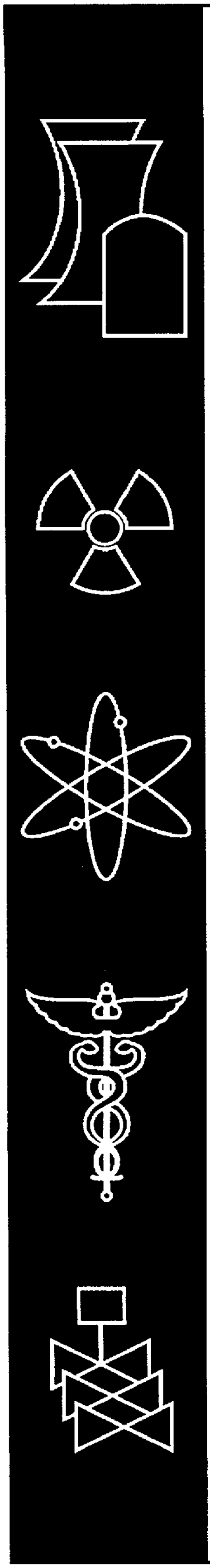
NUREG/CR-6597
SAND99-1320



Results and Insights on the Impact of Smoke on Digital Instrumentation and Control

Sandia National Laboratories

**U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001**

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at www.nrc.gov/NRC/ADAMS/index.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer,
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address www.nrc.gov/NRC/NUREGS/indexnum.html are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

NUREG/CR-6597
SAND99-1320

Results and Insights on the Impact of Smoke on Digital Instrumentation and Control

Manuscript Completed: September 2000
Date Published: January 2001

Prepared by
T. J. Tanaka, S. P. Nowlen

Sandia National Laboratories
Albuquerque, NM 87185-0748

C. Antonescu, NRC Project Manager

Prepared for
Division of Systems Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code W6051

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: (202) 512-1800 Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

ISBN 0-16-050737-5

Previous reports in series:

NUREG/CR-6476, SAND96-2633, Tina J. Tanaka, Steven P. Nowlen, and Dennis J. Anderson, "Circuit Bridging of Components by Smoke," Sandia National Laboratories, Albuquerque, NM, October 1996.

NUREG/CR-6543, SAND97-25, Tina J. Tanaka, "Effects of Smoke on Functional Circuits," Sandia National Laboratories, Albuquerque, NM, October 1997.

Abstract

Smoke can cause interruptions and upsets in active electronics. Because nuclear power plants are replacing analog with digital instrumentation and control systems, qualification guidelines for new systems are being reviewed for severe environments such as smoke and electromagnetic interference. Active digital systems, individual components, and active circuits have been exposed to smoke in a program sponsored by the U.S. Nuclear Regulatory Commission. The circuits and systems were all monitored during the smoke exposure, indicating any immediate effects of the smoke. The major effect of smoke has been to increase leakage currents (through circuit bridging across contacts and leads) and to cause momentary upsets and failures in digital systems. This report summarizes two previous reports and presents new results from conformal coating, memory chip, and hard drive tests. The report describes practices for mitigation of smoke damage through digital system design, fire barriers, ventilation, fire suppressants, and post fire procedures.

CONTENTS ....Page

Figures

Tables

Executive Summary

This report summarizes and draws insights from a study of the effects of smoke on digital instrumentation and control equipment. Several important conclusions can be drawn from project findings. Based on the investigation of smoke susceptibility and the resulting understanding of key failure mechanisms, it is clear that smoke can result in adverse consequences. However, there is no practical repeatable testing methodology, so it is not feasible to assess smoke susceptibility as part of environmental qualification. As a result, the most reasonable approach to minimizing smoke susceptibility is to employ design, implementation, and procedural practices that can reduce the possibility of smoke exposure and enhance smoke tolerance. In particular, current fire protection methods are an appropriate preventative approach, employing isolation and detection practices. Additionally, post-event recovery procedures can mitigate the extent of smoke damage. Finally, there are design choices and implementation practices that can reduce equipment susceptibility to smoke exposure, such as chip packaging and conformal coatings.

Smoke can result in immediate failure of electronic equipment through increased leakage currents. These currents are caused primarily by circuit bridging by charged smoke particles in the air and smoke deposits on surfaces. Other effects are possible, such as metal corrosion from acidic smoke and coating of contacts with a non-conducting material; however, these effects are slower to cause failure in digital circuits since the circuits have few thin metal contacts or moving parts. The circuits that are most susceptible to smoke have high voltage and high impedance.

Circuits can be protected from smoke by conformally coating the printed circuits and by controlling the movement of smoke. The coatings themselves, however, are typically flammable. The best classes of conformal coatings have been found to be parylene, polyurethane, and acrylic (dipped). Other coatings, such as epoxy and silicone, did not protect as well. Ventilation and reduction of humidity after a fire are very important for preserving electronics. Location may reduce the chances of smoke exposure if equipment is not located where fires are likely to occur and fire barriers are used.

Circuit boards can be thoroughly cleaned and refurbished after a fire. They are best cleaned with a detergent and water mixture instead of a halogenated solvent. Conformally coated boards, however, are not easy to clean as the smoke may penetrate the top surface of the coating. Cleanliness is usually measured by chloride concentration.

At this time, addressing smoke exposure as a part of environmental qualification is not feasible since there are no testing standards available. A systematic repeatable smoke exposure test does not exist and is not likely given that smoke production is difficult to control and measure. As an alternative, the most reasonable approach is to use smoke-tolerant circuits and technologies, protective fire barriers, and conformal coatings to minimize the risk of smoke damage for digital circuits.

Acknowledgments

The authors wish to thank the following people for their contributions to this project: Christina Antonescu of the U.S. Nuclear Regulatory Commission for her help in initiating, planning, and supporting this study; Nathan Siu of the U.S. Nuclear Regulatory Commission for support of the high-voltage AC studies; Dennis J. Anderson and Dennis Huffman for planning the experiments, specifying the equipment model and statistically analyzing the results; Specialty Coating Inc., for their suggestions on conformal coatings and prompt application of these coatings to the functional boards; D. Michael Ramirez, Edward Baynes, John Garcia, and Bob Nichols for their technical support; students Lizdabel Morales, Andrea Hirst, Karla Waters, Paul Lucero and Michael Dandini for writing programs, analyzing data, and sessions of cutting and pasting; and Ruth Haas for her steadfast editing. Kofi Korsah and Richard T. Wood of Oak Ridge National Laboratory collaborated on the selection of digital equipment and drawing conclusions on the results.

The authors also wish to thank Stephen J. Martin for his steadfast support and technical contributions.

