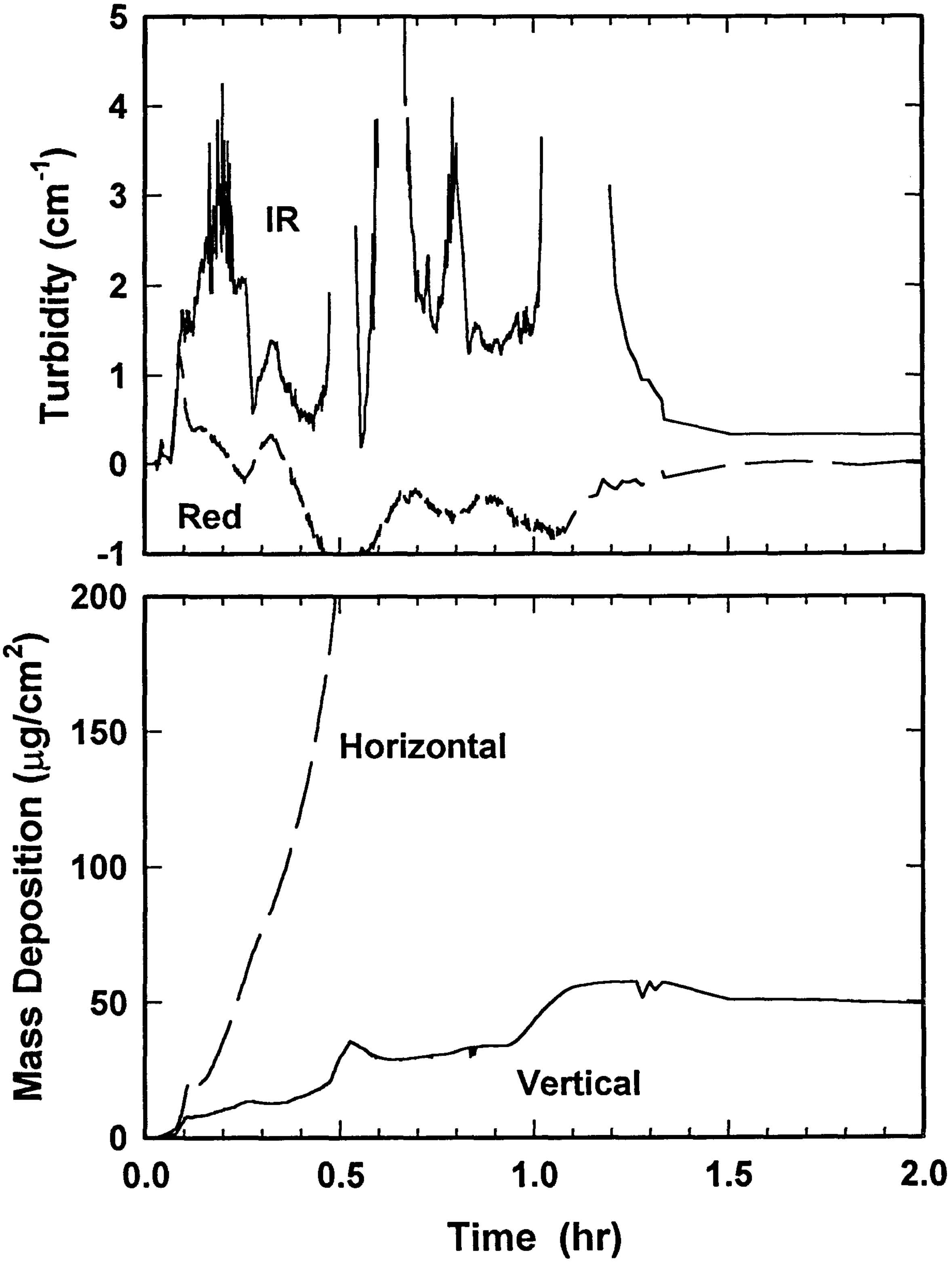
Temperature in chamber (_C):

TC	Minimum	Maximum	Mean	SD
T0	14.06	27.75	21.49	3.5
T1	14.02	31.91	25.47	5.0
T2	14.04	36.07	25.64	5.6
T3	13.80	31.76	24.32	5.1
T4	13.90	34.69	25.82	5.5
T5	12.56	30.48	23.17	4.9
T6	12.49	31.64	23.88	4.6
T7	12.85	44.87	24.56	6.5
T8	11.93	34.37	22.39	6.0
T9	12.34	34.03	21.74	5.4
T12	18.91	40.24	30.94	6.5
T13	18.55	42.70	32.18	5.9
T17	18.60	25.52	22.44	0.7
T18	9.898	18.99	14.40	1.6
T19	9.874	19.13	14.40	1.6


Chamber Temperature (°C)
Test 7
Top
T5
T6
T7
T8
T9
Bottom
T0
T1
T2
T3
T4
Temperature (°C)
50
45
40
35
30
25
20
15
10
0
5
10
15
20
25
Time (hr)

Smoke Optical Density and Accumulation

Test 7



Test 8

Test name: ORNL8
Test date: June 15, 1995
Test time: 12:53:28 EDT

Baseline Information: 17.5-hour temperature test for fiber optic modules on June 14, 1995, starting at 12:53:28. See temperature plot.

Cable Mixture:

Cable Name	Insulation	Jacket	% plastic	Lamp 1 g	Lamp 2 g	Lamp 3 and 4 g
Rockbestos Firewall III	FRXLPE	CSPE	56.7	1.94	8.91	29.81
Anaconda Flameguard 1kv	EPR	CSPE	75	1.04	4.03	13.45
Brand Rex XLPE	XLPE	CSPE	54.6	0.00	5.41	14.60
Okonite Okolon	EPR	CSPE	60.9	0.00	4.47	12.15
Kerite HTK			73	1.02	3.99	12.51
Rockbestos Coax (le)			58	0.43	3.09	10.16
Raychem XLPE	XLPE		71	0.30	2.30	6.17
Dekoran Dekorad	EPDM	CSPE	54.2	0.48	1.81	6.64
BIW	EPR	CSPE	75.6	0.00	2.05	6.00
Kerite FR			65.6	0.00	1.81	5.11
PVC	PVC	PVC	56	0.00	1.21	3.41

Heat flux: 50 kW/m^2 on all four lamps
Ignition: Sparkers only until ignited, no flame on lamp 4
Mass loss of cables: Tray 1, 2.43 g (flaming); Tray 2, 15.45 g (flaming); Tray 3, 23.14 g (flaming); Tray 4, 23.28 g (smoldering).
Time for 10-90% loss of cable mass: Lamp 1, 2:27 min.; lamp 2, 5:26 min.; lamp 3, 6:20 min., lamp 4, 8:20 min.

Suppression system: None
Sorption tube time: 4 hours

Sorption tube results:

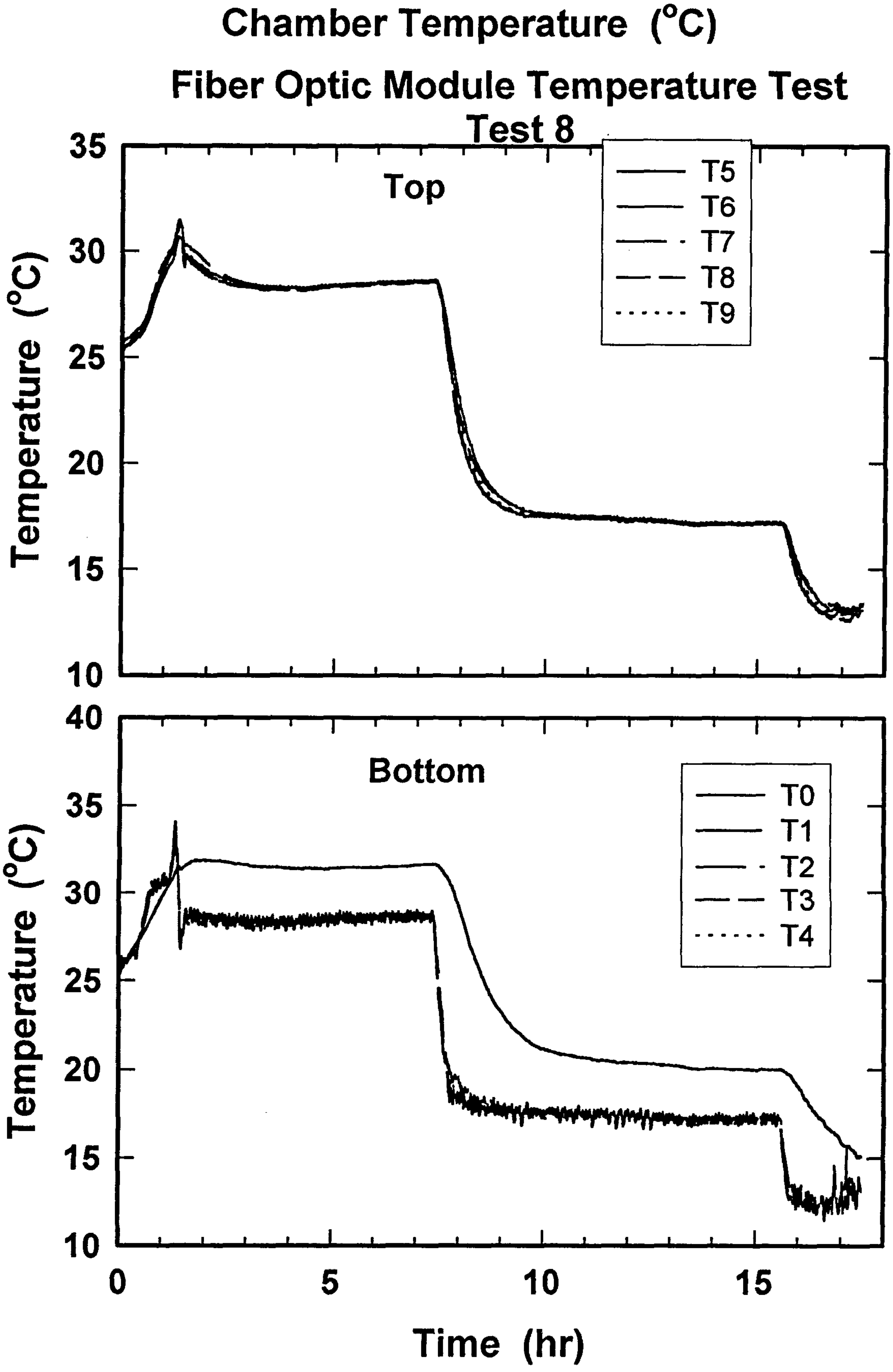
Chloride		Sulfate		Bromide	
Front filter	Back filter	Front filter	Back filter	Front filter	Back filter
0.124 mg	0.050 mg	0.012 mg	0.006 mg	0.075 mg Est.	ND

Filter paper results:

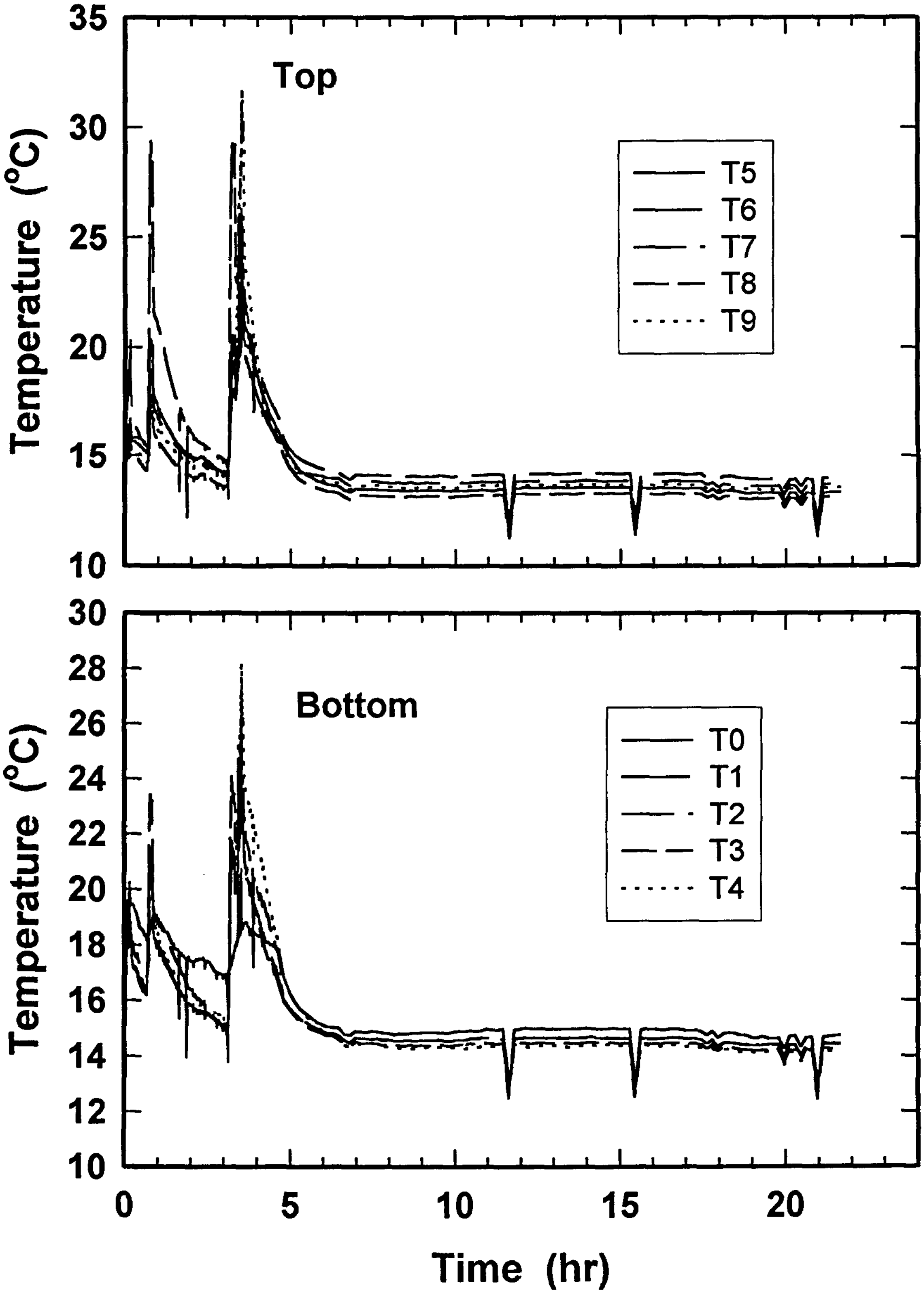
Chloride	Sulfate	Bromide
0.509 mg	0.010 mg	0.512 mg Estimate

Temperature in chamber (_C):

TC	Minimum	Maximum	Mean	SD
T0	12.93	20.76	17.74	1.2
T1	12.66	24.84	18.49	2.6
T2	12.66	24.81	18.60	2.8
T3	12.49	25.69	18.87	3.2
T4	12.42	28.31	18.95	3.4
T5	11.54	24.69	17.40	2.8
T6	11.86	23.18	17.17	2.3
T7	12.20	29.53	17.92	3.6
T8	11.28	29.45	18.31	5.0
T9	11.74	31.81	17.82	4.6
Tq1	13.87	26.42	19.39	2.8
Tq2	13.87	26.39	19.43	2.9
T12	18.48	30.60	25.23	2.3
T13	18.16	28.43	23.07	2.0
T17	19.13	26.10	23.29	0.86
T18	9.39	14.55	11.71	0.49
T19	9.29	14.50	11.64	0.53

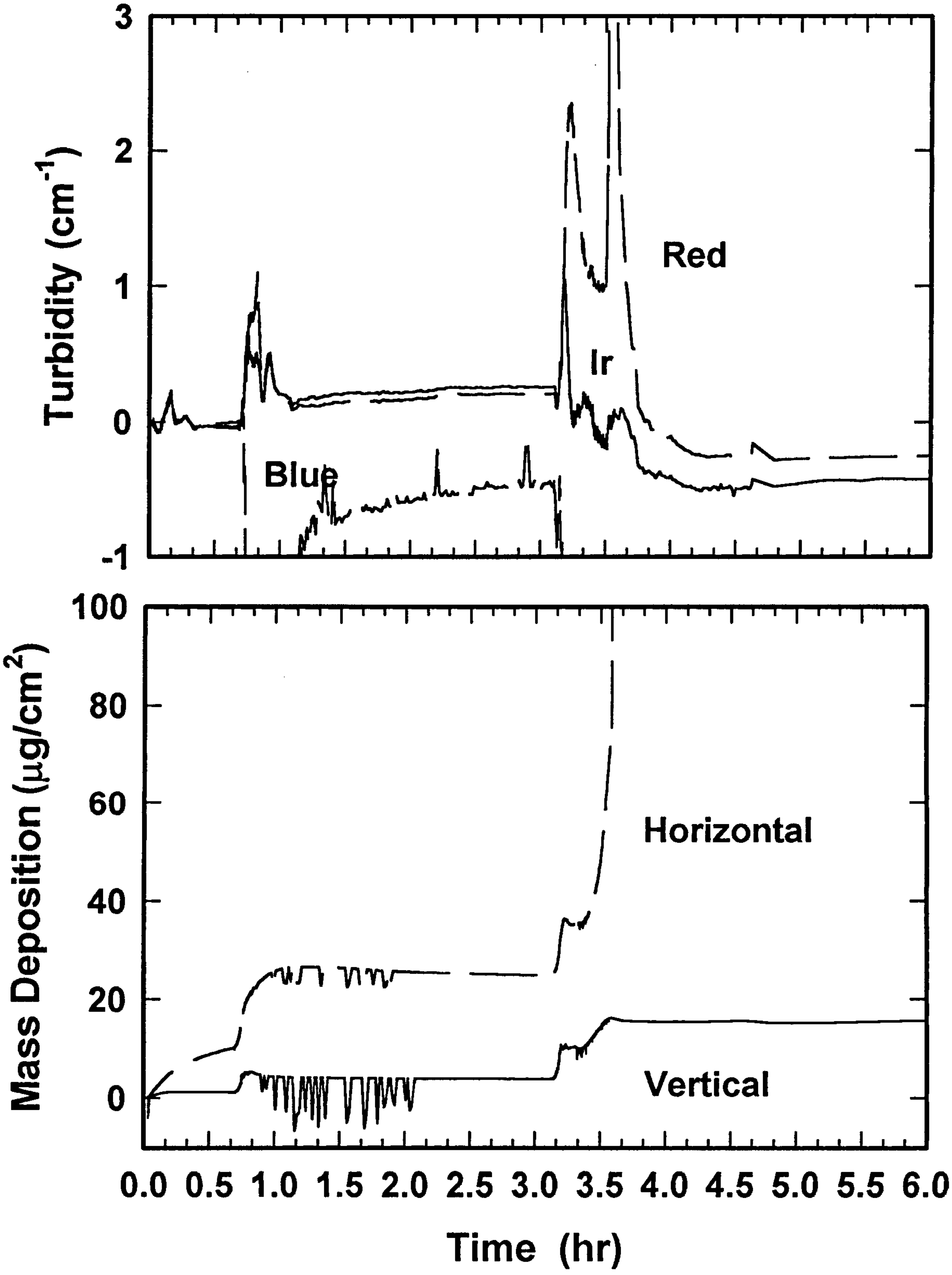

Chamber Temperature (°C)
Fiber Optic Module Temperature Test
Test 8
Top
T5
T6
T7
T8
T9
Bottom
T0
T1
T2
T3
T4
Temperature (°C)
Temperature (°C)
35
30
25
20
15
10
40
35
30
25
20
15
10
0
5
10
15
Time (hr)

Chamber Temperature (°C)
Test 8



Smoke Optical Density and Accumulation

Test 8



Conclusions

The smoke exposures for the ORNL experimental digital system were sucessful in providing a general indication of whether a digital safety system would perform under smoke conditions. Three levels of smoke density were tested: low (approximately 3 g of fuel/m^3), medium (approximately 20 g of fuel/m^3), and high (more than 60 g of fuel/m^3). For high levels of smoke density, the fuel near the end of the exposure would not ignite, but instead smouldered. This indicates that there was not enough oxygen to support open combustion at this level. The grab sample from test 7 also supported this theory because the level of CO was much higher than in any other tests and the level of oxygen was down to only 13.6%.

Several fire suppression simulations were part of these tests. This included the addition of humidity in the form of steam and CO_2 from a fire extinguisher. When humidity was added during the smoke exposure, the objective was to reach at least 80% RH. This was accomplished using a simple calculation of the amount of water required in the chamber to raise the humidity to this level given the temperature that was expected at the end of the exposure. The addition of CO_2 was accompanied with a test of CO_2 alone from the fire extinguisher. The CO_2 had very little effect on the equipment, although the temperatures in the exposure chamber dropped drastically. Filters that were placed in the exposure chamber to determine the chemical composition of the soot were blown away by the action of the fire extinguisher and were not analyzed.

The method of igniting the fire was changed partway through these tests because the DTC was found to be too sensitive to the EMI generated by the sparkers. A butane lighter was used instead. The lighter burned very cleanly and was used only for a short time to ignite the fuel after it had been heated. The sparkers were used as a source of ignition when the test equipment did not have failures from the EMI that they produced.

The results of this series of tests have shown that the SNL large smoke exposure chamber can produce consistent smoke exposures as measured by the chemical products of gases and soot. This is very important when considering the need for a standardized test and for the upcoming circuit bridging series.

References

Bustard, L., and Holzman, P., 1994. "Low-Voltage Environmentally Qualified Cable License Renewal Industry Report; Revision 1," TR-103841, published by Electric Power Research Institute, Palo Alto, CA.

Kessel, Stephen L., Bennett, James G. Jr., and Rogers, Charles E., 1994. "Corrosivity Test Methods for Polymeric Materials. Part 1–Radiant Furnace Test Method [1]," *Journal of Fire Sciences*, Vol. 12, No. 2, pp. 107–133.

Korsah, K., Tanaka, Tina J., and Wilson, T. L., to be published. "Environmental Testing of an Experimental Digital Safety System," NUREG/CR 6406, Oak Ridge National Laboratory, Oak Ridge, TN.

Reagor, Barbara T., 1992. "Smoke Corrosivity: Generation, Impact, Detection, and Protection," *Journal of Fire Sciences*, Vol. 10, pp. 169–179.

Appendix E

Impact of Smoke on Advanced I & C: Selection of Sample Components and Test Matrix

A letter report to the USNRC, Office of Research

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July 27, 1995

Abstract

Smoke can be a serious threat to electrical equipment. A number of plants are starting to retrofit their safety systems and may upgrade them to microprocessor based systems. Because of the smaller size and density of the newer equipment, smoke may cause more widespread problems in the replacement system than in the original equipment. As a result of the concern about the effects of smoke in nuclear power plants, the Nuclear Regulatory Commission (NRC) sponsored a study by Sandia National Laboratory on the impact of smoke on advanced instrumentation and control (I&C) equipment. This report describes some of the equipment that SNL will expose to smoke, and the specific scenarios that it will simulate for this effort. Three types of equipment will be exposed: surface insulation resistance (SIR) boards, individual components (i.e., chips), and functional circuit boards. The SIR test patterns imprinted on printed circuit boards will be used to measure surface conductivity as a function of smoke deposition. Individual component samples will be tested to determine the effect of smoke on various kinds of chip packaging. Smoke obscuration of optical isolators will also be studied. For the functional board tests, SNL will use a single standardized circuit board to assess the effects of smoke on functional circuits of various types. To test individual components, SNL will vary the exposure conditions such as burn temperature, fuel-to-air ratio, presence of galvanic metals, humidity level, and fire suppression agents. The range of exposure conditions for the functional circuit tests will be based on the results of the individual component tests. SNL will determine what exposure conditions will cause functional boards to fail. Using this approach, the tests will cover both variations in smoke exposure scenarios and variations in their effect on different types of advanced digital instrumentation.

Acknowledgments

I would like to acknowledge the assistance of Dr. Kofi Korsah of Oak Ridge National Laboratory, Dr. Mahbubul Hassan of Brookhaven National Laboratory, and Dr. David Palmer and Dr. Dennis Anderson, both of Sandia National Laboratory, for educating me on digital components and component reliability. Ms. Christina Antonescu has been invaluable in procuring funding from the U.S. Nuclear Regulatory Commission and in providing advice on the project direction. This work was supported by the U.S. Nuclear Regulatory Commission and was performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under Contract DE-AC04-94AL85000.

Table of Contents

1. Introduction

Smoke can be a serious threat to both digital and analog electrical equipment. Research by telecommunications companies shows that in a fire, up to 95% of the damage to electronic equipment results from smoke.[1] This threat also affects nuclear power plants. In many cases nuclear power plants have had to upgrade their safety systems with microprocessor-based systems because no analog replacement parts are available. The newer digital equipment is more compact and can combine many functions, such as transmitting several different reactor instrument readings over one cable, by using networking techniques. However, as a result of this reduction in size and combination of functions, an environmental hazard such as smoke may cause more widespread problems in a replacement digital system than it would in the original analog system.

In a nuclear power plant, the first few hours after a fire are critical for plant safety (the time required to achieve safe shutdown). Little information is available on the reliability of electronic equipment that is exposed to fire and smoke for this critical period, although some data exist on the reliability of electrical equipment in the long term (more than several days after the fire). Short-term effects may include intermittent short circuits and may depend on conditions such as humidity or the presence of fire suppression agents. There have been a few fire tests in which operating electronic equipment was exposed to smoke, but there is no standard procedure for such exposures. As a result of concern about the effects of smoke in nuclear power plants, the U. S. Nuclear Regulatory Commission (NRC) began a program at Sandia National Laboratories (SNL) in 1994 to study the impact of smoke on advanced instrumentation and control equipment (I&C).

The types of digital equipment that can be used to retrofit safety systems can vary widely. In order to limit time and effort in this project, SNL will test a limited set of typical digital equipment. The smoke tests will expose three types of equipment: SIR boards with a specialized test circuit, individual components (i.e., chips), and functional circuits. This report describes the various components that will be tested and the likely failures anticipated. SIR boards and individual components will be tested between August and December 1995. The tests of the functional circuits are planned for 1996.

In a related effort, SNL and Oak Ridge National Laboratories (ORNL) are cooperating on testing the effect of smoke on a simulated operating reactor trip system. ORNL designed, assembled and programmed the system, certain parts of which were exposed to smoke under their program on Advanced Instrumentation and Control. The tests took place in December 1994 and May-June 1995 and the results will be published shortly.[2,3]

2. Summary of Likely Failures in Microprocessor-Based Systems

When determining the type of equipment to test and the diagnostics required to assess performance, it is important to determine the likely failure modes of a microprocessor system. Based on a review of the literature and discussions with experts in digital circuits, four likely modes of smoke damage have been identified: circuit bridging, contact fouling, corrosion, and

Table 1. Summary of Anticipated Failure Modes of Electronic Components in a Smoke Environment

Failure mechanism	Failure cause
Corrosion	Acid gases can combine with water to corrode metal contacts and cause open circuits.
Shorts	Soot can act as a circuit bridge between contacts and cause leakage of currents and shorts.
Increased contact resistance	Electrical contacts can be coated with soot , causing increased contact resistance.
Mechanical binding	Mechanical equipment, such as timers, may be impeded by soot
Obscuration	Smoke and soot may coat optical interfaces and reduce optical transmission
Galvanic salt shorts	Chlorine gases can combine with zinc from galvanized surfaces to form ZnCl. This compound is hygroscopic and conductive. When it combines with water it forms a syrup-like liquid that can then drip onto electronics and cause shorts.

hindering mechanical motion. Optical components may also fail because of obscuration. Failure mechanisms from smoke are believed to be similar to those due to a polluted environment. Although failures caused by pollution may occur over decades, the soot and smoke from a fire can produce failures in minutes to weeks. Table 1 summarizes the types of failures anticipated for electronic equipment. For advanced digital equipment, we expect failures primarily due to corrosion and circuit bridging shorts. Contact fouling and mechanical binding are considered unique to older analog equipment.

As a part of their collaborative work, in December 1994, ORNL and SNL exposed a small microprocessor-based digital system to smoke.[2] These tests provided information on the kinds of failure modes that may be possible. In the tests, a host computer interrogated the condition of the exposed digital system, but remained outside of the exposure. For one of the smoke exposures, the interrogation program stopped, which indicated an error in the exposed system, but once the system was restarted it then acted normally. Other failures occurred in the first 24 hours of exposure, but also were intermittent. After exposure to smoke, the uncleaned system again worked as designed. The system was periodically tested over 1 month without failure until humidity was added with a cool-mist humidifier. The humidifier water condensed on the board and shorted some of the contacts. This caused the same error that was seen during the smoke test; however, in this case the equipment would not restart.

Based on this experience, we believe that during the smoke exposure, currents leaking from the circuit bridging caused by soot probably caused a transient error which in turn caused the program to stop, but these shorts were of such limited duration that they did not destroy the equipment. Shorts caused by circuit bridging were expected to take place during the smoke exposure and the likelihood of such shorts is probably strengthened by the introduction of humidity. This happened within an hour of the smoke exposure. Other effects, such as contact corrosion, take place more slowly, perhaps over months. Since the time during and immediately after a fire is so critical for a nuclear power plant if shutdown is required, SNL plans to mainly investigate failure modes that are immediate (i.e., shorting and obscuration) rather than longer term (i.e., corrosion).

3. Equipment to be Tested

Advanced microprocessor-based equipment can be classified in many ways, but all are based on a printed circuit board populated with integrated circuits (ICs) or chips. ICs are designed using various technologies: transistor-transistor logic (TTL), complementary metal-oxide semiconductor technology (CMOS) and emitter-coupled logic (ECL). Within each of these broad categories there as subcategories such as low-power Schottky (LS), advanced low-power Schottky (ALS) and advanced Schottky (FAST), which are all TTL-based designs.[4] The choice of technology in a circuit is based on speed, power consumption, output, supply voltage, and noise considerations.

The complexity of the IC determines the design and packaging of the final component. An IC by itself is very small and delicate; it is the packaging that allows digital equipment to be handled and assembled. As memory and logic chips become more complex, the density of interconnections within the chip grows. The number of connecting pins on the final package also grows with each advance in digital technology. These smaller, more densely packed connections make the circuitry more susceptible to shorts or open circuits.

With respect to corrosive failures, the particular technology type, speed, or complexity of a chip should have little effect; however, the way the ICs are packaged and mounted should affect reliability greatly. Since the IC is encased in a package, the smoke will attack the package first. Important considerations affecting corrosion include the metal or combination of metal contacts, contact spacing, applied voltages, bonding techniques, and the material which protects the chip.[5]

In order to understand the relative importance of these aspects, SIR boards, ICs, and functional boards will be exposed to smoke at SNL. The SIR boards and ICs will be exposed simultaneously while the functional boards will be tested separately in 1996. The sections which follow describe the test items.

3.1. SIR Boards

Soot from a fire can form a semiconductive layer on printed circuit boards. This layer can induce current leakage between contacts on the boards and lead to immediate failure. One way to measure the change in resistance of the surface of a printed circuit board is to measure the surface insulation resistance (SIR). This is done with a dual comb pattern made of interlaced conducting tines (see Figure 1). A voltage across the comb pattern will create a field on the surface of the board. To measure surface insulation, the current leakage between the comb patterns is monitored. The Institute for Interconnecting and Packaging Electronic Circuits (IPC) has developed several standard SIR boards and procedures for use in measuring surface insulation resistance.[6] Although SIR is not a standard measure for smoke corrosivity testing, a collaborative effort of AT&T, DuPont and Underwriter's Laboratory (UL) is planning some smoke exposures in 1995 using this technique to evaluate its use as a standard.

SNL will measure surface insulation resistance using one of these standard printed circuit boards (IPC-B-24). The surface insulation resistance will be actively monitored during the smoke exposure. In order to study the effect of various coatings, three boards will be tested simultaneously in the smoke chamber while another will be monitored as a control board outside of the smoke exposure chamber. The boards in the smoke chamber will include an uncoated board, a conformally coated board, and a board enclosed in a metal box. The control board will be at the same temperature and humidity conditions as the rest of the boards, but will not be exposed to the smoke. The SIR will be measured at three different voltages: 5 V, 50 V, and 160 V. The 5-V measurement corresponds to the voltage found on many printed circuit boards. The 160-V measurement was chosen to match the fields on similar boards to be tested at UL. The 50-V measurement was chosen because it is in between the low and high voltage level and may aid in determining the effect of different voltages on these circuits. Since the smoke deposition can be affected by fields near the boards, the comb patterns will remain at the test voltage even between measurements.

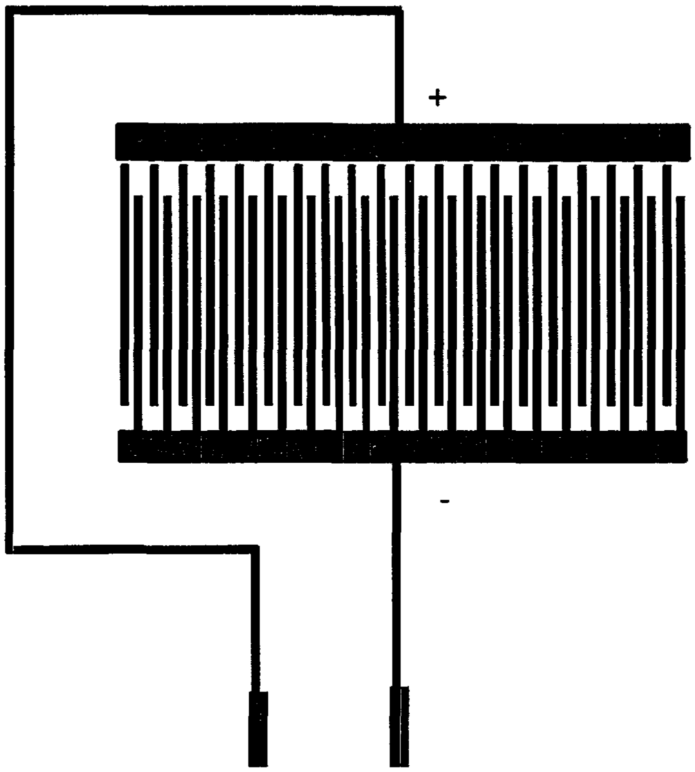


Figure 1. Comb pattern

3.2. Integrated Circuits

Integrated circuits are generally contained in a package that allows for electrical connections but which protects the IC from the environment. Many of these packages are made of either plastic, ceramic, or metal bodies with copper contacts. The packages come in seven families: (1) transistor outline (TO) can, (2) single-in-line package (SIP), (3) dual-in-line package (DIP), (4) small-outline integrated circuit (SOIC) package, (5) chip carrier (this can be leadless or leaded), (6) flatpack made of ceramic or metal, and (7) grid array.[7] See Figure 2 for illustrations of some of these chip packages. The first three families, the TO can, SIP, and DIP package, are mounted to a printed circuit board by drilling holes in the board and soldering the connectors to the board (through-hole mounting). The last four families are surface-mounted packages. The surface-mounted packages are connected by coating bonding pads on the printed circuit board with solder paste, then placing the chips on the board and heating the board.

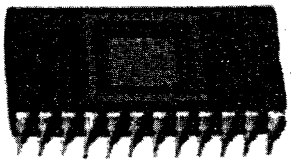
Newer surface mounting techniques allow many more connections per surface area than older through-hole mounting schemes. Compact circuits not only allow for smaller packages, but also improve the speed of a circuit. In a smoke environment, however, these smaller, more closely packed connections can prove to be less reliable than the older through-hole mounted chips. Conductors that are spaced more closely together may be easier to bridge with soot and smaller conductors may corrode faster.

SNL will investigate the effects of smoke on the chip-to-printed circuit board mounts by measuring the resistance between leads on empty chip packages. Seven different chip packages will be mounted on a printed circuit board and tested in four different configurations: exposed to smoke, coated with a conformal coating and then exposed to smoke, packaged in a protective box and then exposed to smoke, and unexposed to smoke. The seven chip packages are shown in Figure 2.

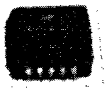
Chip packages such as the ceramic dip, ceramic flat pack, ceramic leadless chip carrier, and TO can are initially manufactured without an IC. Typically the IC is then bonded to the connections inside the package and the package is sealed later. To test these chip packages, empty packages (sealed but without an internal IC) will be mounted on a printed circuit board so that the resistance between adjacent connectors can be measured during the smoke exposure. There will be no connections inside the chip packages. Every other connector will either be connected to ground or 5 V. The insulation resistance between the connectors will be monitored during the smoke exposure. We expect that the insulation resistance will drop as the soot gets deposited, indicating the possibility of circuit bridging or leakage currents.

Dual-in-line (DIP)
Plastic

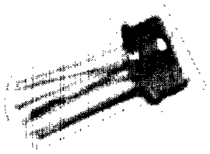
Small Outline IC (SOIC)
Plastic



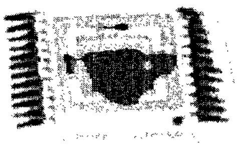
Dual-in-line (DIP)
Ceramic



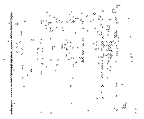
Leaded Chip Carrier (PLCC)
Plastic



Transistor Outline Can (TO)
Metal



Flatpack
Ceramic



Leadless Chip Carrier
Ceramic

Figure 2. Chip packages used in chip mounting tests.

Plastic-bodied chips are manufactured by first connecting the IC to the connectors, then molding the plastic body around the IC. It is difficult to obtain this type of chip package without an interconnecting IC. Instead, SNL will use simple chips that contain several independent circuits and will measure the resistance between adjacent connectors that are not on the same circuit and thus should have no interconnection. One such type of chip is the 74/04 quad hex inverter containing four independent circuits which should have no interconnection. We purchased both a DIP- and SOIC-style hex inverter. These chips will also be mounted on the same printed circuit board as the empty chip packages and will be subjected to the same tests.

Plastic leaded chip carrier (PLCC) bodies are only manufactured for complex integrated circuits. The simplest PLCC circuit we were able to identify is an 8 bit A/D converter with serial interface (this contains 1370 transistors!). This CMOS chip exhibits high resistance between contacts on the input terminals when the chip is powered; therefore the chip will be powered while the resistance between adjacent contacts is measured. This chip will be mounted on the same printed circuit board as the empty chip packages and two hex inverter chips.

Chip packaging protects the IC from stresses due to vibration and chemical attack. Ceramic and metal packages are hermetically sealed, that is, moisture cannot get into the package; however, plastic chip bodies are permeable and exhibit less reliability in humidity tests.[8] To study the difference between plastic and ceramic packages, 16 K memory chips using both packages will be exposed to smoke. The chips will be tested for functionality before and after the exposure. During the smoke exposure, the chips will be powered with 5 V; however, they will not be active. These tests should determine how smoke affects the integrity of the two kinds of packaging.

Optical isolators are commonly used to isolate electrical signals from the rest of the circuit. The electrical signal is converted to an optical signal (with perhaps a light-emitting-diode, LED) and the optical signal is then converted back into an electrical signal with a photodiode. Electrical signals generated on the photodiode side of the circuit are not allowed to pass through to the other (LED) side of the circuit. Optical isolators are usually packaged the same way as transistors, either in metal cans or in plastic sealed packages. Because of their rather unique operation, unique failure modes are expected.

SNL will actively monitor the function of a 6N135 optical isolator. This isolator is sold in a molded plastic DIP form. Previous tests showed that the smoke was the most dense within minutes of the start of the test; therefore the performance of the isolator will be continuously monitored during the smoke exposure test.