Abbreviations

ACRS	Advisory Committee for Reactor Safeguards
ASTM	American Society for Testing and Materials
BNL	Brookhaven National Laboratory
CMOS	complementary metal-oxide semiconductor
COTS	commercial off-the-shelf
CSPE	chlorosulfonated polyethylene
D_0	Optical extinction coefficient
DOE	Department of Energy
ECL	emitter-coupled logic
EMI/RFI	electromagnetic interference/radio frequency interference
EPR	ethylene propylene rubber
EPDM	ethylene propylene diene monomer
EPROM	erasable programmable read-only memory
FACT	advanced CMOS
FAST	advanced Schottkey TTL
FRXLPE	fire-resistant cross-linked polyethylene
HCLV	high current low voltage
HDR	Heiss Dampf reactor
HF TL	high-frequency transmission line
HSD	high-speed digital
HVLC	high voltage low current
I&C	instrumentation and control
IPC	Institute for Interconnecting and Packaging Electronic Circuits
KfK	Kernforschungszentrum Karlsruhe
LPF	low-pass filter
LRSTF	low-residue soldering task force
NAND	Not-AND
NEMA	National Electrical Manufacturer's Association
NIST	National Institute of Standards and Technology
NRL	Naval Research Laboratory
ORNL	Oak Ridge National Laboratory
PGA	pin grid array
PTH	plated-through hole
PVC	polyvinyl chloride
RH	relative humidity
SIR	surface insulation resistance
SMT	surface-mounted technology
SNL	Sandia National Laboratories
SRAM	static random access memory
STD	standard deviation
TOC	transistor outline can
TTL	transistor-to-transistor logic
USNRC	United States Nuclear Regulatory Commission
V dc	volts direct current
XLPE	cross-linked polyethylene

1 INTRODUCTION

1.1 Rationale for the Program

Nuclear power plants are replacing analog instrumentation and control (I&C) equipment with digital I&C equipment. Changes in equipment raises concerns on how new equipment will react to abnormal severe environmental conditions. One concern is how smoke from a fire will affect these new control systems. It was widely thought that smoke would cause long-term degradation (over several weeks) in performance; however, not much concern was focused on the immediate effects of smoke on the equipment during a fire. The Office of Nuclear Reactor Research of the US Nuclear Regulatory Commission (USNRC) had several motives in funding this program, including a user need letter from the Office of Nuclear Regulatory Regulation requesting information on the effects of smoke. In addition, the Advisory Committee for Reactor Safeguards (ACRS) requested that smoke be included in the investigation of environmental qualification.

1.2 History of the Program

In March 1994 the USNRC initiated a program at Sandia National Laboratories (SNL) to determine the impact of smoke on advanced instrumentation and controls. This program was a small part of a larger program at Oak Ridge National Laboratory (ORNL) on the environmental qualifications for microprocessor-based I&C.[1] The ORNL program included environmental qualification for electromagnetic interference,[2] temperature, humidity, and smoke. [3] A third laboratory, Brookhaven National Laboratory (BNL), was also involved in this effort by determining the relative risk posed by various environmental hazards for digital I&C and hence for a nuclear power plant.[4] This program on the impact of smoke helped support these other programs by determining the necessity of including smoke in the risk assessments (BNL) and by producing smoke environments for testing the experimental digital safety system (ORNL).

At the time the USNRC program was started, there had been very few controlled tests to determine how electronics would behave while exposed to smoke from a fire. However, there were data to indicate that smoke causes substantial problems. For example, a fire in Hinsdale, IL in 1985 caused widespread smoke damage to electronics in a telecommunications central office.[5] The major focus of research based on this fire was (1) estimating the amount of soot or chemical deposits that can cause long-term damage to electronics, (2) determining which types of cable insulation and jackets will produce the least damaging chemicals, and (3) developing methods to control the movement of smoke. Most of the concern about the electronics was focused on determining if the equipment could continue to operate after a fire or, if not, be could be salvaged (generally involves cleaning off soot deposits). The salvage question is important to insurance companies.

Nuclear power plants require continuous control of and feedback from the reactor. The ability to salvage equipment after a fire is not an adequate indication of damage because smoke might cause equipment malfunction during a fire. Tests on active electronic equipment were required to ensure that the function of such equipment during a fire is unaffected, or if affected, will fail in a safe manner. Since very few other industries besides nuclear power are so concerned about active, continuous control over a process, SNL assumed, and later verified, that there would be little data on the function of equipment during a fire and proposed to do some tests. Figure 1 shows some of the smoke measurement targets and electronic equipment tested in this program.

A testing program such as this required background studies to determine the answers to several questions:

- What is known about the effects of smoke on electronics?

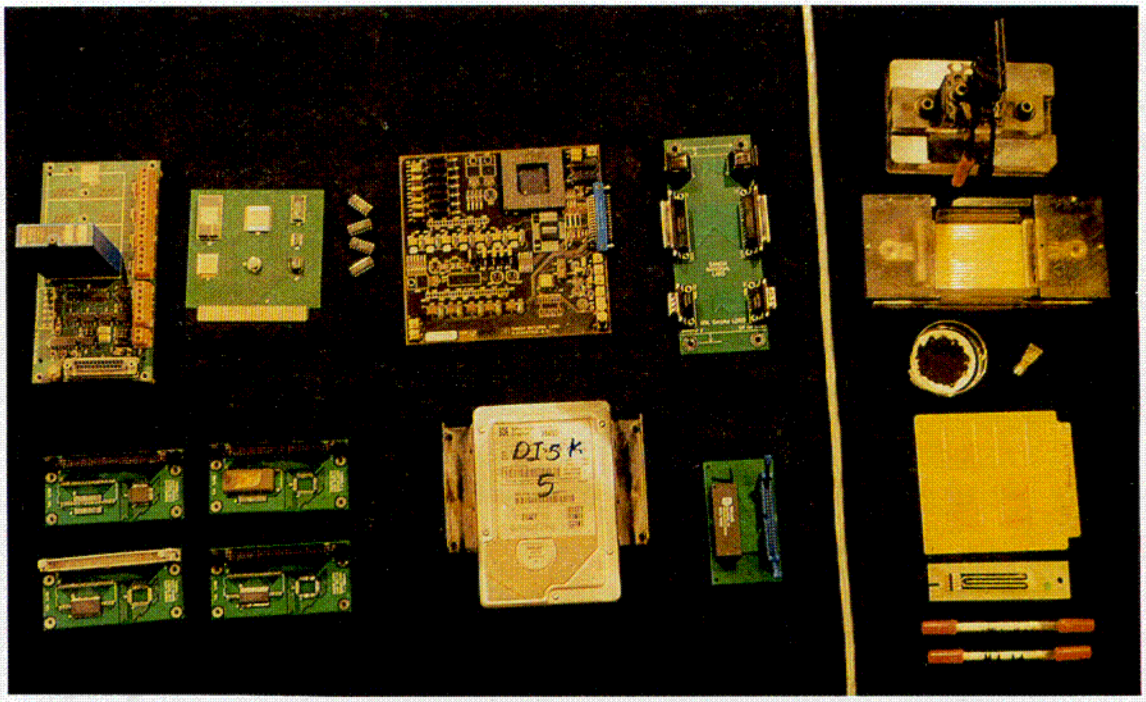


Figure 1. This program exposed a range of components and samples to smoke.