3.3. Functional Board Tests

The functional board tests will use a multifunctional board developed by the Low-Residue Solder Task Force whose goal is to investigate ways to reduce the amount of ozone-depleting chemicals used in the manufacture of printed circuit boards.[9] The task force is composed of experts in printed circuit assemblies from the military and military contractors, Department of Energy, and the Environmental Protection Agency. This task force developed a multifunctional board to test the effectiveness of various soldering processes. The board contains four different types of functional circuits: high voltage and low current, low voltage and high current, high-speed digital, and high frequency. Each of these circuits includes a mixture of through-hole and surface-mount components. In many respects, the goal in testing a functional board that uses different soldering and cleaning processes is similar to the goal of the SNL smoke tests. In both cases, deposits on the board could affect their function.

SNL plans to assess the impact of smoke on these functional boards as the third type of smoke exposure. By testing functional boards after the individual component tests, we will be able to correlate the change in resistance to actual failures of functional circuits. The smoke exposure conditions selected for these tests will be based on the results of the component tests.

4. Schedule

4.1. Total Test Matrix

The test conditions for a smoke scenario are affected by many factors, as discussed by Nowlen in an earlier report.[10] These include the fuel composition, fuel-to-air ratio, temperature of burn, humidity, presence of galvanic metals, and presence of fire suppression agents. To limit the scope of the SIR board and individual component tests, we will allow only two conditions for each characteristic; a high or low value, or the presence or absence of a chemical. In all cases the fuel composition will be a mixture of the most common cable insulation and jacket materials that are now in use at commercial nuclear power plants.[11] This reduces the complexity of the tests somewhat, but since we have identified five characteristics, each with two states, there are still 32 possible environments to test (2^5). To increase the robustness of the test results, each test should be performed twice, yielding 64 tests.

Some tests can be eliminated as not applicable to fires in a nuclear power plant. For example, a high-temperature fire implies that the fire is quite large; in such a case, all of the equipment in the cabinet where the fire originates would most likely be destroyed. Thus, the effects of a large fire inside an equipment cabinet will not be tested. Using this reasoning, we eliminated tests for a high fuel /air ratio that also includes high heat flux (note that a small fire with the smoke confined to a single cabinet results in the highest fire/air ratio). In most cases the relative humidity will be high following a fire. The only case in which it would remain low is if a small fire were confined to a single panel in the control room. This eliminates all conditions where a low fuel/air ratio can occur in conjunction with low humidity.

By considering only credible combinations of fire conditions, the total number of fire environments can be reduced to 14 (see Table 2). For the sake of robustness, each test will be performed twice (a total of 28). Each of these tests will include SIR boards, the chip mounting tests, the chip packaging tests, and optical isolator tests.

Functional board testing will begin in 1996, but the test conditions are not yet determined. Each of the functional board tests will be more complicated than the tests for the components, and hence fewer tests will be conducted. The test matrix for the functional board tests will not be defined until we have the results of the initial test series described here.

4.2. Schedule of Testing

Each smoke exposure test requires three days. The first day of each test sequence will include setup and assembly of test parts. On the second day, the 24-hour smoke exposure test will begin, and on the third day we will clean up the test chamber. The total testing period will require 84 testing days if there are no interruptions. We plan to start testing in August and finish by December 22, 1995.

Testing of functional boards will begin in June 1996 and continue through September 1996. This will allow time to evaluate the results of the individual components tests and procure the functional boards.

5. Summary

This paper has described the test specimens and fire scenarios selected to study the impact of smoke on digital equipment. Three types of equipment will be exposed to smoke: SIR boards, individual components, and functional circuits. The tests of individual components are designed to study the impact of smoke on circuit bridging, obscuration, and short-term corrosion. In these tests, exposure conditions such as burn temperature, fuel-to-air ratio, presence of galvanic metals, humidity level, and suppression effects will be varied. Standard surface-insulation-resistance boards will indicate the amount of resistance lost as a function of smoke deposition. In 1996 functional circuits will be exposed to smoke for a limited number of exposure conditions as determined by the individual components tests. These tests will enable correlation to be made between insulation resistance loss and functional board failure. Overall these tests will provide a comprehensive first evaluation of the effects of smoke environments on advance I&C being planned for the next generation of power reactors.

Table 2. Smoke test matrix - SIR Board and Individual Components Tests

Characteristic	Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fuel Quantity	High	*	*	*	*	*	*								
	low							*	*	*	*	*	*	*	*
Burning Mode	High							*	*	*	*				
	low	*	*	*	*	*	*					*	*	*	*
Fire Suppression	None	*	*	*	*			*	*			*	*		
	CO_2					*	*			*	*			*	*
Galvanic Metal	No	*	*			*	*	*		*		*		*	
	Yes			*	*				*		*		*		*
Relative Humidity	Low	*		*		*									
	high		*		*		*	*	*	*	*	*	*	*	*

6. References

1 Karydas, D. M., "Smoke Management Systems for the Telecommunications Industry," in *Network Reliability: A Report to the Nation,* Compendium of Technical Papers Presented by the Federal Communications Commission's Network Reliability Council, National Engineering Consortium, Chicago, IL, June 1993, pp. G15-18.

2 Report to be published by SNL September 1995 on smoke exposures to multiplexer unit.

3 Report of system tests to be published by ORNL in 1995.

4 "Motorola Logic Families, Which is Best for You?", Gary Tharalson, *Motorola Master Selection Guide Rev .7,* p. 3.1-3 - 3.1-6, 1994.

5 "Electronic Components and Assemblies: Reliability and Testing" by R. B. Comizzoli and J. D. Sinclair, *Encyclopedia of Applied Physics,* Vol. 6, 1993 VCH Publishers, Inc. pp. 21-44.

6 "IPC Cleaning and Cleanliness Test Program: Phase 3 Water Soluble Fluxes Part 1" Douglas Pauls, September 30, 1992, Institute for Interconnecting and Packaging Electronic Circuits (IPC). Presented at IPC 1992 Fall Meeting Oct. 12-15, 1992.

7 "Overview of Chip-Level Packaging," Barry C. Johnson, *Electronic Materials Handbook,* ASM International Handbook Committee. pp. 398-407.

8 "Corrosion Criteria for Electronic Packaging: Part III–Corrosion by Package Family," Carl E. Hoge, *IEEE Trans. on Components, Hybrids, and Manufacturing Technology,* Vol 13, no 4 p. 1105, 1990.

9 "Test Plan for the Evaluation of Low-Residue Soldering in Military Applications," Prepared by the Low-Residue Soldering Task Force, R. Iman, Sandia National Laboratories, March 1, 1994.

10 "Defining Credible Smoke Exposure Scenarios," A letter report to the NRC, prepared by Steve Nowlen, Sandia National Laboratories, Albuquerque, NM, September 1994.

11 "Low-Voltage Environmentally Qualified Cable License Renewal Industry Report; Revision 1," by L. Bustard and P. Holzman, TR-103841, Published by Electric Power Research Institute, Palo Alto, CA, July 1994,

Appendix F

Component Test Results

This appendix is composed of tables and plots of information from the component tests and includes the physical and chemical measurements of the smoke environment, scatter plots of the resistance of the circuit bridging measurements, and coefficients that model resistances from the circuit bridging measurements. These measurements may be useful for comparing smoke exposure tests and for in-depth analysis of the results.

Table 1. Temperature and humidity during smoke exposures.

Test	Ave Temp	Min Temp	Max Temp	Ave Hum	Min Hum	Max Hum
1	25.1	22.9	30.8	70.9	61.4	76.8
2	24.3	21.4	28.7	73.2	64.8	77.2
3	24.4	21.3	27.3	71.2	61.5	75.6
4	26.2	-3.4	31.2	70.6	63.7	79.6
5	26.7	21.0	31.7	70.3	63.5	78.6
6	25.4	21.8	32.5	68.4	57.9	76.9
7	26.3	21.5	31.4	71.2	65.3	78.9
8	25.4	8.7	32.7	69.4	53.1	79.0
9	24.8	22.3	28.9	71.7	36.2	76.3
10	25.0	20.8	28.8	71.5	51.1	78.4
11	25.1	21.5	31.9	69.5	54.6	79.8
12	27.0	22.3	31.9	20.1	19.2	28.5
13	25.8	22.2	30.9	21.4	20.3	24.4
14	25.5	2.2	30.5	22.2	20.4	24.9
15	25.2	23.0	33.0	66.8	54.5	77.2
16	26.3	23.1	33.3	70.0	59.9	78.6
17	29.6	22.2	41.2	58.5	40.2	77.6
18	29.9	22.4	38.1	60.1	42.2	76.4
19	24.6	21.2	32.3	18.1	13.6	20.5
20	24.1	22.6	27.3	15.8	11.4	18.7
21	25.9	21.7	29.6	72.3	64.7	76.9
22	24.0	20.2	29.6	15.9	9.3	18.8
23	24.0	21.3	32.2	13.0	11.5	14.5
24	26.1	21.9	30.5	14.4	12.1	16.5
25	30.0	23.0	40.0	52.1	38.0	77.4
26	29.0	21.5	47.5	63.5	48.8	81.5
27	25.9	22.2	30.2	69.6	61.5	77.3

Table 1 presents the temperatures in the exposure chamber and the humidity that was measured inside the environmental chamber surrounding the exposure chamber. The temperatures in the exposure chamber were measured in 10 locations, 5 near the ceiling of the chamber, and 5 near the floor. The average temperature presented in the table is the average for the entire 24 hour test for all 10 locations. The locations and methods of measurements are the same as those in Appendix 4. The very low temperatures that were recorded for tests 4, 8, and 14 are the result of cooling by the addition of CO_2. Humidity was measured inside the environmental chamber, but outside of the smoke exposure chamber throughout the 24-hour test. The smoke would have affected the accuracy and lifetime of the humidity sensor, therefore, the humidity inside the exposure chamber during the smoke exposure was not recorded. Immediately after the 1 hour smoke exposure, the exposure chamber was vented and the air from the environmental chamber was drawn into the exposure chamber, so the humidity of most of each test is included in Table 1, but not the humidity during the actual smoke exposure.

Measurements of the fuel trays before and after the burn determined the amount of fuel burned in grams. Although this does not indicate how much is deposited, it is a practical measurement for reproduction of the effects. In the main body of this paper, the results of the tests were evaluated in terms of high and low states of such factors as fuel load and burn temperature. These factors determine how much smoke is deposited on the samples, but are not direct measurements of the smoke deposition. Table 2 presents several different measurements of how much smoke was deposited during the smoke exposure tests; some of these measurements are direct while others are measurements of secondary effects. Most of the smoke was deposited on horizontal surfaces, especially as the amount of deposition increased. These measurements are included in this appendix so that comparisons can be made with other experiments.

Quartz crystal microbalances (QCM) actively measured the smoke deposition in two planes, vertical and horizontal, in $\mu g/cm^2$. A description of the QCMs is included in Appendix 4. Mass densities greater than 200 $\mu g/cm^2$ frequently caused the QCM to stop oscillating; therefore, for most high fuel load tests, the QCMs did not provide a measurement for the horizontal plane. Although the QCMs were not placed at the same position in the chamber as the components, the QCM measurements are the most direct measurement of deposition that was obtained in these tests.

The turbidimeter measured the smoke optical density in terms of the extinction coefficient (turbidity). The turbidity in cm^{-1} is presented for three wavelengths, IR (1.060 μ), red (0.6328 μ), and blue (0.4579 μ). The larger extinction coefficients correspond to more opaque smoke. The optical density is often measured on standard smoke tests of materials and was included here for reference.

Many studies on corrosion and electronic equipment damage are based on the density of chlorides, bromides and sulfates on surfaces. Threfore 4.25 cm circles of ashless filter paper were placed in the smoke exposure chamber and were analyzed by ion chromotography for chlorine, bromine, and sulfate. The results of these analyses are presented in Table 2 in terms of milligrams of chemical per filter.

Table 2. Smoke generation measurements.

Test No.	Wt. Loss	Hor. QCM	Vert. QCM	IR	Red	Blue	Cl (norm)	(Cl) lim	Bromide	(Br) lim	Sulfate (norm)	(S) lim
1	2.48	5.6	1.5	--	--	--	--	--	--	--	--	--
2	2.15	15	1.6	--	--	--	0.044	0.005	0.014	0.001	0.005	0.001
3	2.12	10.7	0.8	--	--	--	--	--	--	--	--	--
4	30.8	>200	4.9	--	--	--	--	--	--	--	--	--
5	31.47	>200	7.2	--	--	--	0.175	0.005	0.139	0.005	0.007	0.001
6	2.51	3.1	1.8	--	--	--	0.027	0.005	0.008	0.001	0.003	0.001
7	31.26	194	4	--	--	--	--	--	--	--	--	--
8	2.54	5.1	2.2	--	--	--	--	--	--	--	--	--
9	2.1	10.7	0.7	--	--	--	--	--	--	--	--	--
10	1.6	5.1	0.68	--	--	--	--	--	--	--	--	--
11	2.15	3.5	1.1	--	--	--	--	--	--	--	--	--
12	34.93	>200	2.4	--	--	--	0.098	0.005	0.216	0.005	0.005	0.001

Table 2. Smoke generation measurements (continued).

13	35.97	>200	2.13	--	--	--	0.075	0.005	0.161	0.005	0.002	0.001
14	34.07	>200	11.5	--	--	--	--	--	--	--	--	--
15	2.53	7.6	1.2	--	--	--	--	--	--	--	--	--
16	37.89	>200	4.1	0.17	0.21	0.87	0.113	0.005	0.256	0.005	0.003	0.001
17	69.58	>200	13.2	0.38	0.44	0.82	0.22	0.005	0.393	0.005	0.005	0.001
18	67.74	>200	--	0.37	0.38	--	0.193	0.005	0.409	0.005	0.003	0.001
19	2.56	1.54	0.97	--	--	--	0.008	0.001	0.006	0.001	0.001	0.001
20	1.94	8.4	0.5	0.05	0.03	0.05	0.016	0.001	0.008	0.001	0.001	0.001
21	25.99	175	5.2	--	--	--	0.116	0.005	0.195	0.005	0.002	0.001
22	2.3	11.5	0.64	--	--	--	0.012	0.001	0.011	0.001	0	0.001
23	2.48	1.7	1.7	--	--	--	0.011	0.001	0.01	0.001	0.001	0.001
24	34.66	>200	2.9	0.17	0.24	0.5	0.093	0.005	0.169	0.005	0.003	0.001
25	66.34	>200	8.2	0.41	0.55	0.45	0.207	0.005	0.371	0.005	0.003	0.001
26	67.43	>200	14.4	0.37	0.43	0.64	0.173	0.005	0.287	0.005	0.004	0.001
27	29.65	200	3.8	--	0.16	0.48	0.103	0.005	0.239	0.005	0.002	0.001

The amount of smoke that was produced was not only dependent on the amount of fuel, but also upon the burn temperature. This point is illustrated in Table 3 where the percentage of weight lost by the fuel (including copper conductors) can be compared with the conditions under which the fuel was burned. The lowest percentages of weight lost correspond to the conditions of high fuel and low burning temperature; the highest percentages of weight lost correspond to a small amount of fuel and a high burn temperature. Large amounts of fuel are slower to burn, especially if the burning temperature is low. The burn temperature also influences how much of the available fuel is released in the fire.

Table 3. Percentage of fuel burned.

Test No.	Percent Wt. Loss	Fuel	Burn
1	48.7	0	1
2	40.3	0	0
3	42.5	0	0
4	18.6	1	0
5	18.7	1	0
6	48.5	0	1
7	18.8	1	0
8	49.1	0	1
9	39.3	0	0
10	31.4	0	0
11	44.1	0	1
12	21.3	1	0
13	21.9	1	0
14	20.8	1	0
15	48.6	0	1
16	23.4	1	0
17	42.4	1	1
18	41.8	1	1
19	49.3	0	1
20	39.8	0	0
21	16.2	1	0
22	45.4	0	0
23	48.4	0	1
24	21.2	1	0
25	41.4	1	1
26	41.4	1	1
27	18.5	1	0

Figures 1 to 33 are scatter plots of the resistance for the 7 chips and 4 comb patterns measured in these tests. These plots show how the chips and comb patterns as a whole react to the smoke. Each chip or comb pattern has three plots of $\log_{10}(R)$: pretest value against during smoke, pretest value against after smoke, and during smoke against after smoke. The pretest value was a single measurement; the values for during and after smoke values were averages. Four symbols were used to depict the four board conditions of bare (solid circle), coated (open square), chassis (open triangle), and control (*). A line with a slope of 1 is included for reference. Points that fall on the line indicate no change among the values that are plotted. These plots provide a general indication of how the different components reacted to smoke during the various stages of the test.

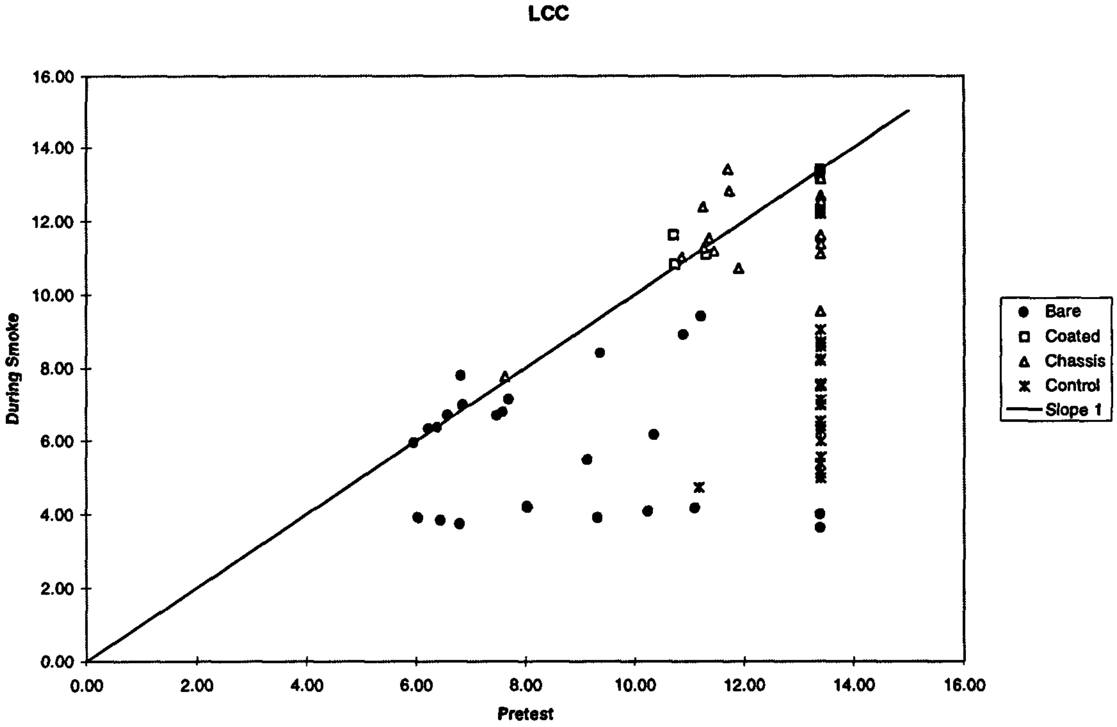


Figure 1. Leadless Chip Carrier $\log_{10}$(R) Pretest vs. During Smoke

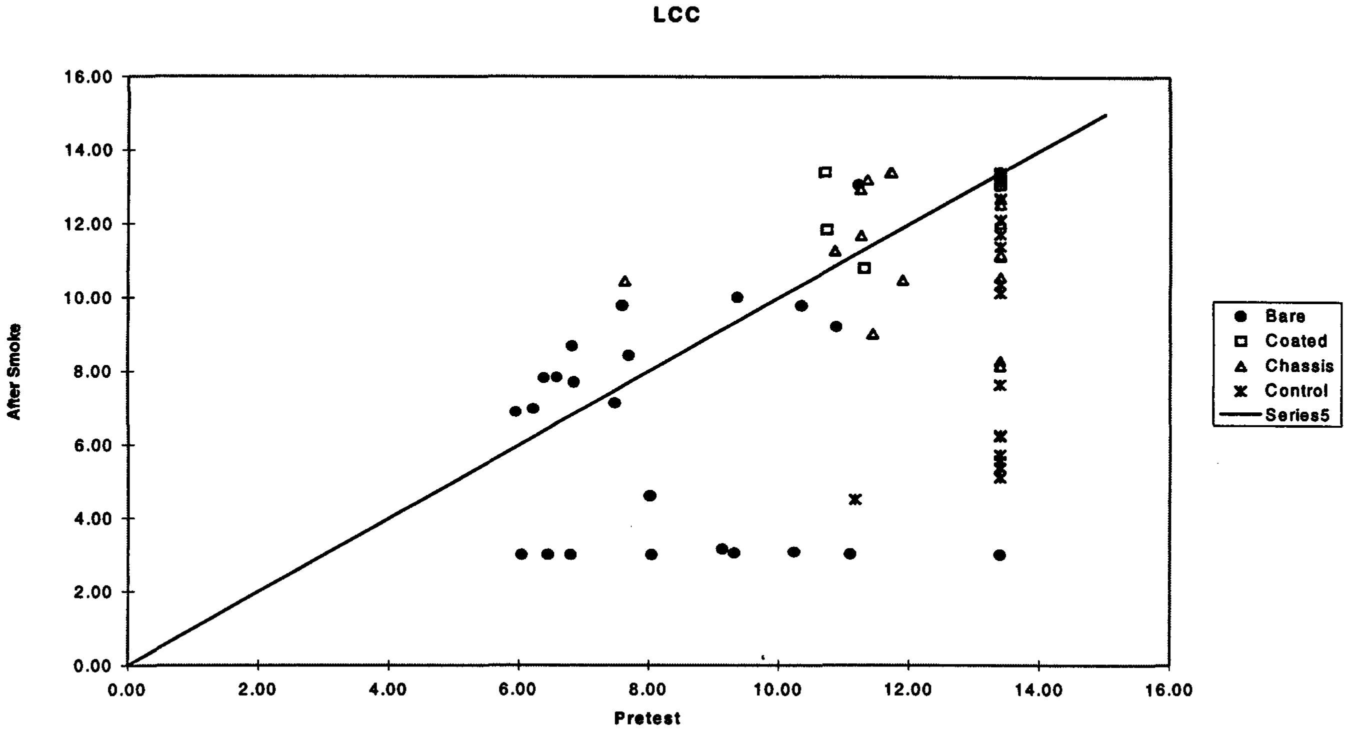


Figure 2. Leadless Chip Carrier Log_{10}(R) Pretest vs. After Smoke

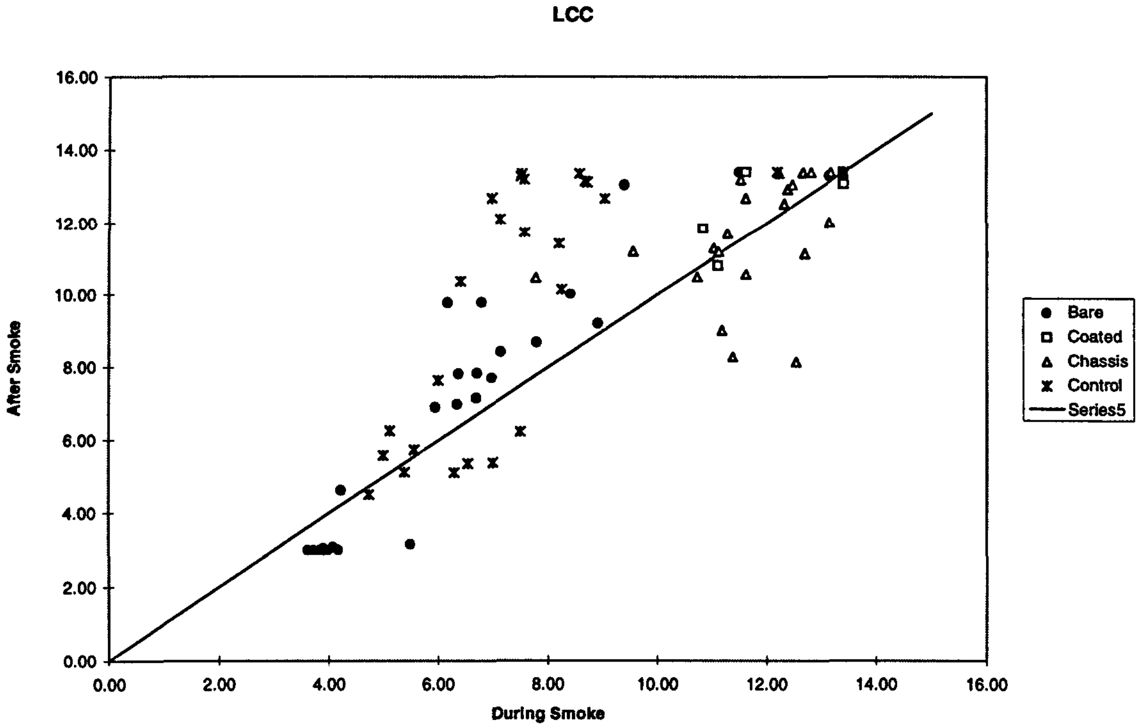


Figure 3. Leadless Chip Carrier Log_{10}(R) During Smoke vs. After Smoke

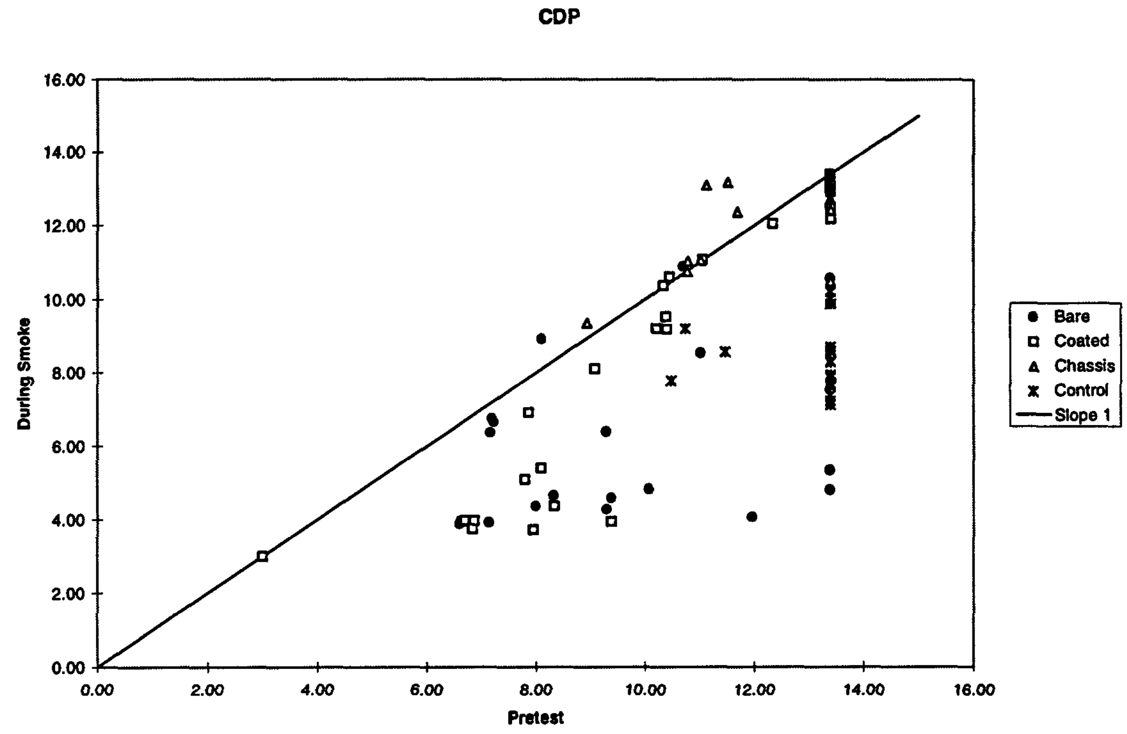


Figure 4. Ceramic DIP $\log_{10}$(R) Pretest vs. During smoke

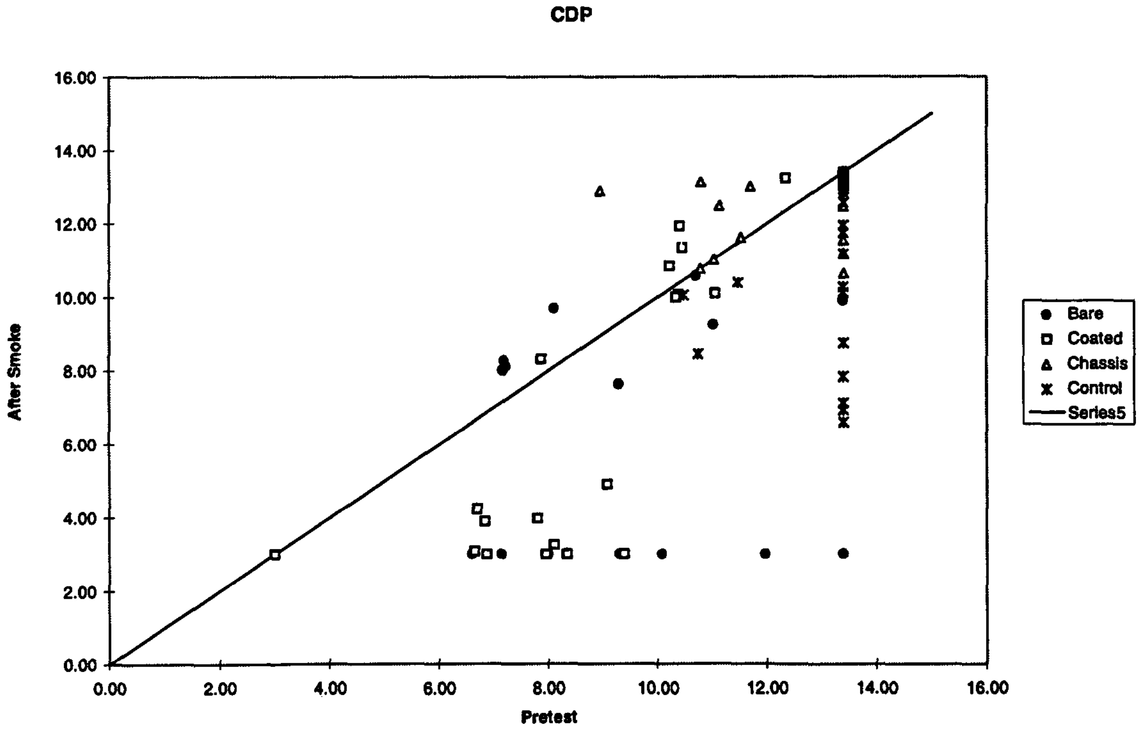


Figure 5. Ceramic DIP $\log_{10}$(R) Pretest vs. After smoke

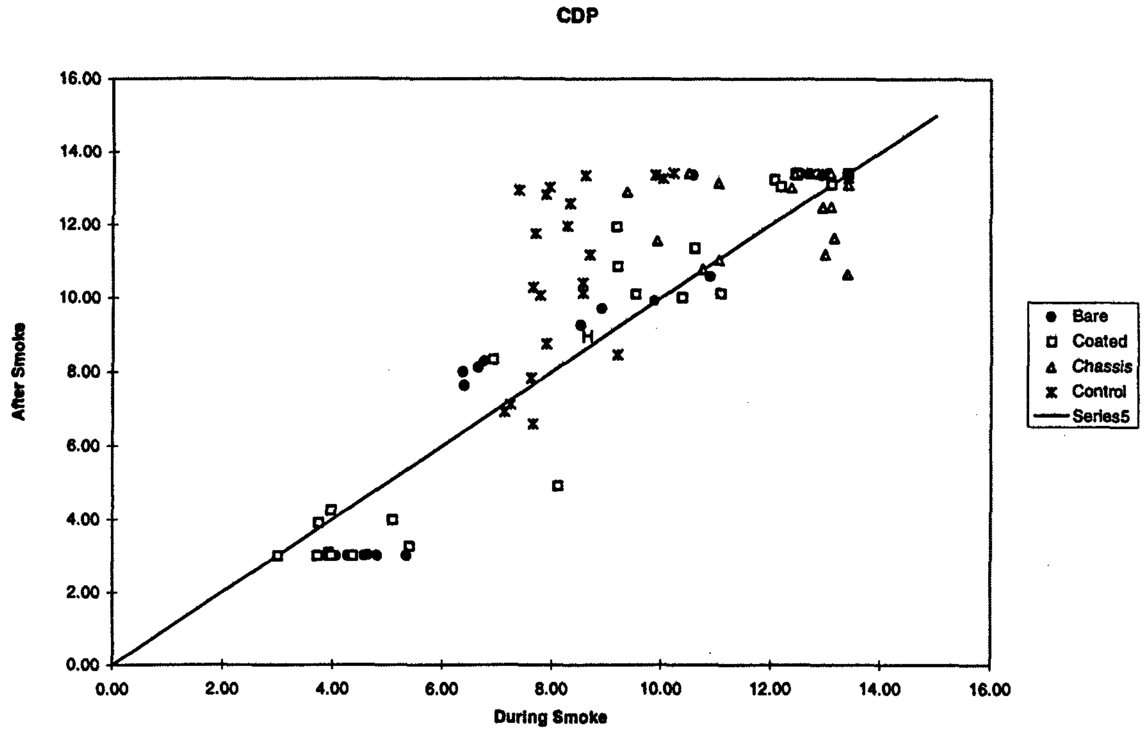


Figure 6. Ceramic DIP $Log_{10}(R)$ During smoke vs. After smoke

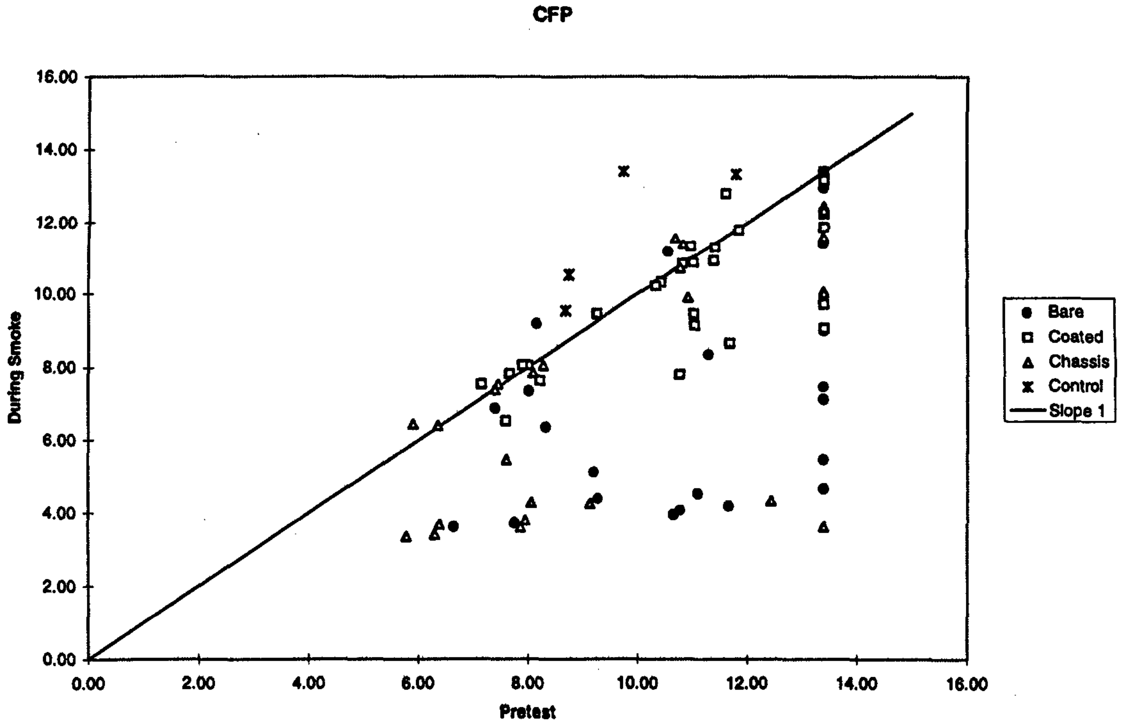


Figure 7. Ceramic Flat Pack $Log_{10}(R)$ Pretest vs. During smoke

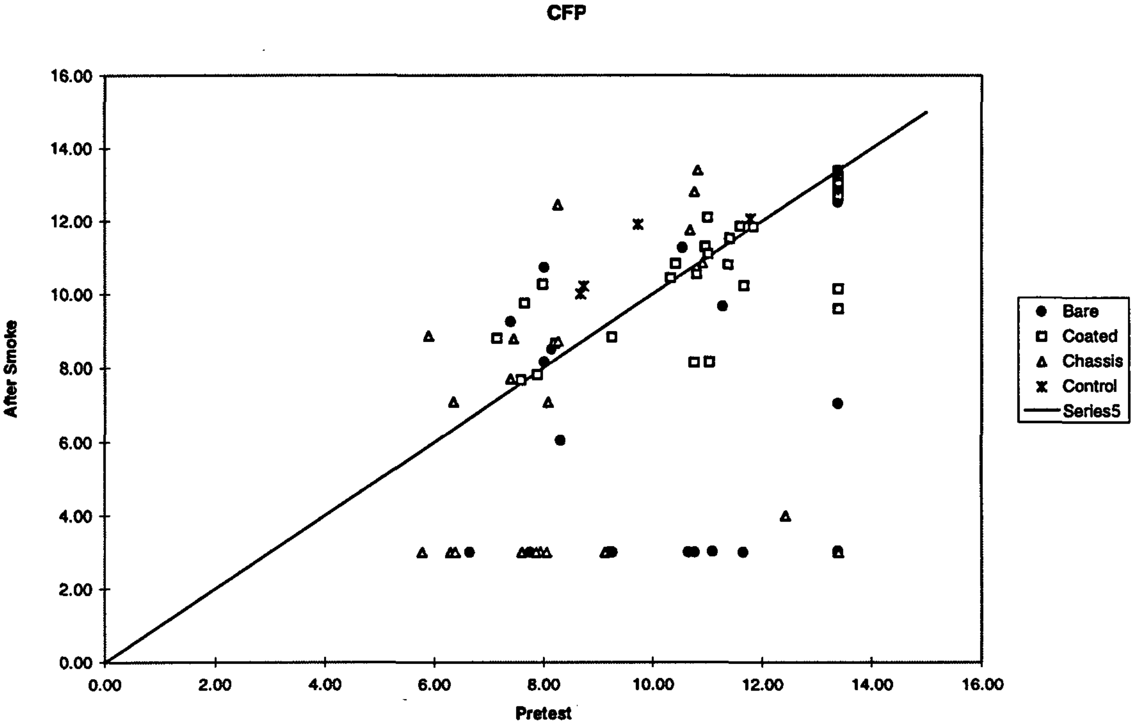


Figure 8. Ceramic Flat Pack Log_{10}(R) Pretest vs. After smoke