C01

- What type of tests should be performed?
- What equipment should be tested to best serve the needs of the USNRC?

A literature review of past fires and test methods yielded little information on the performance of electrical equipment during a fire. In particular, very little information was available on digital equipment. There have been several smoke tests developed to determine which materials, if burned, would produce the most corrosive gases. The relative merits of the different materials were determined by either the acidity of the smoke produced, or the amount of metal that was lost from standard exposure targets through corrosion when exposed to the smoke. The method of producing the smoke and the targets varies by test, and each test has its proponents. None of these standard tests, however, measured the performance of an active digital system.

Of these various standard test methods, the American Society for Testing and Materials (ASTM) draft standard to produce smoke by a radiant heat method was determined to be the method most adaptable to exposing electronic equipment. This method, coincidentally, was also selected by a study performed by Hughes Associates for the Department of Energy (DOE) to determine the "immediate" effects of smoke on electronics, but no tests were performed.[6] SNL also determined what smoke scenarios are likely for nuclear power plants. These scenarios were determined by reviewing past fires and reports on the amount of fuel in electrical cabinets and rooms.

Along with this program, the USNRC requested ORNL to investigate how digital safety systems would be affected by electromagnetic and radio frequency interference (EMI/RFI), temperature, humidity, and smoke.[3] To satisfy this request, ORNL designed and built an experimental digital safety system that contained elements of different proposed commercial digital safety systems. Typical safety systems contain four trip channels. This safety system emulated one channel out of four that would be likely for a real reactor, but it also contained a computer that simulated three other channels of the system and monitored the reaction of the safety channel. Smoke exposure tests of this system were performed using SNL facilities and smoke was shown to cause upsets to the safety system.

SNL has studied the effects of smoke on electrical components and systems of three levels of complexity: digital systems with communications, functional analog circuits, and component packaging. Most of these systems and components are shown in Figure 2. The components and systems that were chosen to test were picked from a wide array of possible designs and configurations. The components tested fulfilled these qualifications:

- The component would be expected to play an important role in an advanced nuclear power instrumentation and control system.

- The component was suspected to be vulnerable to smoke.
- The component might be used in multiple circuits within advanced control and instrumentation systems.
- The component may be tested simply in isolation and is not dependent on complicated simulation hardware to be tested.

Besides components, changes in physical properties were measured. These changes included optical extinction coefficient, loss of metal, loss of insulation resistance on printed circuit boards and between vertical parallel plates, mass of smoke suspended in the air, and chemical composition of the smoke and deposits. These measurements aided in determining the process by which the smoke affected the electrical components. The measurements evolved, as it became apparent that electrically, the most significant effect was the loss of insulation resistance. Hence, at the end of the program, the most important gage of the effect of the smoke was the change in conductance between insulated conductors. The physical property measurements were mainly funded by the Sandia LDRD program as this could be classified more as research into basic physical phenomena rather than testing of components that were likely to be used in nuclear power

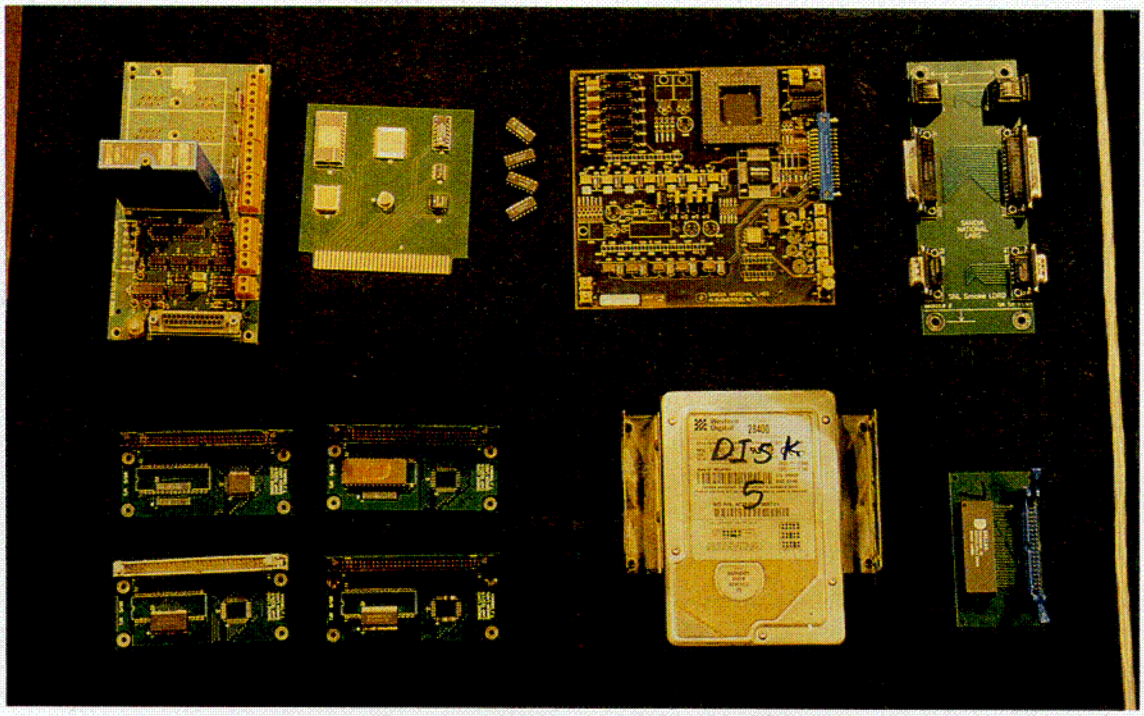


Figure 2. These electrical components were tested at SNL.

Table 1. Tests Performed

Smoke exposure tests	Date of tests	Report completion
Multiplexer (a digital system)	December 1994	August 1995
ORNL Experimental Digital Safety Channel	June 1995	July 1996
Component packaging	February 1996	October 1996
Functional Circuits	November 1996	October 1997
Conformal Coatings	March 1997	Section 2.4.1 (this report)
Digital Throughput (SNL sponsored)	June 1998	Section 2.4.2 (this report)
Memory Chips	December 1998	Section 2.4.3 (this report)
High Voltage AC	March 1999	Section 2.4.5 (this report)
Hard Disk Drives	June 1999	Section 2.4.4 (this report)
Memory Chips (non-volatile SRAMs)	Oct/Nov 1999	Section 2.4.3 (this report)

plants. Figure 3 shows some of the targets and samplers used to measure the effects of smoke on basic electronics and smoke properties.

The order in which these tests were performed is shown in Table 1. Each series of tests were devised to determine either the smoke tolerance of a component or measure smoke effects.