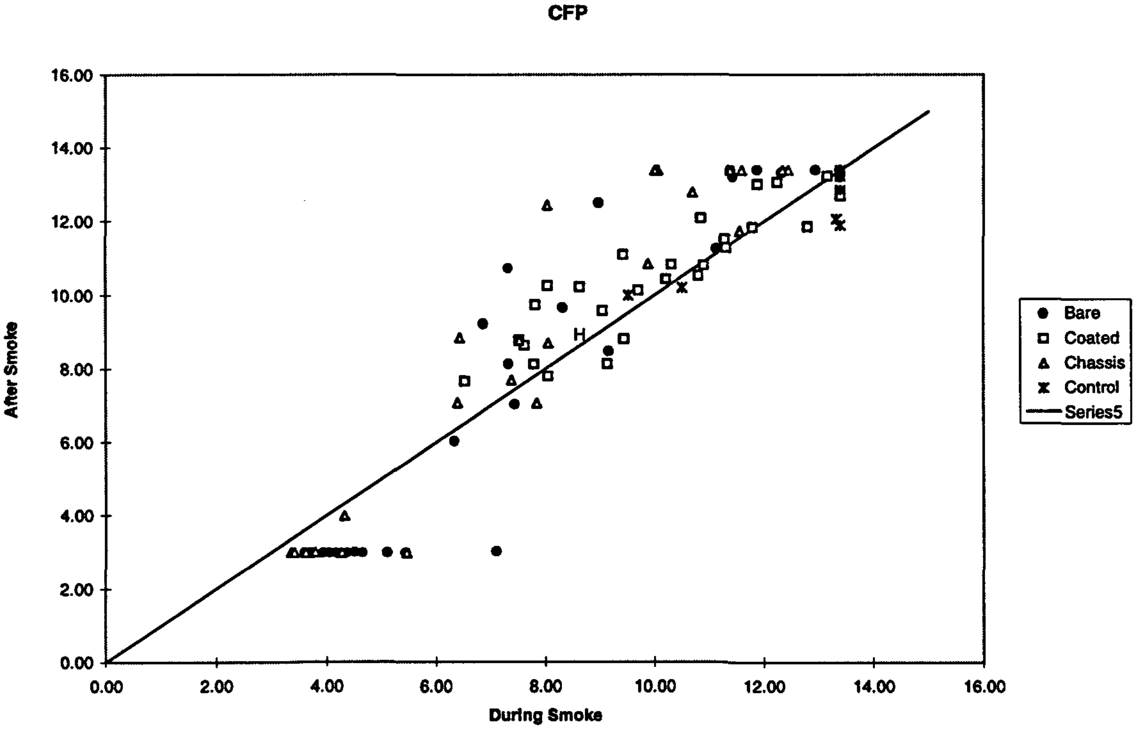


Figure 9. Ceramic Flat Pack Log_{10}(R) During smoke vs. After smoke

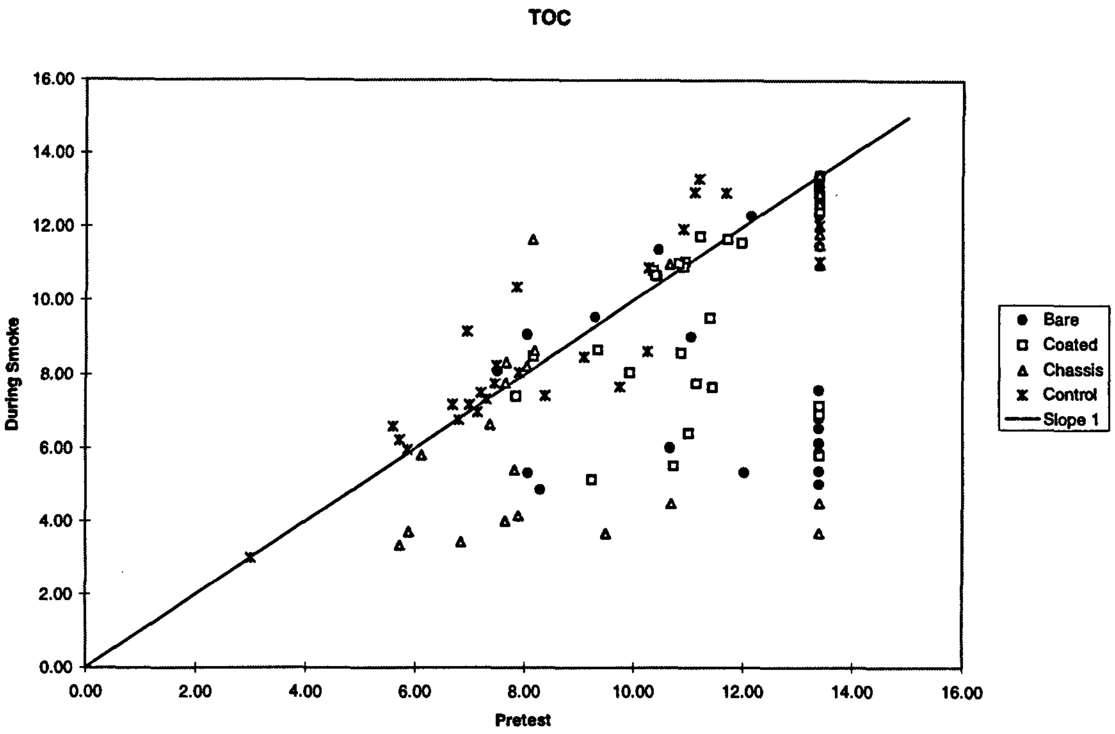


Figure 10. Transistor Outline Can $\mathrm{Log}_{10}(R)$ Pretest vs. During smoke

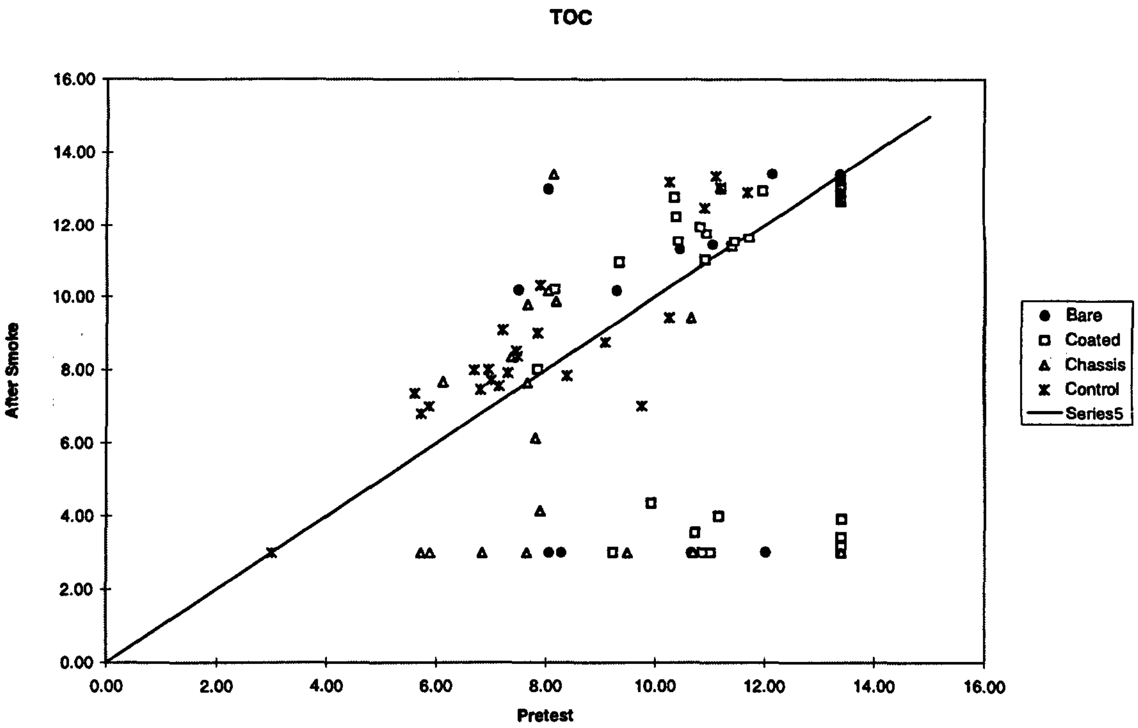


Figure 11. Transistor Outline Can $\mathrm{Log}_{10}(R)$ Pretest vs. After smoke

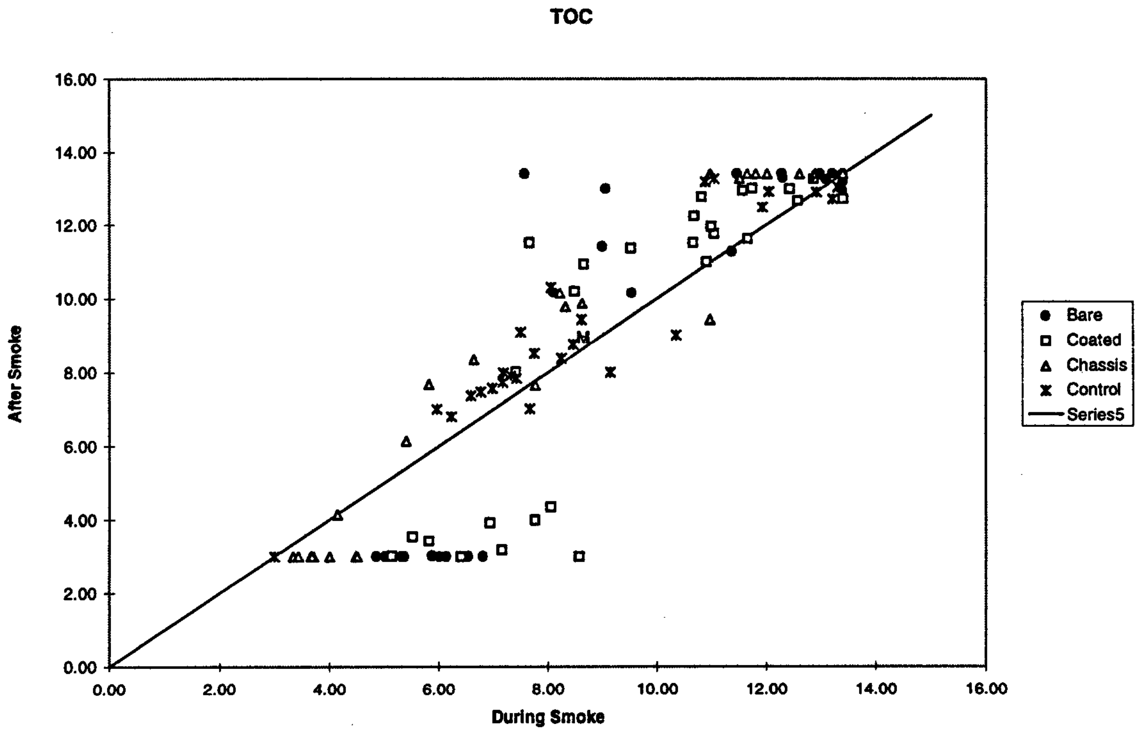


Figure 12. Transistor Outline Can $Lg_{10}(R)$ During smoke vs. After smoke

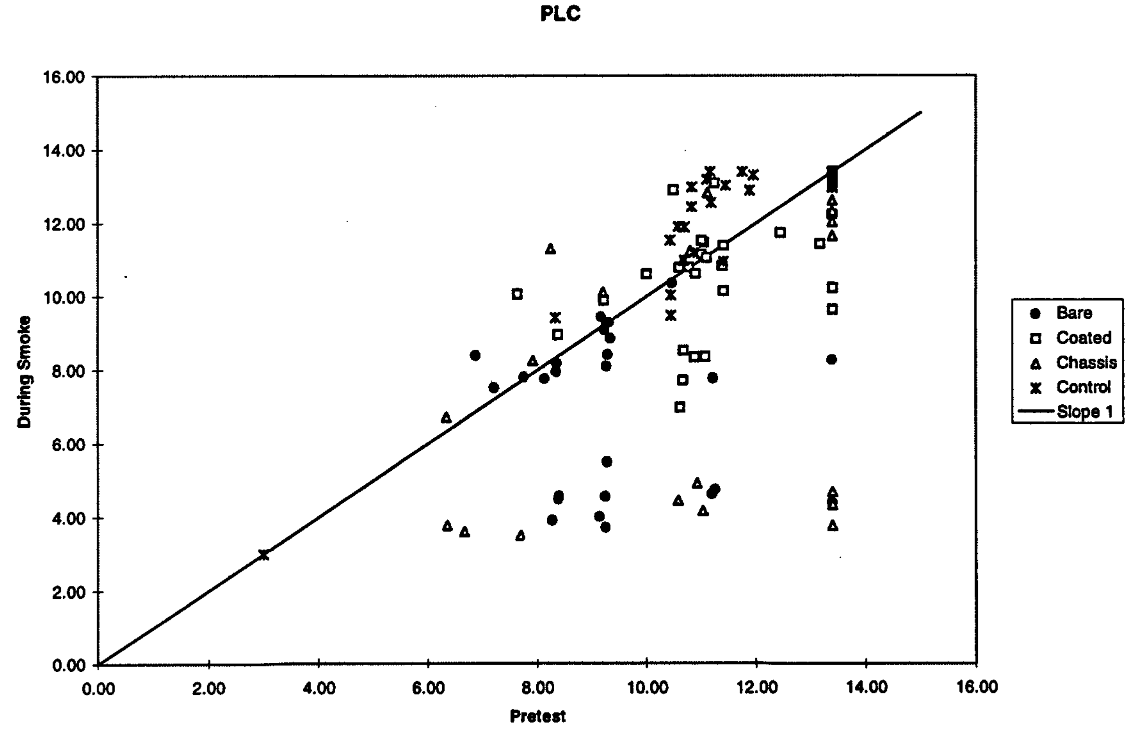


Figure 13. Plastic Leaded Chip Carrier $Log_{10}(R)$ Pretest vs. During smoke

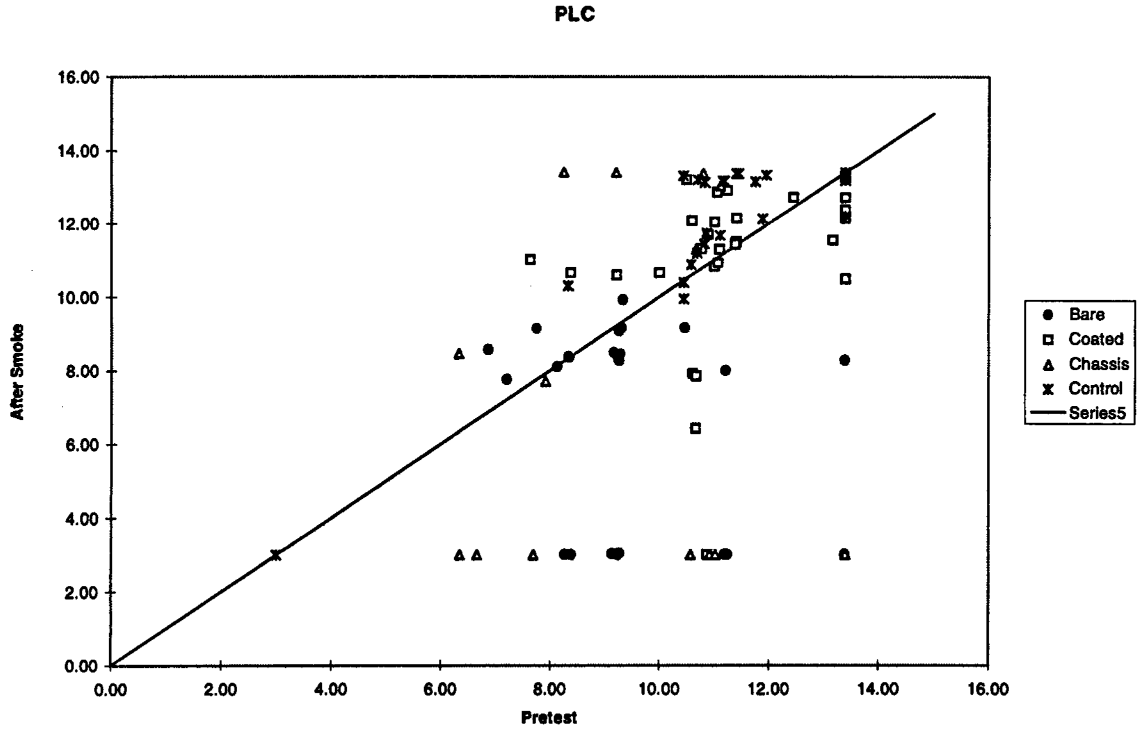


Figure 14. Plastic Leaded Chip Carrier $\mathrm{Log}_{10}(R)$ Pretest vs. After smoke

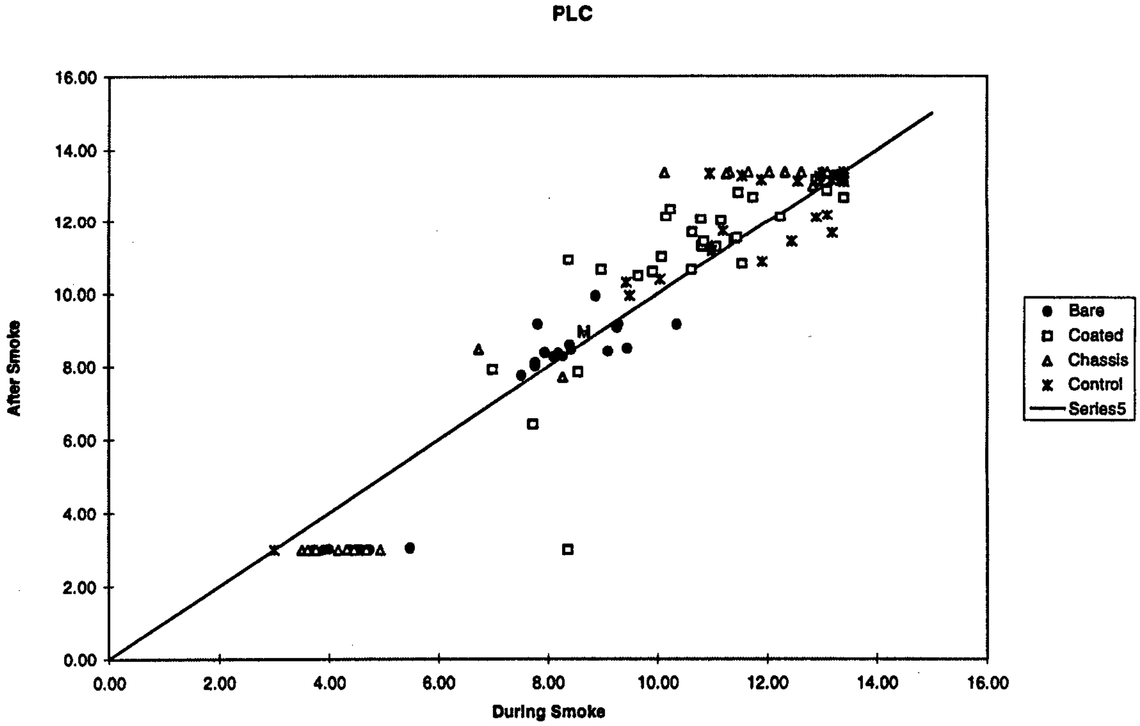


Figure 15. Plasctic Leaded Chip Carrier $\mathrm{Log}_{10}(R)$ During smoke vs. After smoke

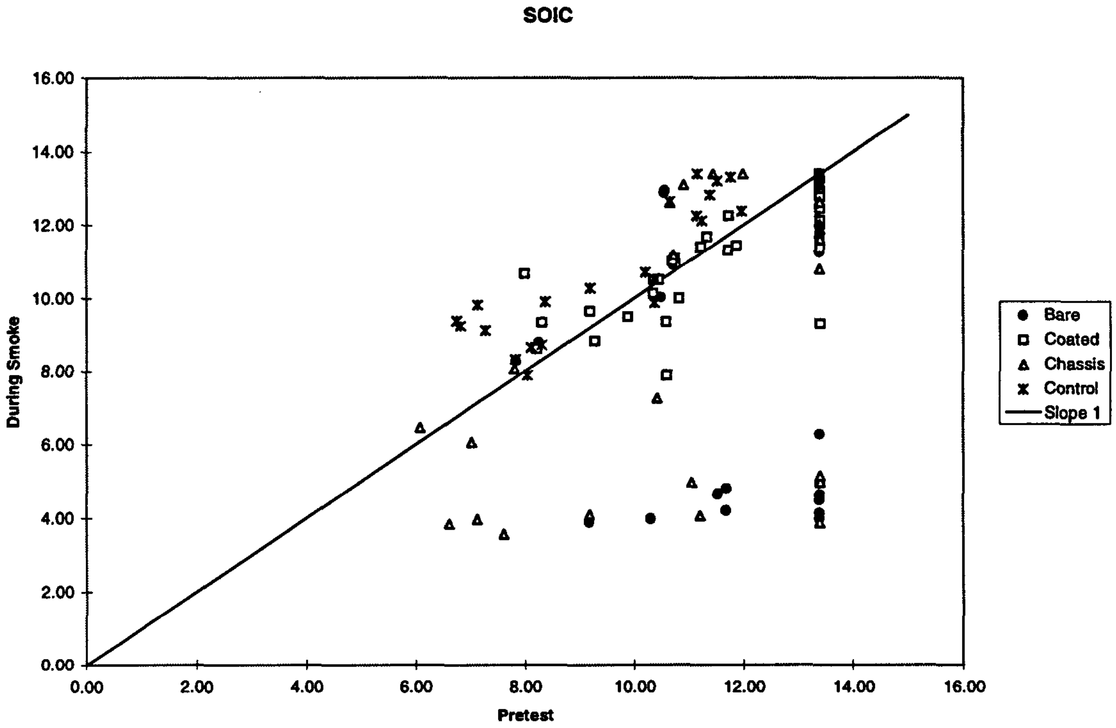


Figure 16. Small Outline Integrated Chip $\text{Log}_{10}(R)$ Pretest vs. During smoke

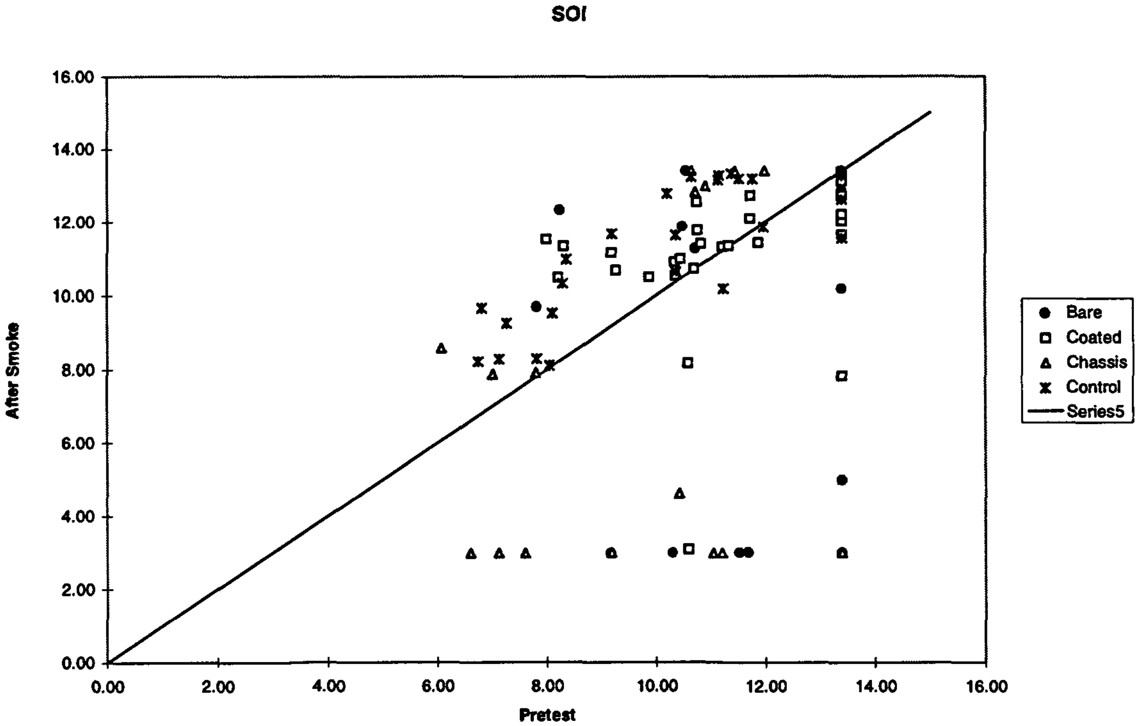


Figure 17. Small Outline Integrated Chip $\text{Log}_{10}(R)$ Pretest vs. After smoke

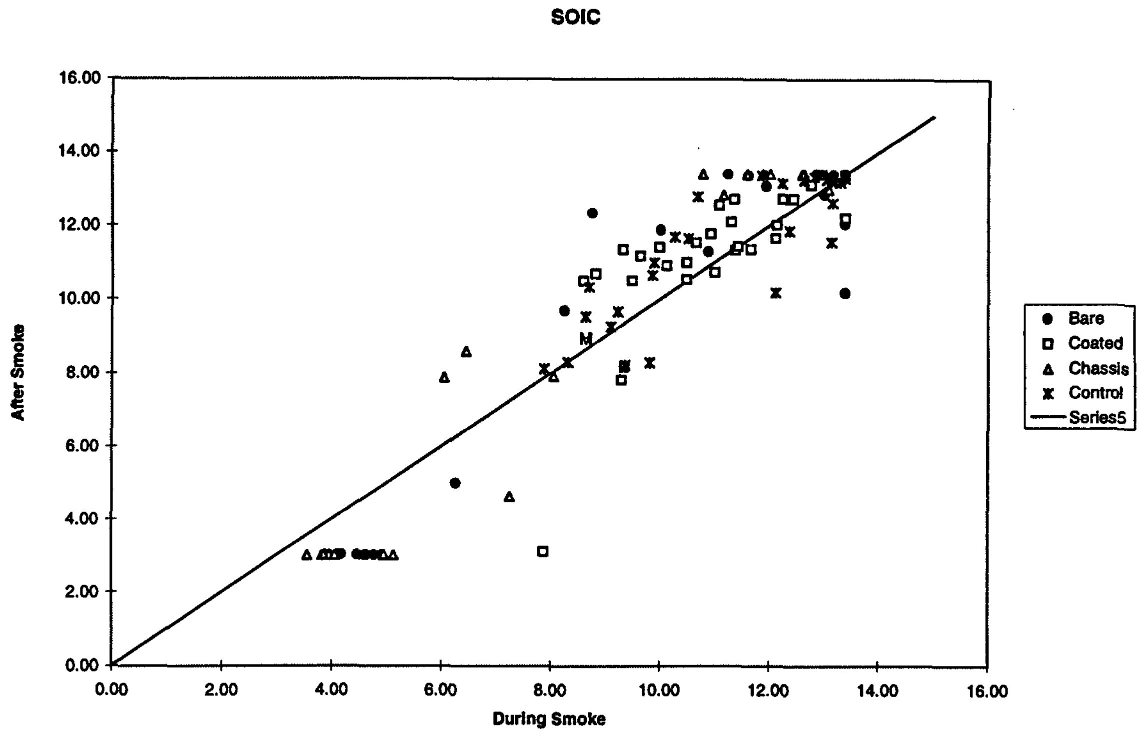


Figure 18. Small Outline Integrated Chip $Log_{10}(R)$ During smoke vs. After smoke