This is the final report of the program to study the impact of smoke on digital I&C equipment. This report provides a brief summary of the project, results and insights that can be drawn from this program, a summary of how the present fire protection rules and regulations can prevent smoke from damaging equipment, and a summary of recovery methods that should be practiced after a fire. It also includes the results of some previously unreported tests on how different types of conformal coatings can protect equipment, the effect of smoke on high-voltage AC circuits, and how memory chips and hard disks will react to smoke.

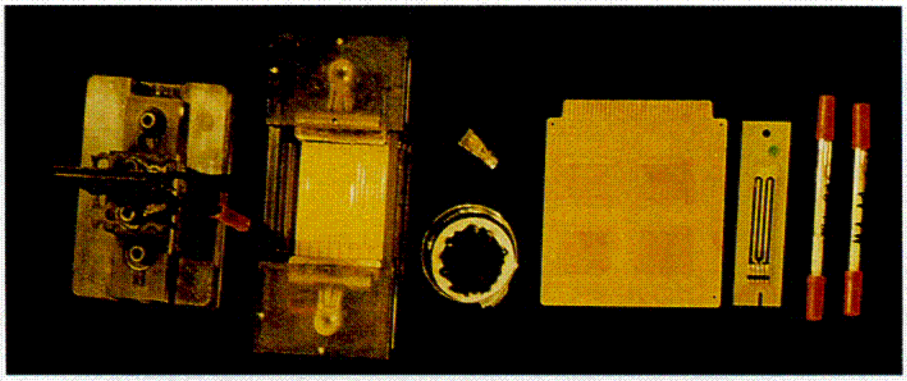


Figure 3. Electrical targets and chemical samplers were determined the effect of smoke on general electrical devices and measured the smoke environment.

C03

2 PROGRAM RESULTS

This section reviews smoke test results and draws conclusions from this program. It contains sections on the background studies, a general description of how SNL performed the smoke tests, a summary of previously reported smoke tests, and results from the recently completed tests on conformal coatings on functional circuit boards, memory chips, digital throughput boards, and hard disks. The details of tests performed before March 1997 have been published in either "Circuit Bridging of Components by Smoke", NUREG/CR-6476[7] or "Effect of Smoke on Functional Circuits", NUREG/CR-6543.[8] Further conclusions on environmental qualifications of microprocessor-based systems are found in Technical Basis for Environmental Qualification of Microprocessor-based Safety-related Equipment in Nuclear Power Plants", NUREG/CR-6479.[9]

2.1 Background Studies

The background studies of this project are reported in the appendices of reference 7 on these subjects: (1) a review of the public literature on smoke damage, (2) the conditions expected during a fire in a nuclear power plant, and (3) the type of equipment that would be tested for this project. This section summarizes the results from the first two reports. The types of equipment that were tested are reviewed in Section 2.3.

2.1.1 Literature Review

As a preliminary step for this project, the public literature was reviewed in 1995 to determine the effects of smoke on electrical equipment.[7] This included searches of FIREDOC (a database administered by the National Institute of Standards and Technology), the nuclear power plant fire event database,[10] and various other databases, such as those administered by Compendix and the DOE. The review yielded few tests of electrical equipment reliability during smoke exposure, although accidental fires and smoke corrosivity testing (material tests) are the subjects of many smoke-related articles.

Smoke is known to cause considerable damage to electrical equipment. Estimates of equipment losses due to smoke range from 90 to 95% of losses due to fire.[5] Smoke losses are recognized by insurance companies as well as federal agencies such as the DOE.[6]

The DOE has been concerned about the effects of fire on electrical equipment such as computers and control systems. Since the SNL background studies were performed, the DOE has published a very complete literature review on the thermal and nonthermal effects of fires on electrical equipment.[6] This review recommends some of the same types of tests that have been performed in this program and calls them tests of immediate failure.

Thus, the needs of the DOE overlap those of the USNRC. Active monitoring of equipment during a smoke test is more involved than analysis of equipment before and after exposure to smoke.

Smoke from fires can cause loss of control and instrumentation during the fire. During the Hinsdale fire, the fire alarms were intermittent indicating that power or signal cables could have been destroyed or smoke could have caused shorts. The intermittent phenomena have not been well investigated, mainly because most industries do not need information on equipment performance during a fire. In a nuclear power plant, such failures (intermittent or continual) during a fire could cause the loss of control or the loss of critical information within a plant.

Most of the damage analysis has been done after, not during, a fire. Companies who do post-fire recovery work reduce losses by quickly reducing the humidity around smoke-exposed equipment and cleaning the equipment to remove soot and smoke deposits that can corrode the equipment. Equipment exposed to smoke corrodes because smoke contains acidic gases. The amount of acid depends on the type and quantity of material burned. To reduce the corrosion of electronic equipment by fires, the telecommunications industry has promoted different testing methods to determine which cables will produce the lowest amount of acidic smoke.

Several smoke failure mechanisms are predicted in the literature. These include loss of contact metal, an increase in leakage currents between exposed contacts, loss of conduction of mechanical contacts, and loss of fine motion of electromechanical systems such as hard disks and chart recorders. Loss of contact metal occurs because the metallic material combines with chlorine or oxygen to form salts or rust, which are not as conductive as the purer metal. Leakage currents increase through the formation of paths of ionic chemicals between the insulated conductors. Mechanical contacts loose conductivity as they get coated with soot and mechanical systems that depend on fine motion and narrow tolerances may fail because particulate matter can inhibit motion. Despite all of these hypothesized mechanisms, very few controlled tests had been performed prior to those in this program to compare the likelihood of failures from the various mechanisms.[7]

Smoke Test Methods

Many different smoke test methods have been endorsed by different standards organizations throughout the world.[11] The primary purpose of the smoke test methods have been to determine which materials, when burned, would produce the least harmful smoke. The standards vary in their method of producing and collecting the smoke and determining how harmful the smoke is. The three main indications of damage to electronics were measurements of smoke acidity, metal loss (variation in weight or resistance of thin metallic deposits), or increased leakage current. Although acidity and metal loss measurements are aimed at detecting failures from loss of conductor material, leakage current measurements consider a separate failure mode, the increase of conduction between insulated conductors (e.g., the creation of "smoke circuit paths").

The leakage current measurements have been adopted from studies of the breakdown of equipment from exposure to polluted air.[12] [13] [14] Electronic equipment has been found to fail because of increased leakage currents (shorts) when exposed to airborne pollutants. Surface insulation resistance measures circuit bridging for a printed circuit board, and is performed on parallel, non-intersecting conductive traces on a printed wiring board.[15] Manufacturers of printed wiring boards use surface insulation resistance to determine how clean their processes are. The best assemblies are clean and have high surface insulation resistance. Air pollutants and soldering residue reduce the insulation resistance and increase leakage currents in electronics. Leakage current measurements are being adopted to evaluate smoke, [16] [17] and may allow smoke corrosivity measurements to correlate better to actual damage to electronics.