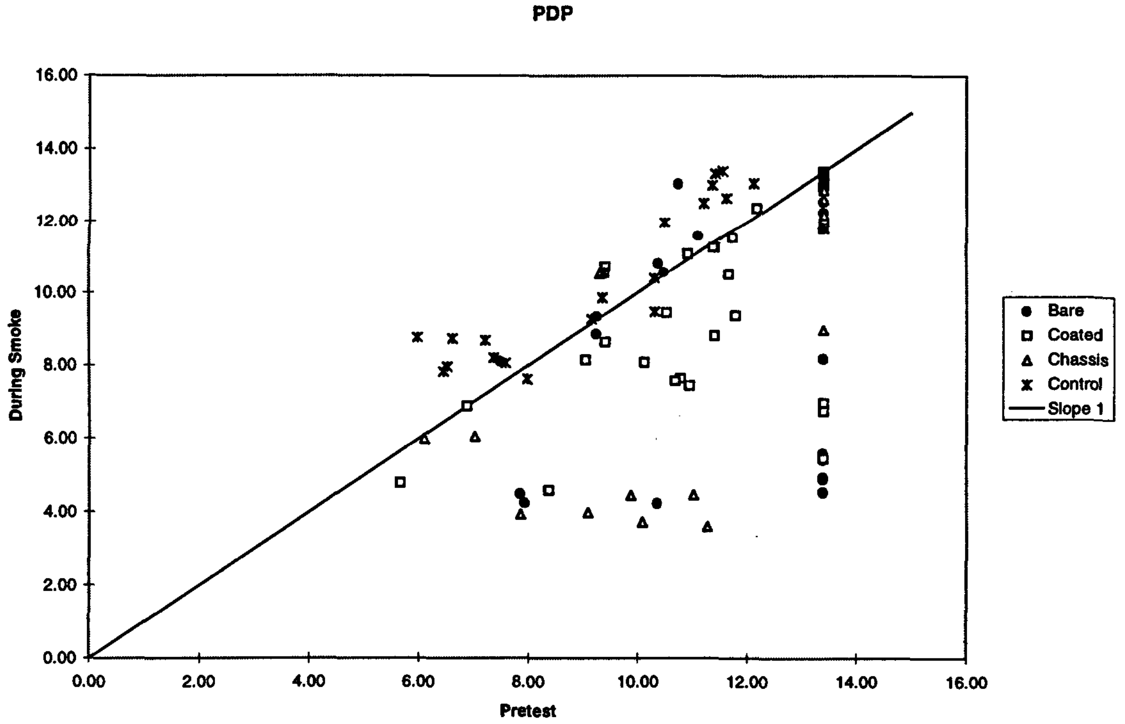


Figure 19. Plastic DIP $Log_{10}(R)$ Pretest vs. During smoke

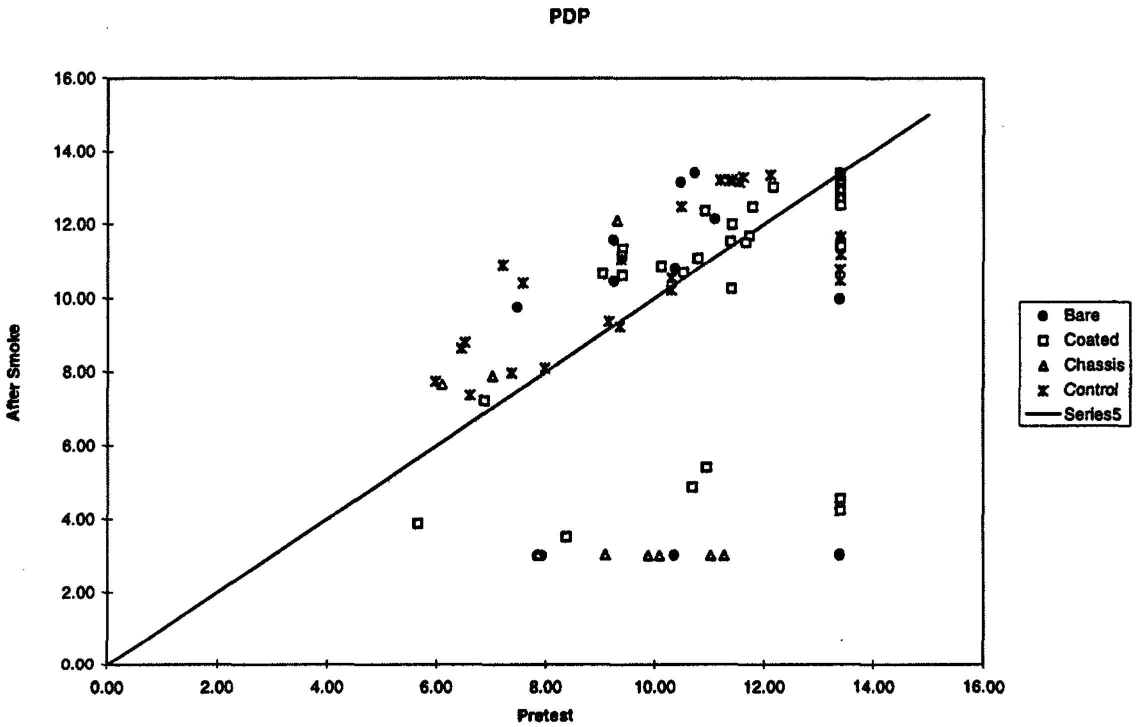


Figure 20. Plastic DIP $\mathrm{Log}_{10}(R)$ Pretest vs. After smoke

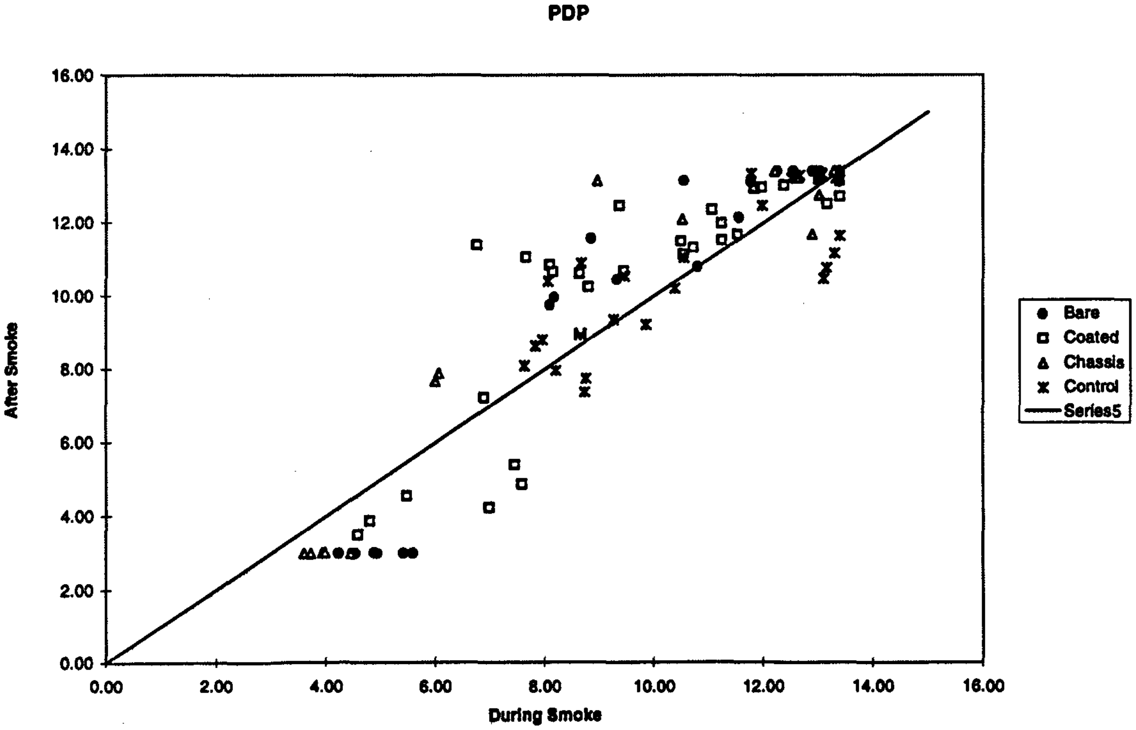


Figure 21. Plastic DIP $\mathrm{Log}_{10}(R)$ During smoke vs. After smoke

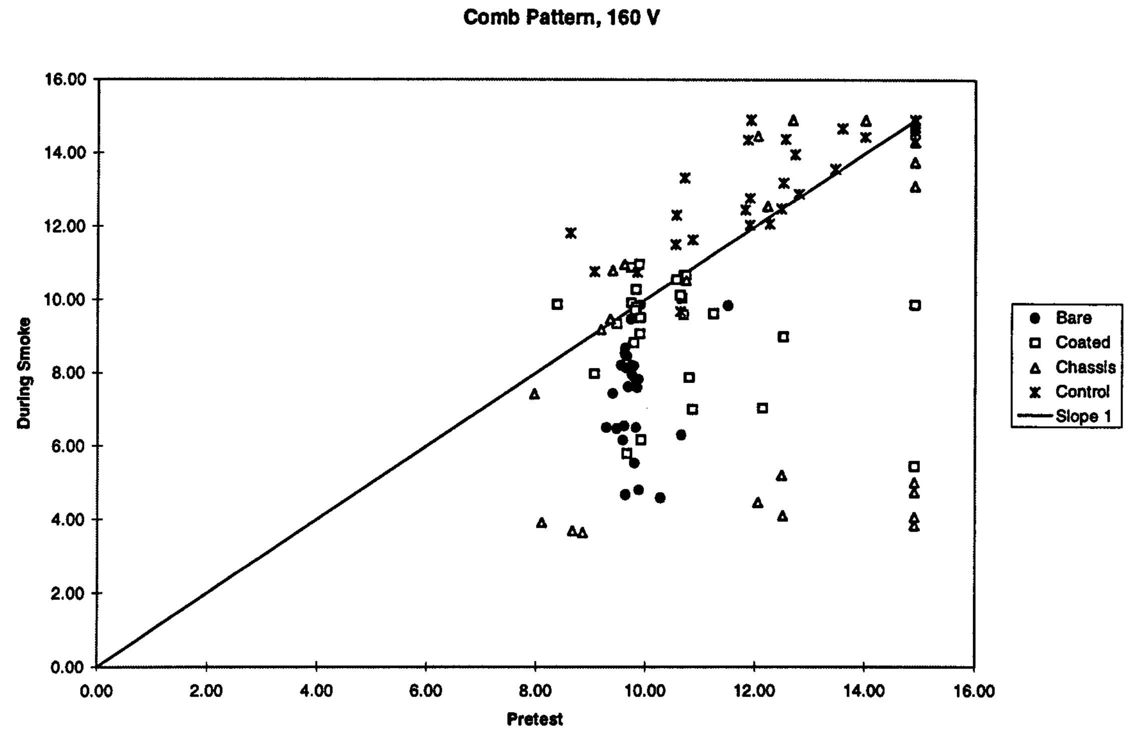


Figure 22. Comb Pattern, 160 V, $Log_{10}(R)$ Pretest vs. During smoke

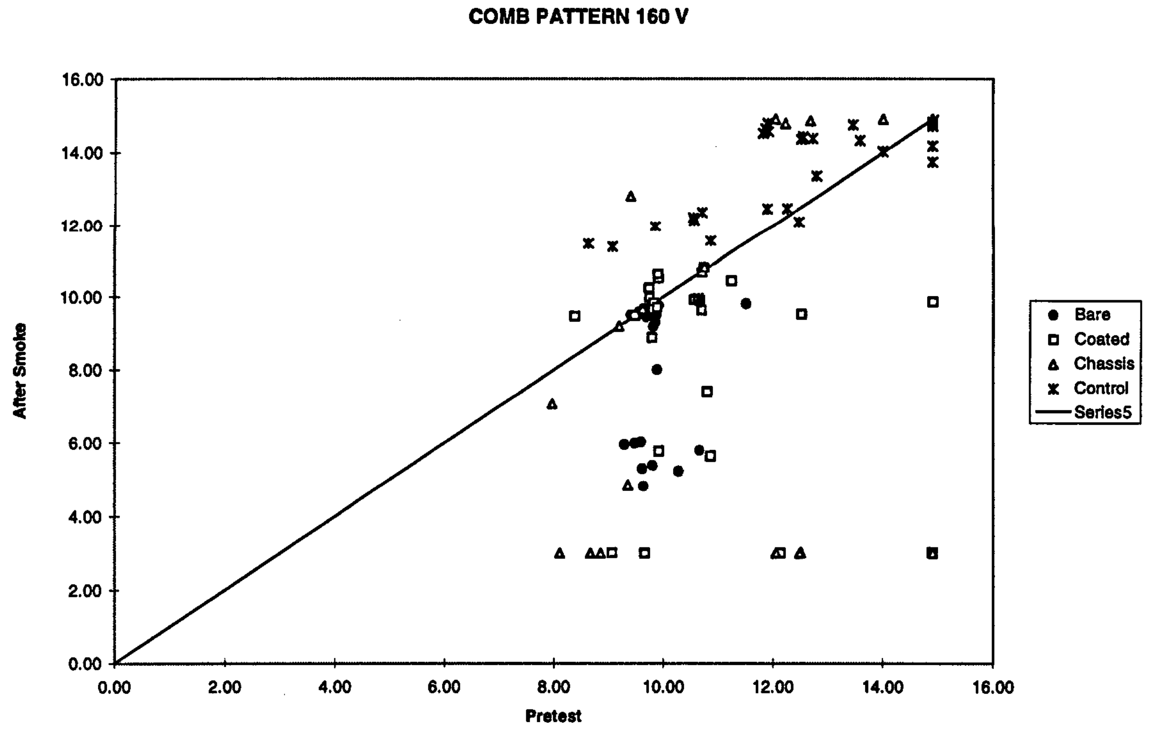


Figure 23. Comb Pattern, 160 V, $Log_{10}(R)$ Pretest vs. After smoke

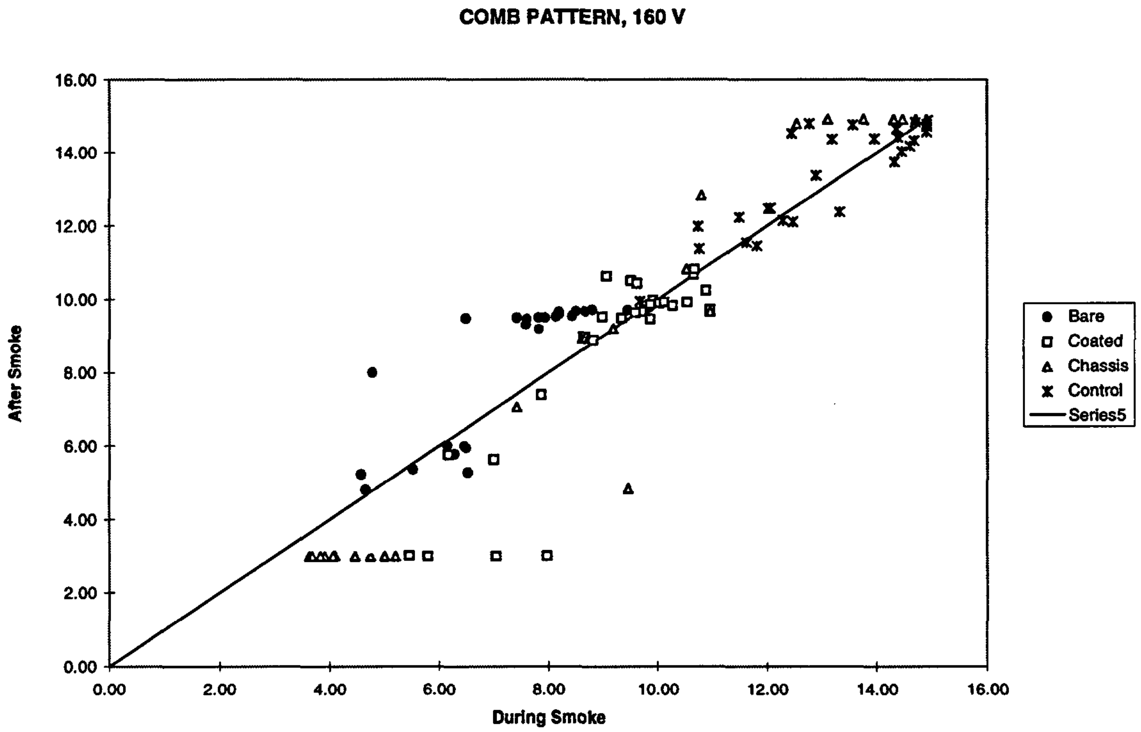


Figure 24. Comb Pattern, 160 V, Log_{10}(R) During smoke vs. After smoke

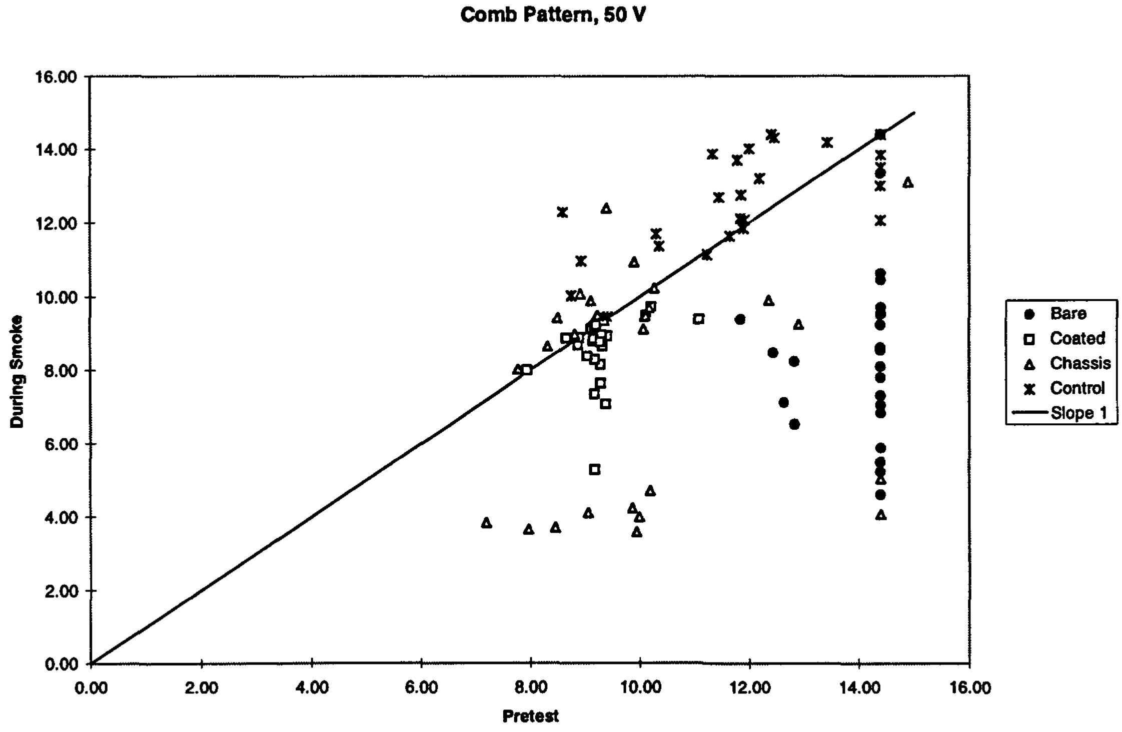


Figure 25. Comb Pattern, 50 V, Log_{10}(R) Pretest vs. During smoke

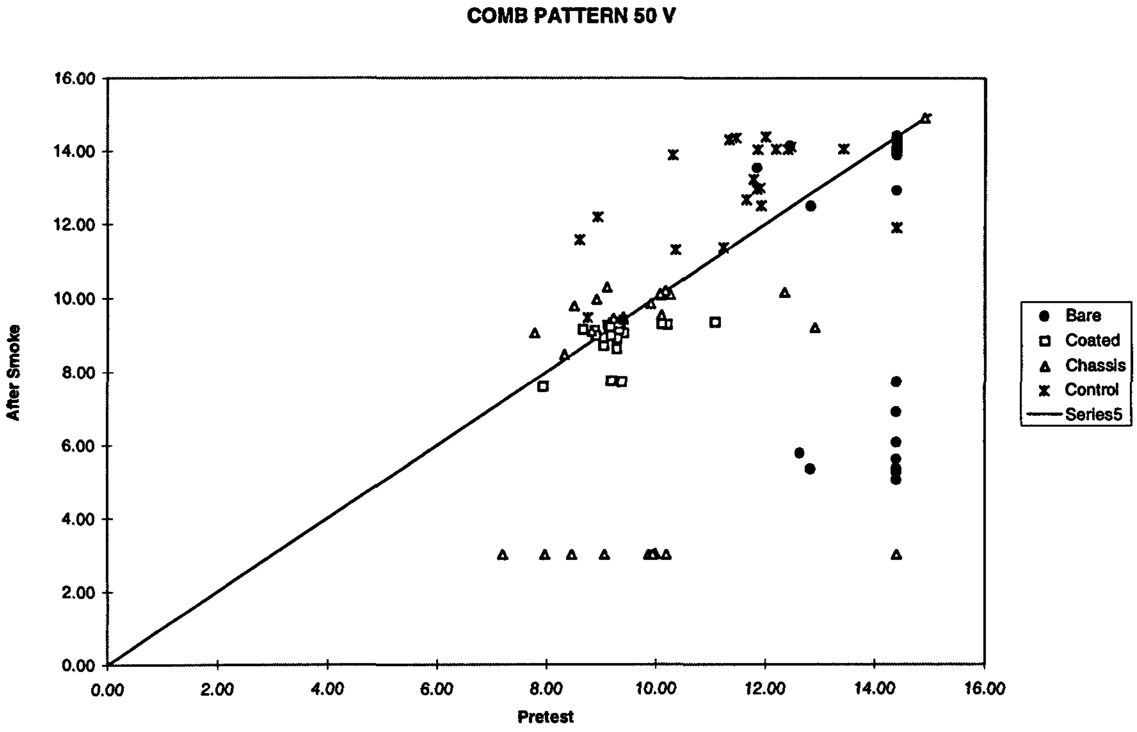


Figure 26. Comb Pattern, 50 V, $Log_{10}(R)$ Pretest vs. After smoke

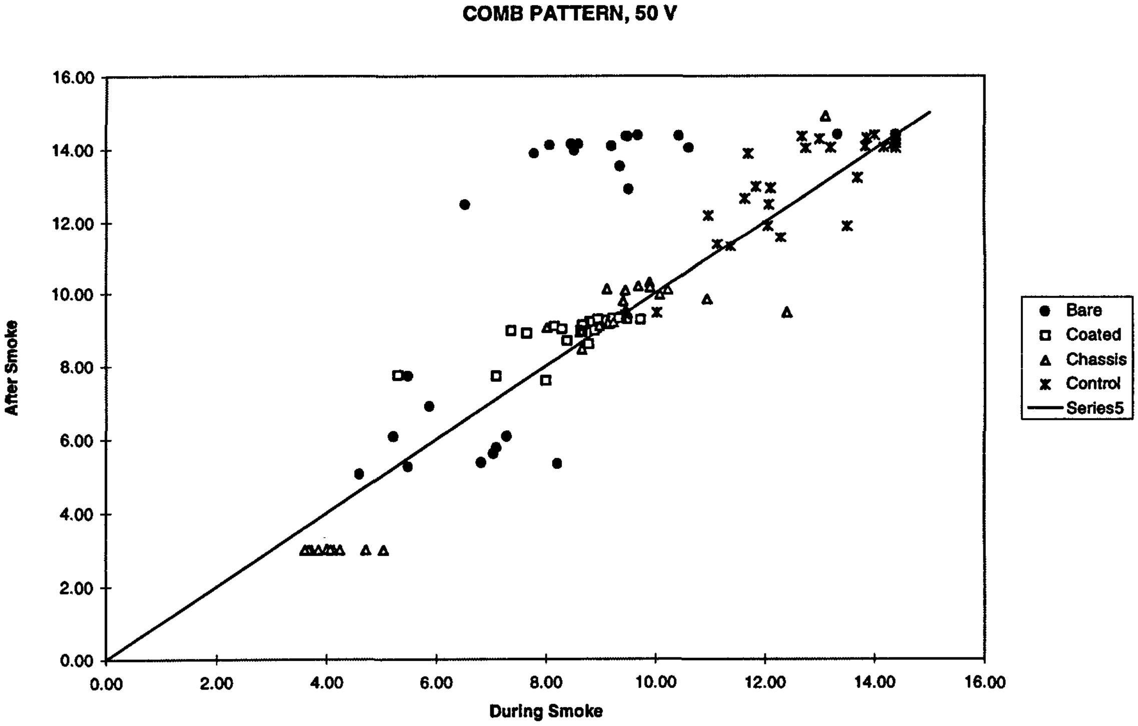


Figure 27. Comb Pattern, 50 V, $Log_{10}(R)$ During smoke vs. After smoke

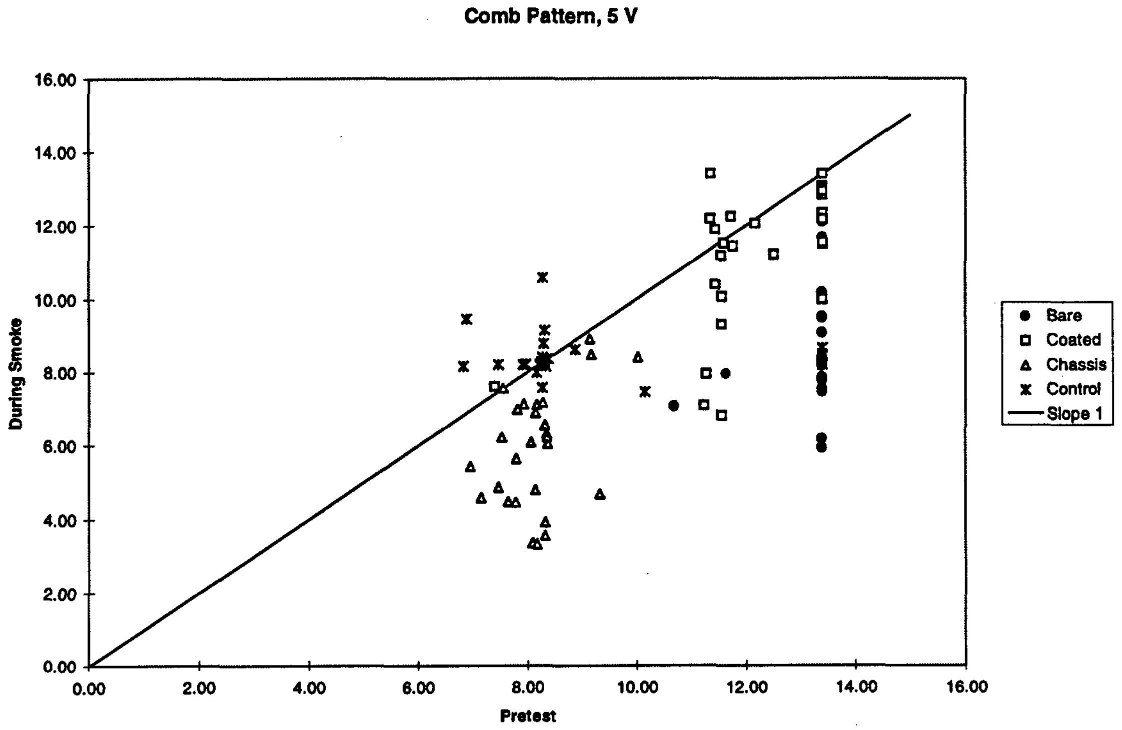


Figure 28. Comb Pattern, 5 V, Log_{10}(R) Pretest vs. During smoke

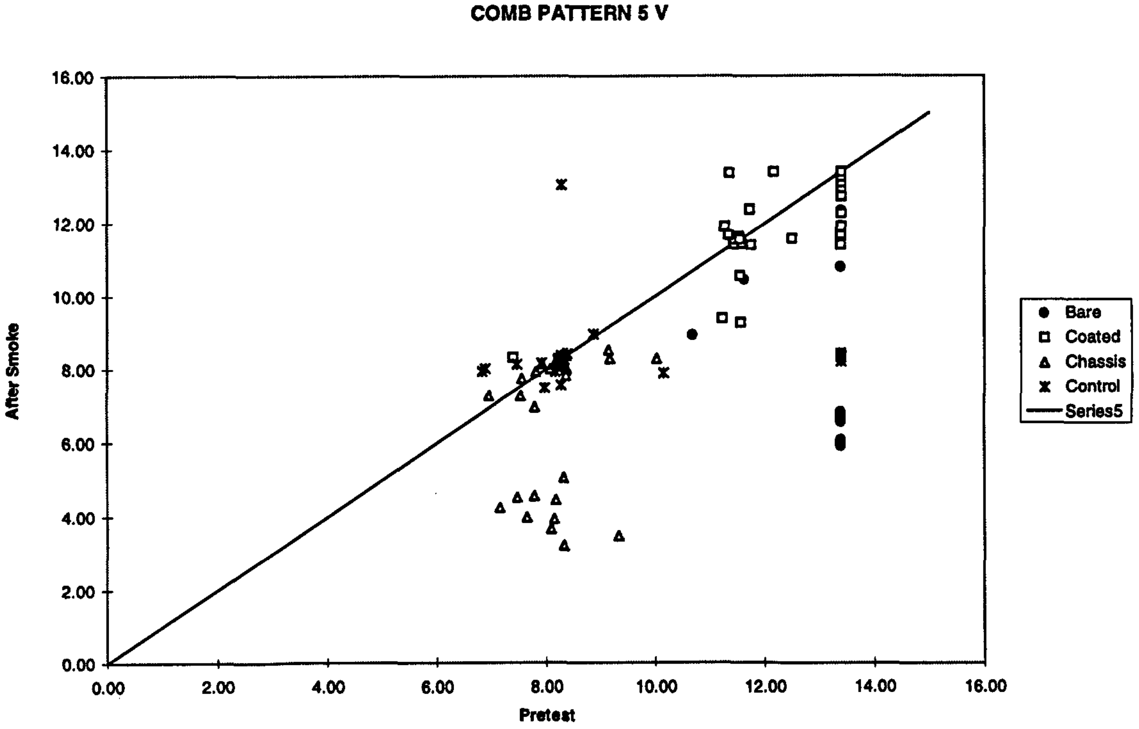


Figure 29. Comb Pattern, 5 V, Log_{10}(R) Pretest vs. After smoke

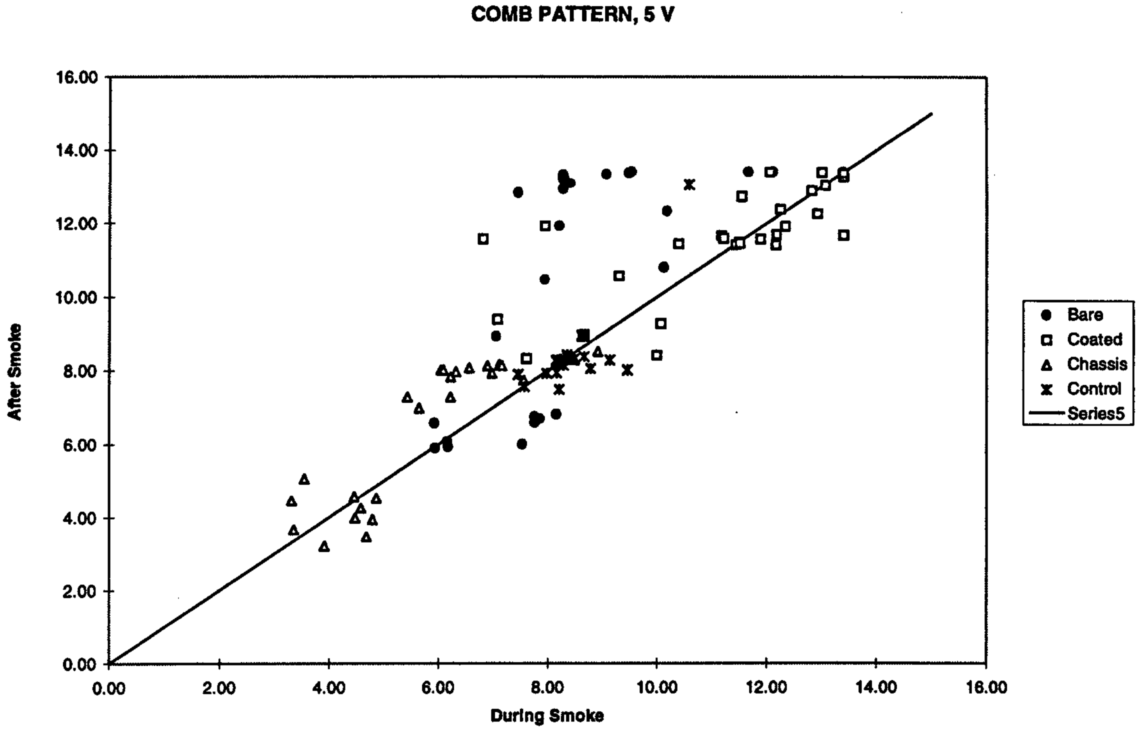


Figure 30. Comb Pattern, 5 V, Log$_{10}$(R) During smoke vs. After smoke

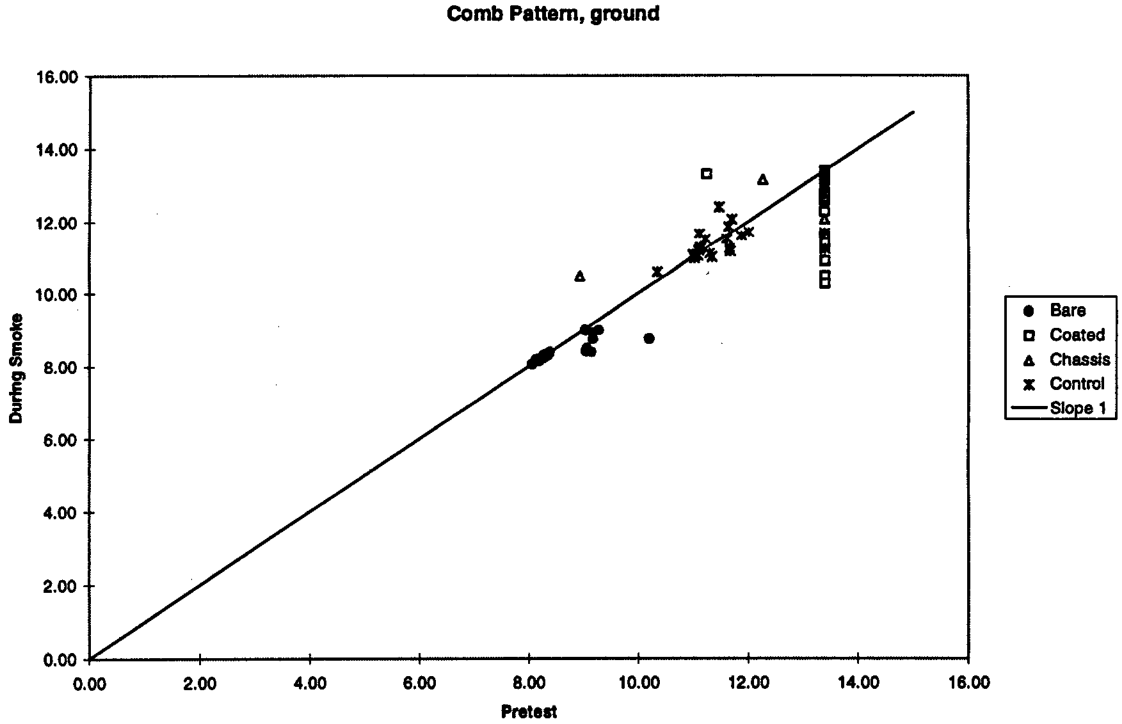


Figure 31. Comb Pattern, Grounded, Log$_{10}$(R) Pretest vs. During smoke

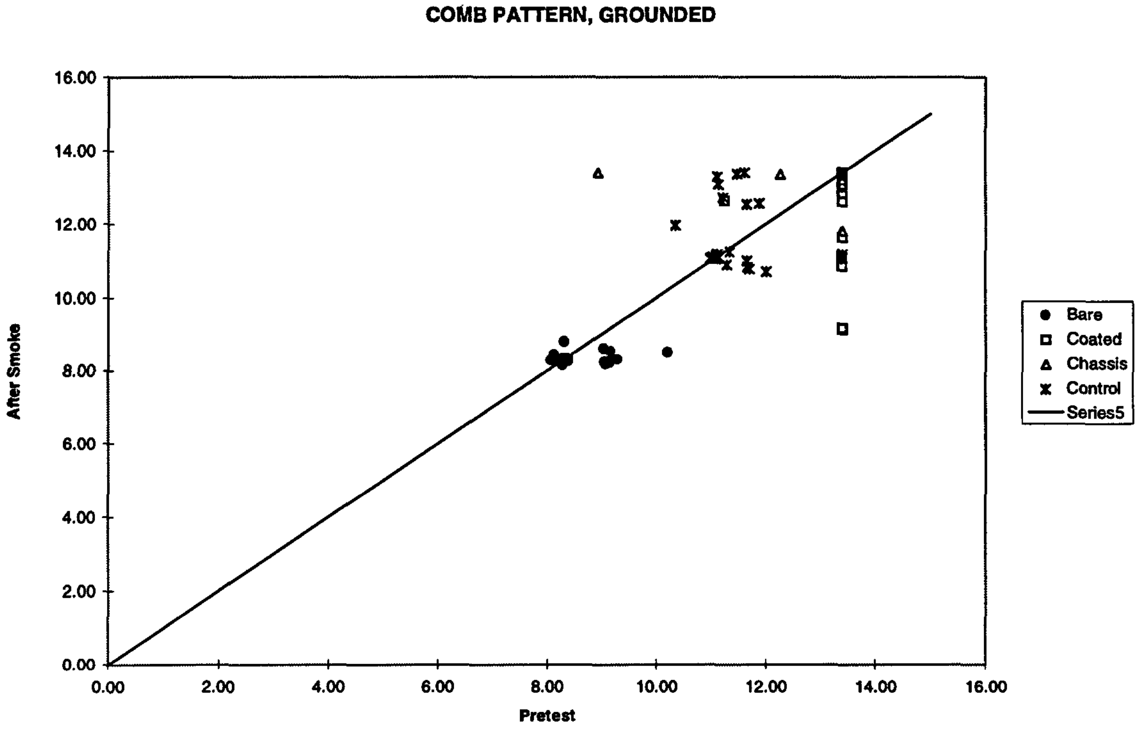


Figure 32. Comb Pattern, Grounded, Log_{10}(R) Pretest vs. After smoke

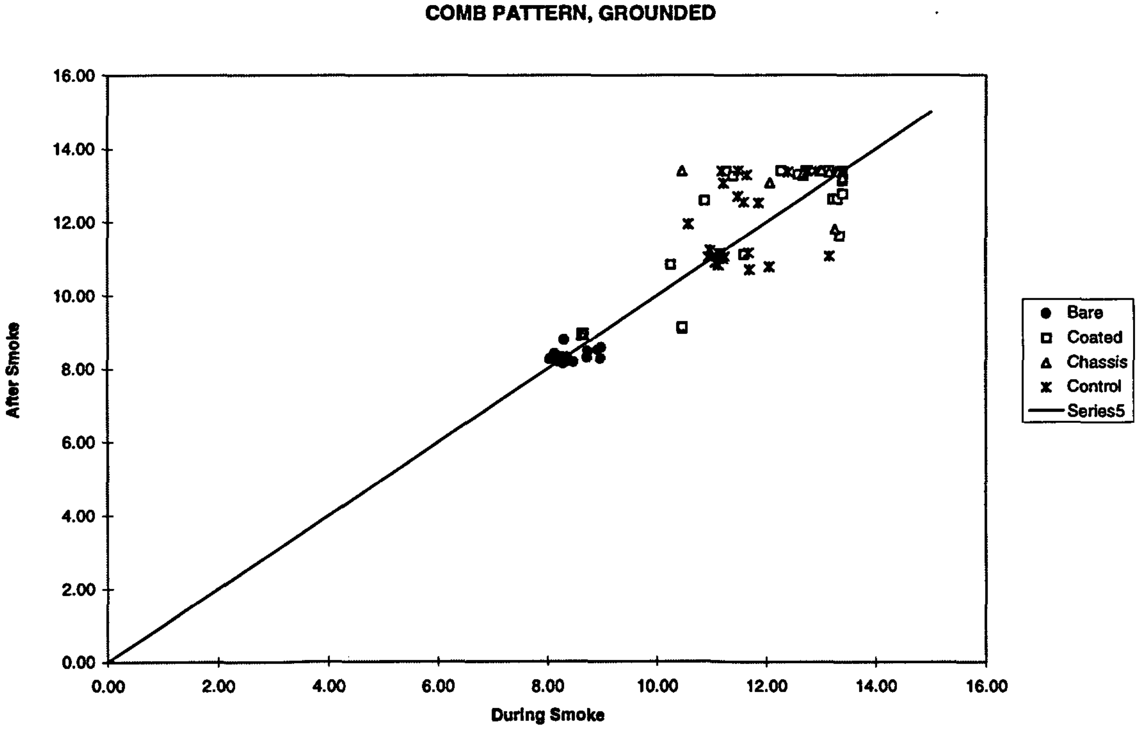


Figure 33. Comb Pattern, Grounded, Log_{10}(R) During smoke vs. After smoke

Table 4 presents the coefficients for the equations from the general linear regression analyses. The resistance responses that were modeled were those that were plotted in Figures 1 to 33: $\log_{10}(R)$ at pretest, during the smoke production, and after the smoke exposure. The coefficients in the table are for the factors determined to be significant. Abbreviations have been used in this table to depict fuel level (F), burn temperature (B), PVC (P), humidity (H), galvanic metal (G), and suppression (S). Combinations of terms are indicated by *F x B x G,* for example. The column labeled R^2 quantifies the percent of the observed variation in the response variable that is explained by the model.

Table 4. General Linear Modeling Results

Component	Parameter	R^2	Constant	Bare	Coated	Chassis	Fuel	Burn	PVC	Humidity	Suppression	BxBare	FxBare
Ceramic	Before	0.77	13.16	-4.04	-1.62							4.28	
Leadless	During	0.82	10.67			1.66	-2.39	-3.69				4.28	-1.38
Chip Carrier	After	0.83	12.57					-6.36				6.50	-5.13
Ceramic	Before	0.60	12.76										
DIP	During	0.75	10.99	1.68		1.75							
	After	0.75	12.29										
Ceramic	Before	0.49	13.00							-2.19			
flat pack	During	0.90	14.59	-2.13	-1.95	-3.70				-2.26	-0.81		-3.17
	After	0.86	13.13							-2.57			-4.55
Transistor	Before	0.48	12.27			1.09				-4.61			
Outline	During	0.72	12.14							-2.88			
Can	After	0.88	11.83	1.53		1.88				-3.26			
Plastic	Before	0.26	12.20	-1.87						-1.22			
leaded	During	0.85	12.43	-4.10									
Chip Carrier	After	0.85	12.77	-4.07									
Small Outline	Before	0.43	12.56							-2.07			
Integrated	During	0.85	12.43							-2.13			
Chip	After	0.90	13.01							-1.60			
Plastic	Before	0.28	12.84							-1.72			
DIP	During	0.59	12.85							-2.44			
	After	0.69	13.07							-1.50			
Comb	Before	0.37	13.15	-2.75	-2.24					-0.82			
160 V	During	0.88	13.34	-4.53	-3.08							-1.73	
	After	0.81	13.40	-3.84	-3.79							-3.08	
Comb	Before	0.67	12.61	2.03	-2.75	-2.10				-0.83			
50 V	During	0.90	13.77		-4.62	-4.12				-1.72		-7.61	-3.21
	After	0.91	13.38		-4.15	-3.40						-7.50	1.30
Comb	Before	0.85	8.90	4.44	3.38				-0.48				
5 V	During	0.91	8.40	5.00	3.96	-0.71						-5.55	-4.04
	After	0.85	8.21	4.47	3.65							-6.27	
Comb	Before	0.93	11.76	-3.23	1.62	1.59							
Grounded	During	0.91	11.60	-3.23	1.52	1.58							
	After	0.88	11.92	-3.61	1.23	1.39							

Table 4. General Linear Modeling Results

Component	Parameter	HxBare	SxBare	GxBare	BxCoated	FxCoated	PVCxCoated	HxCoated	GxCoated	BxChassis	FxChassis
Ceramic	Before			-1.97							
Leadless	During	-3.38				5.12				3.46	1.92
Chip Carrier	After	-4.18								6.59	
Ceramic	Before	-2.72				-5.67	2.79				
DIP	During	-4.41				-3.12					
	After	-2.87				-7.06	3.08				
Ceramic	Before								-2.26		
flat pack	During										
	After						-1.72				
Transistor	Before	3.82						3.05			
Outline	During	1.68					-1.66				
Can	After	2.01						3.14			
Plastic	Before										
leaded	During							-1.95			
Chip Carrier	After							-2.68			
Small Outline	Before	2.17			1.51						
Integrated	During	1.11									
Chip	After										
Plastic	Before						-1.65				
DIP	During					-3.38					
	After					-2.22					
Comb	Before									-1.27	
160 V	During										
	After									-1.57	
Comb	Before										
50 V	During		-1.81					1.39			
	After										
Comb	Before										
5 V	During	-3.03					-1.78			-2.97	-1.14
	After									-4.13	
Comb	Before										
Grounded	During										
	After				-0.88						

Table 4. General Linear Modeling Results

Component	Parameter	HxChassis	GxChassis	FxB	BxH	BxS	FxH	FxS	SxG	FxBxBare	PxBxBare	BxHxBare
Ceramic	Before									2.06		-4.81
Leadless	During											
Chip Carrier	After											
Ceramic	Before											
DIP	During						-3.47					
	After			-3.40						3.40		
Ceramic	Before	-2.35										-1.52
flat pack	During						-1.63					-2.01
	After	-1.76										
Transistor	Before											
Outline	During						-1.24					
Can	After											
Plastic	Before											
leaded	During						-1.13	-1.16	1.52			