Our literature search has found two tests on actual electronic equipment, Jacobus in 1986 [18] and Bridger in 1994.[19] Jacobus exposed various electrical equipment, including strip chart recorders, an electronic counters, amplifiers, mechanical relays, switches, and power supplies, to a full-scale cabinet fires. Only the switches, relays, power supplies, and amplifiers were monitored continuously during the fire. Leakage currents were blamed for failure of the electronic counter as a result of corrosive action of chlorides in particulates deposited on the circuit boards. The strip chart recorders failed mechanically due to particulates deposited on pen slider mechanisms. An amplifier experienced errors, which was explained as a thermal drift problem because it returned to normal after the test was over. Some of the relays and switches had increased contact resistance at low voltages. Chlorides generated in the fire were combined with particulates and less hydrogen chloride vapor was in the air than previously predicted by small-scale tests.

Bridger exposed switchgear and tested the conductivity of various switchgear (but not leakage current) after exposure to smoke from different types of cables. These measurements were performed immediately after the exposure and several weeks after the exposure. The resistance of the mechanical contacts increased with time after the fire. Bridger found that non-halogen based cables were superior to halogen-based cables because there was less smoke, the smoke was less corrosive and there were fewer toxic effects from the non-halogenated cables.

2.1.2 Smoke Scenarios

A second background study was conducted on the types of fires to be expected in nuclear power plants and to what smoke conditions the electronics would be exposed. This background study is published as appendix A of reference 7. Since smoke can be generated under many different conditions and environments, a limited number of test variables that could cover a range of smoke scenarios were considered. Three aspects of smoke from fires were considered: quantity of smoke, quality of smoke, and duration of exposure.

Quantity refers to the amount of smoke per volume of affected air. These values were determined from estimates of how much fuel (i.e., plastic and materials) is available in a control panel and how much volume there is in either a control room, general room, or within an electrical cabinet. No ventilation systems were considered because active ventilation would decrease the smoke density within a room with a fire. Quantities considered in this project ranged from fuel loads of 3 g/m^3 to 200 g/m^3. All of the quantities were scaled by air volume. However, at the time of this report, it was unclear whether volume or exposed surface area should scale the tests. Volume scaling implies smoke density is predominant while surface area scaling implies smoke deposition is of primary importance. Later tests have shown that significant effects of smoke are a result of the smoke density in the air, thus, it is better to scale by volume than surface area. (Section 2.4.5)

Quality refers to the composition of the smoke and interactions with fire suppressants. The chemical composition of smoke is highly dependent on the composition of the fuel, how it is burned, and how far the fire is from the equipment. The distance of the equipment from the fire is important because particulates and certain gases may not be transported equally to all sites. Many different fuel materials are available in nuclear power plants, including plastic (cable insulation), liquid fuels such as diesel oil, paper and wood. The fuel expected to be the most damaging is plastic because it contains a large amount of chlorine, which when burned produces hydrochloric acid. Throughout this project, cable insulation has been burned because it is a representative fuel and is the most corrosive. Humidity and CO_2 were added to simulate the effect of using fire suppressants.

The exposure duration was addressed in two ways: (1) the length of time the equipment could be exposed to a smoke-filled environment and (2) the length of time equipment would be required to be operational after a fire. Based on typical fire scenarios, we developed a standard test procedure that included 15 minutes of burn time and an additional 45 minutes of exposure before the smoke was vented. The equipment was monitored for a total of 24 hours from the beginning of the exposure. The total monitoring time was determined by the amount of time that was judge to be necessary to stabilize a power plant after a fire event.

A third background study on the types of electronics to be tested was published as Appendix E of "Circuit Bridging of Components by Smoke", reference 7. This background study was published at the beginning of the program. Subsequently, our reasons for testing different equipment changed as we discovered how the smoke was causing failures in electronics. Results found in our experiments indicated what types if equipment were more likely to fail and the course of experiments were realigned as results became available to test the weakest links that were likely to be in a safety system. The information that follows in Section 2.2.2 on equipment that was tested throughout this program is a more accurate summary of the work done for the project.

2.2 SNL Testing Method

The needs of the nuclear power industry for smoke tests are different from those of most other industries. The former requires active control and monitoring of a potentially dangerous facility during and immediately following a fire, whereas other industries need to recover either data or equipment only well after the fire is extinguished. This need was a primary reason for performing smoke exposure tests at SNL.

Fire tests are somewhat variable under the best of conditions. Small changes in the environment, such as the layout of the fuel and the heat flux that ignites the fire, may change the quality and quantity of the smoke that is produced. Because the smoke can be so variable, it is important to expose as many targets and make as many measurements as possible during each exposure to reduce the uncertainty of the results.

Smoke production techniques vary widely. To compare failure modes and conditions, we needed to produce smoke consistently and in a manner that is like a true fire. We developed a procedure that was modeled on a smoke corrosivity draft standard using the radiant heat method as described in the draft ASTM E05.21.70 committee standard.[20] This production method had several features important for real-time testing.

1. This procedure is a static production method—all of the smoke that is produced is contained in the smoke exposure chamber rather than continuously vented or sampled. This represents a worst-case scenario of all possible smoke being contained within a limited volume and insures that the exposure represents an accurate smoke sample comparable to that of a real fire.

2. The exposure volume is large enough to include electronic equipment, such as computer boards.

3. The burning conditions can be controlled and varied. For dynamic tests, the only method of exposing electronics to the smoke is to pump air through the fire and onto the sample. No low-oxygen tests can be performed with a dynamic test.

Using the ASTM draft standard as a basis, a smoke test procedure was developed. Several criteria from the draft standard have been followed in this test procedure: the configuration and size (0.2 m^3) of the exposure chamber, the combustion unit, radiant heat lamps, method of measuring heat fluxes, and duration of smoke exposure and monitoring. Figure 4 shows the smoke chamber built to the ASTM E05.21.70 draft standard. As in the draft standard, the humidity (75% RH) and temperature (23.9 °C or 75 °F) were controlled before and after the exposure; however, because the smoke production takes place in an enclosed volume, the temperature and humidity were not controlled during the 1-hour exposure period. For the first tests on the multiplexer board, the humidity and temperature were not well controlled, but starting with the test on the digital safety channel, the entire smoke chamber was placed inside a large walk-in environmental chamber that could control these parameters. Figure 5 shows the smoke chamber inside of the environmental chamber.

The digital safety system was too large to place in the standard ASTM exposure chamber, so SNL built a chamber that was five times larger in volume (1m^3) and had four combustion chambers instead of one. This larger chamber was used for two sets of tests: (1) the digital safety system and (2) the component packaging tests in which the protection provided by a personal computer chassis was being investigated. The smaller standard configuration was used for the other

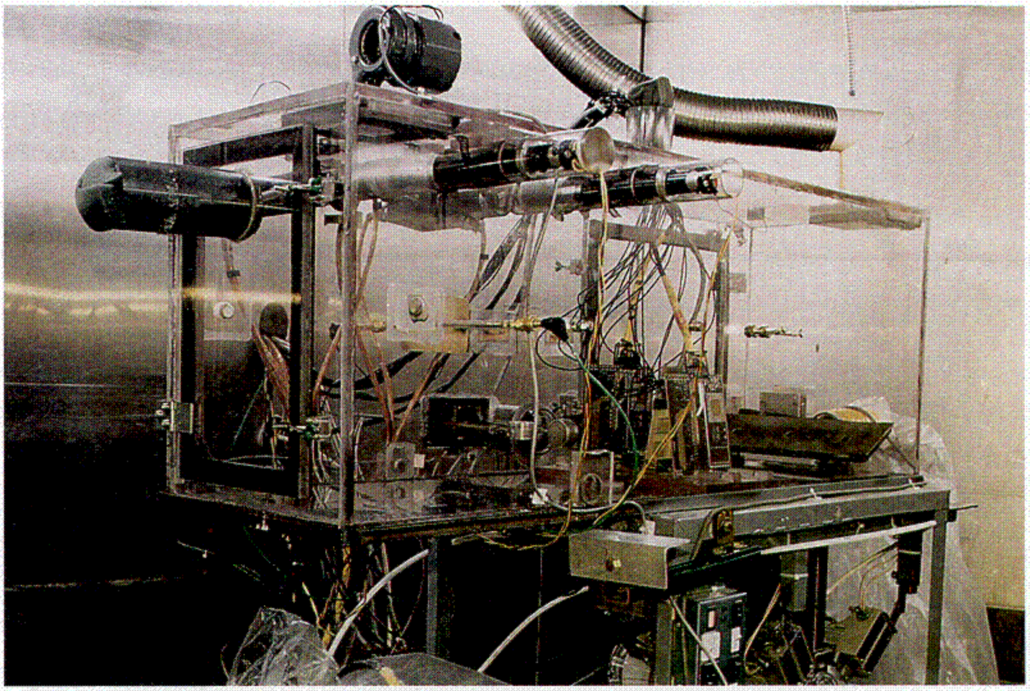


Figure 4. The small smoke exposure chamber was built to the dimensions of ASTM E05.70.21 draft smoke corrosivity test and used for the memory chip, electrical, hard disk and digital throughput tests.

C04

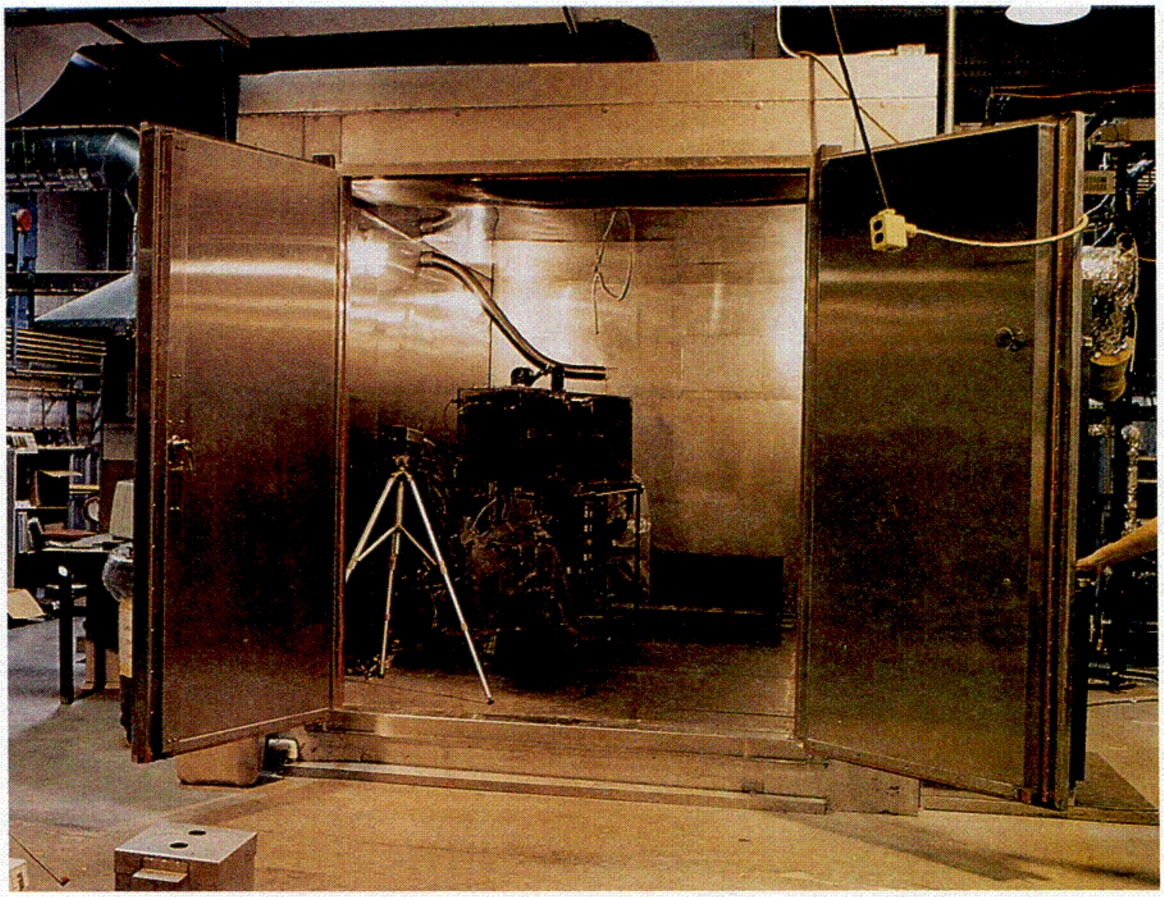


Figure 5. All of the smoke tests other than the multiplexer tests were performed in an environmental chamber to control initial temperature and humidity.

tests because the cleanup was faster and less cable was burned in the smaller chamber. This larger chamber is shown in Figure 6.

Most of the smoke measurements were automated by computer and logged. Because of the range of equipment tested, one computer was generally devoted to the test equipment and a separate computer controlled the ignition lamps and recorded the automated measurements such as temperature and extinction coefficient. With each new piece of equipment to be monitored, the programming for one computer would change, whereas, only moderate changes were made to the program that controlled ignition and measured the environment.