Chip Carrier	After				-0.88		-1.35					
Small Outline	Before			1.71	-2.19							
Integrated	During	2.56										
Chip	After	1.99					-1.09					
Plastic	Before					-2.33						
DIP	During											
	After						-2.51					
Comb	Before											
160 V	During				-0.85							
	After											
Comb	Before											
50 V	During	2.16										3.77
	After						-0.69				2.29	
Comb	Before	-0.93										
5 V	During											3.38
	After									-4.06		3.77
Comb	Before		-4.42									
Grounded	During											
	After											

Table 4. General Linear Modeling Results

Component	Parameter	BxGxBare	FxHxBare	FxSxBare	FxGxBare	HxSxBare	SxGxBare	FxBxCoated	PxBxCoated	BxHxCoated
Ceramic	Before					-2.32	6.59			
Leadless	During									
Chip Carrier	After									
Ceramic	Before	-2.84								
DIP	During								-5.18	
	After		-6.42							
Ceramic	Before									
flat pack	During									
	After		-3.27		2.54					
Transistor	Before									
Outline	During		-3.70	-2.78						
Can	After		-9.11							
Plastic	Before									
leaded	During		-2.73							
Chip Carrier	After		-3.69	-3.17						2.95
Small Outline	Before									
Integrated	During		-6.71	-3.49						
Chip	After		-6.89	-4.22						
Plastic	Before									
DIP	During		-5.58							
	After		-6.06							
Comb	Before							1.85		
160 V	During		-1.08							
	After									
Comb	Before									
50 V	During							-1.99		
	After									
Comb	Before									
5 V	During		1.73					-3.13		
	After	-3.55								
Comb	Before									
Grounded	During									-1.76
	After									

Table 4. General Linear Modeling Results

Component	Parameter	BxSxCoated	BxGxCoated	FxHxCoated	FxSxCoated	FxGxCoated	PxHxCoated	SxHxCoated	GxHxCoated
Ceramic	Before								
Leadless	During								
Chip Carrier	After								
Ceramic	Before	-9.76							
DIP	During	-7.09	6.75				4.94		-3.44
	After	-8.34							
Ceramic	Before								
flat pack	During		-2.29						
	After								
Transistor	Before								
Outline	During								
Can	After			-7.77					
Plastic	Before								
leaded	During								
Chip Carrier	After								
Small Outline	Before								
Integrated	During								
Chip	After				-4.43				
Plastic	Before								
DIP	During								
	After								
Comb	Before								
160 V	During			-2.40					
	After			-4.11	3.01	2.62			
Comb	Before								
50 V	During								
	After								
Comb	Before		-4.89					1.28	
5 V	During		-4.75			1.55			
	After						-1.12		
Comb	Before				-1.05				
Grounded	During								
	After		-3.13						

Table 4. General Linear Modeling Results

Component	Parameter	SxGxCoated	FxBxChassis	PxBxChassis	BxHxChassis	BxSxChassis	BxGxChassis	FxHxChassis	FxGxChassis
Ceramic	Before						-5.53		
Leadless	During								
Chip Carrier	After							-2.22	
Ceramic	Before	6.07							
DIP	During								
	After								
Ceramic	Before								
flat pack	During							-2.93	
	After						4.12	-5.70	
Transistor	Before								
Outline	During				-1.56			-3.36	
Can	After				-1.41			-6.47	
Plastic	Before						-3.21		
leaded	During				-1.51		-3.25	-6.39	
Chip Carrier	After							-8.07	
Small Outline	Before								
Integrated	During		4.84		-6.01	5.04		-7.83	
Chip	After		5.00		-5.27	4.99		-9.04	
Plastic	Before						-5.03		
DIP	During							-2.96	
	After								
Comb	Before								
160 V	During						-5.07	-8.59	
	After							-9.77	
Comb	Before								2.20
50 V	During							-5.99	
	After							-6.29	
Comb	Before	4.73							
5 V	During	5.40							
	After			1.79					
Comb	Before						4.47		4.15
Grounded	During	2.04							
	After	3.63							

Table 4. General Linear Modeling Results

Component	Parameter	PxHxChassis	SxHxChassis	SxGxChassis	FxSxH	FxGxH
Ceramic	Before		-1.88	7.65		
Leadless	During					
Chip Carrier	After					
Ceramic	Before					
DIP	During					
	After					
Ceramic	Before					
flat pack	During			3.56		
	After					
Transistor	Before					
Outline	During					
Can	After					
Plastic	Before					
leaded	During					
Chip Carrier	After					
Small Outline	Before		2.55		-1.93	
Integrated	During					
Chip	After					
Plastic	Before			9.63		
DIP	During					
	After	-2.99				
Comb	Before					
160 V	During		-1.51	8.56		
	After					
Comb	Before					
50 V	During					
	After					
Comb	Before					2.00
5 V	During					
	After					
Comb	Before					0.63
Grounded	During					
	After					

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C. Antonescu, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Smoke can adversely affect digital electronics; in the short term, it can lead to circuit bridging and in the long term to corrosion of metal parts. This report is a summary of the work to date and component-level tests by Sandia National Laboratories for the Nuclear Regulatory Commission to determine the impact of smoke on digital instrumentation and control equipment. The component tests focused on short-term effects such as circuit bridging in typical components and the factors that can influence how much the smoke will affect them. These factors include the component technology and packaging, physical board protection, and environmental conditions such as the amount of smoke, temperature of burn, and humidity level. The likelihood of circuit bridging was tested by measuring leakage currents and converting those currents to resistance in ohms. Hermetically sealed ceramic packages were more resistant to smoke than plastic packages. Coating the boards with an acrylic spray provided some protection against circuit bridging. The smoke generation factors that affect the resistance the most are humidity, fuel level, and burn temperature. The use of CO_2 as a fire suppressant, the presence of galvanic metal, and the presence of PVC did not significantly affect the outcome of these results.

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