C05

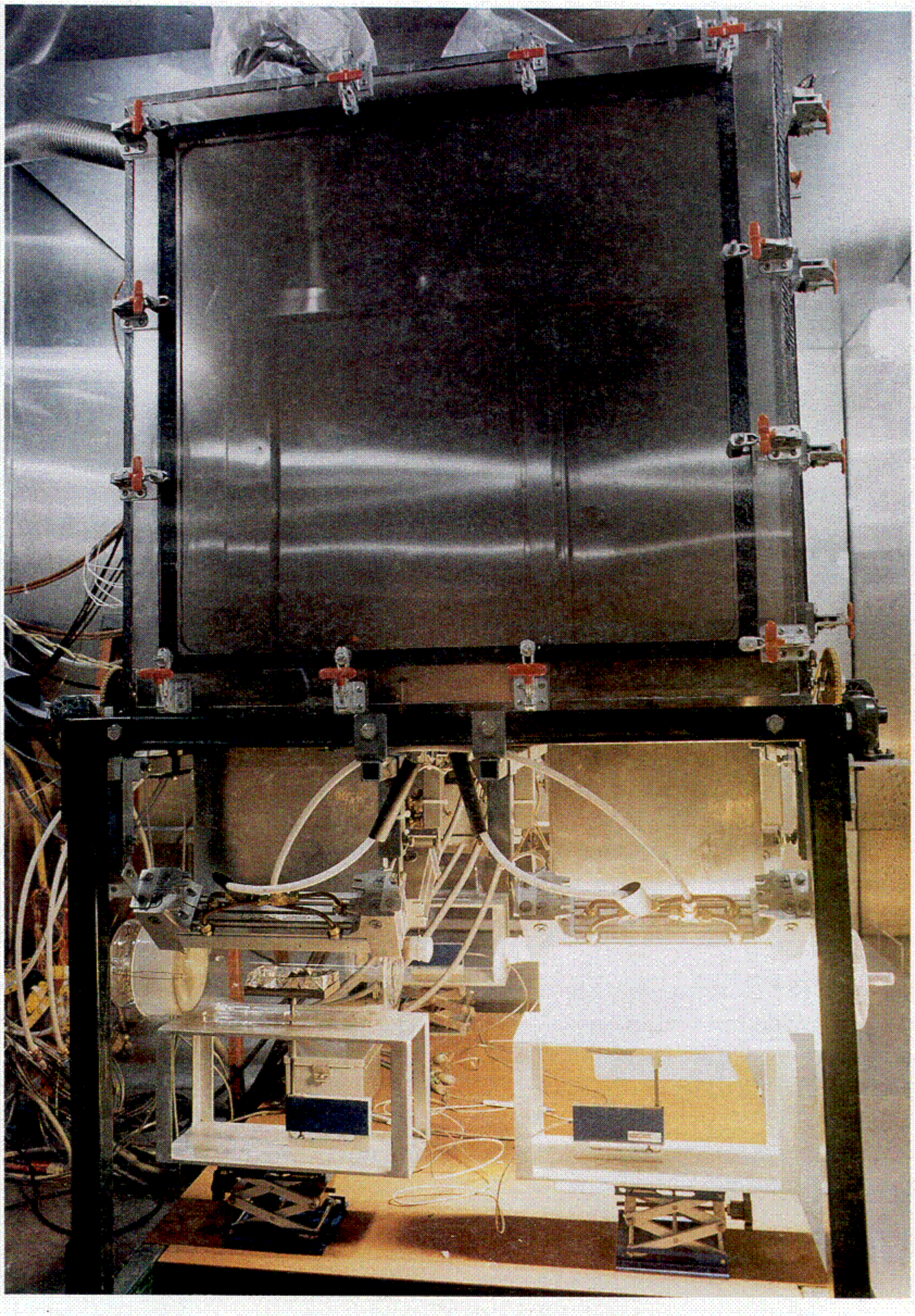


Figure 6. The large smoke exposure chamber was used for testing the digital safety system and component tests.

C06

2.2.1 Fuels Burned

With the exception of some limited tests with polyvinyl chloride (PVC) cable, most of the cables burned for this program have been nuclear-qualified cables. For the first tests on the multiplexer boards, only one cable type at a time was burned, but for the remainder of the tests, a mixture of cables based on the frequency of plant use was burned. Polyvinyl chloride is widely acknowledged to cause increased corrosion from smoke and, while it does not ignite as easily as materials with no chlorine, it will nevertheless burn vigorously and produce a lot of smoke. Although power plants do not currently use PVC cable, they have not removed all such cables from the plants and these cables are therefore available as fuel for a cable fire. Therefore component packaging tests included approximately 5% PVC in the mixture of fuels to determine if a small amount of PVC would contribute significantly to electrical failure. Generally, the mixture did not include PVC, however, most of these cables use halogens such as chlorine or bromine as a fire retardant. For the functional board and coating tests, the fuel was analyzed by Swartzkopf Laboratories (Woodside, NY) for heat of combustion and chemical analysis of the ashes. In general the cable materials produce 2.4×10^7 J/kg and contained 23% ash (mostly carbon), 0.95% Br, 12.60% Cl, and 0.49% F.

Manufacturers include halogens in cable formulae because they reduce material flammability. Halogens tend to combine with the same chemicals as oxygen during a fire, hence preventing fires by excluding oxygen. Halogens are blamed for increasing smoke corrosivity and damage to electronics because when halogenated cable burns, they produce strong acids, such as hydrochloric acid. Therefore some organizations such as the British Navy and many the telecommunications companies in Europe do not allow the use of halogenated cables. However, many of the non-halogenated cables are more flammable than halogenated ones.

For the ORNL experimental digital safety system, pieces of cable from Table 2 were stacked in a tray and burned with the conductor material in it. For tests starting with the component packaging tests, the cable insulation and jacket was stripped from the conductor and ground to make a mixture of cables from Table 2. The fuel was mounded in a tray inside of the quartz combustion chamber (Figure 7) located under the smoke exposure chamber. Figure 8 shows the combustion chamber during a smoke test. Most of the light is a result of the quartz lamps as they heat the fuel. A pilot spark, gas lighter, or electrical coil provided an ignition source for flaming tests, but was omitted during smoldering tests.

Table 2. Nuclear Qualified Low-Power Cables Burned in Smoke Exposures

Cable name	Insulation	Jacket
Rockbestos Firewall III	FRXLPE	CSPE
Anaconda Flameguard 1kV	EPR	CSPE
Brand Rex XLPE	XLPE	CSPE
Okonite Okolon	EPR	CSPE
Kerite HTK	unk*	unk
Rockbestos Coax (le)	unk	unk
Raychem	XLPE	XLPE
Dekoran Dekorad	EPDM	CSPE
BIW	EPR	CSPE
Kerite FR	unk	unk

*unk=unknown material, not specified by manufacturer.

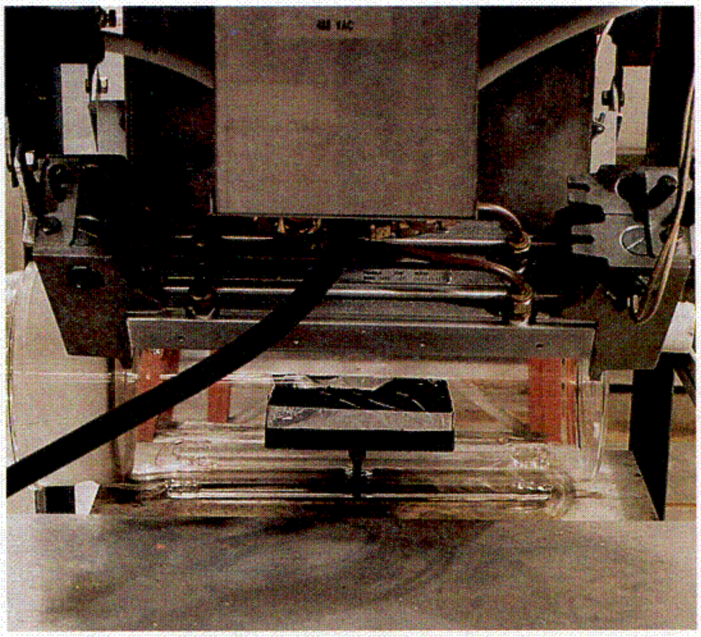


Figure 7. Fuel was loaded in the combustion chamber in tray below the stainless steel chimney (large rectangular shape at top center).

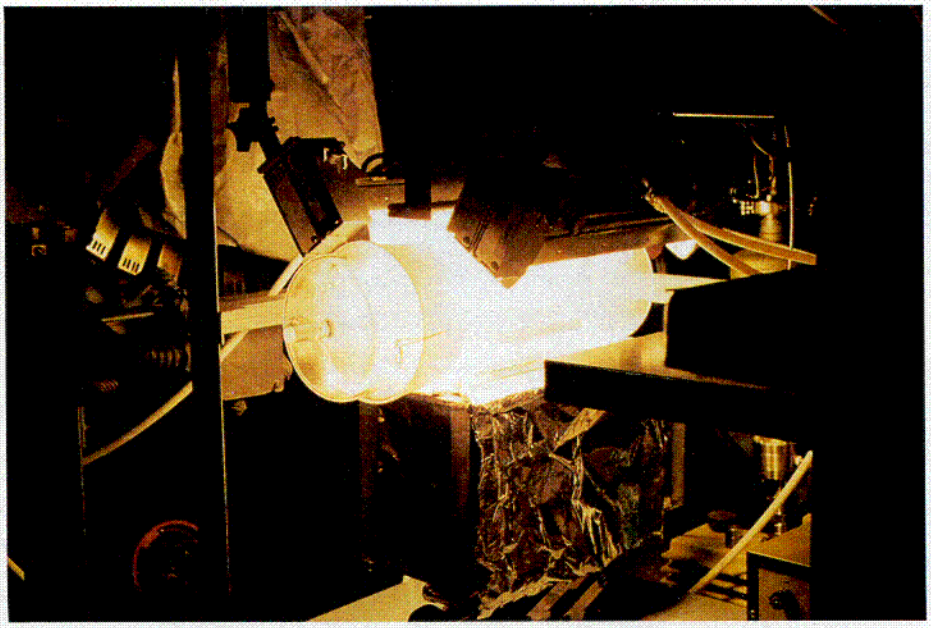


Figure 8. Quartz radiant heat lamps heated the fuel in the combustion chamber and smoke flowed up the chimney to the smoke chamber.

C07

2.2.2 Digital Equipment Tested

A wide variety of equipment has been exposed to smoke through this program. Most of the electronics that were exposed were actively monitored throughout the smoke exposure. The components and assemblies that were tested are shown in Figure 1, with the components on the left and the smoke effects test assemblies on the right. Starting with the components, top left is the multiplexer board, then to its right is the empty chip board, the chips tested for critical resistance, the functional board, the digital throughput board. On the second row are four memory chips, the hard disk drive and the non-volatile memory chip. From the bottom of the electrical effects devices are two absorption tubes to measure the acid generated in the smoke, the Rohrback probe, and the surface insulation resistance board. Side by side are the silver membrane filter to measure the smoke in the air and the humidity sensor. Above these are the mass vs. conductivity board in its holder, and the parallel plates to test voltage breakdown.

The first equipment tested, commercial off-the-shelf (COTS) multiplexer boards, converted digital signals to 4–20 mA DC current output and back again to digital data. A serial cable to a personal computer placed outside the exposure chamber connected the boards. The software for this board was written by ORNL and did not have any method to recover from time-out errors. Therefore, when smoke-induced time-out errors stopped the monitoring program data collection was interrupted.

The second system tested, the experimental digital safety system (not shown), was also developed by ORNL out of COTS parts. This was a three-node networked computer system that emulated a safety channel for a nuclear power plant. The first computer—the process multiplexing unit—performed signal conditioning, data acquisition, and multiplexing of process signals. The data was then passed onto the second computer—the trip logic computer—via a fiber distributed data interchange (FDDI) network. These trip logic units simulated channel trip logic elements and performed voting logic calculations. The third computer monitored the performance of the entire system. Reference 3 provides further details of the system.

The third set of tests was performed on COTS component packages. Circuit-bridging tests measured leakage currents generated by the addition of smoke to empty component packages (no devices installed), plastic chip packages, and surface insulation resistance patterns. In addition, complementary metal-oxide semiconductor (CMOS) memory chips were measured for function and performance before and after the exposures and an optical isolator chip was continuously monitored. Both surface-mounted technology (SMT) and plated-through-hole (PTH) packages were tested. The spacing between these components varied from 0.43 to 1.0 mm.

The fourth set of tests was performed on functional circuit boards developed by the Low-residue Soldering Task Force (LRSTF).[21] The boards were developed to determine how different low-residue soldering practices would affect the quality and cleanliness of circuit boards. This board contained different types of circuits constructed of COTS and milspec components. These circuits featured different properties such as high voltage low current (HVLC), high current low voltage (HCLV), high frequency (HF), and high-speed digital (HSD). These different circuits allowed the determination of which failure mechanisms were the most likely, including increased leakage currents, increased rise and fall times, solder joint faults, and increased stray capacitance.

A fifth series of tests determined the relative merits of conformal coatings on boards developed by the LRSTF. Several different conformal coatings were used to protect electronics from smoke exposures. These included a sprayed-on acrylic (used for the component packages only), brushed-on polyurethane, a dipped polyurethane, silicone, epoxy, acrylic, and parylene. The last six coatings listed were used to protect the functional circuit boards.

A sixth set of test determined if smoke would upset the transmission of digital data through common communications connectors. These connectors included the subminiature D nine-pin connector, commonly used for serial ports; the subminiature D 25-pin connector, commonly used for parallel ports, and the RJ-45 connector, commonly used for Ethernet connections. This test series was sponsored by the LDRD program and included wood, jet fuel, and PVC cable as fuels.

A seventh set of tests determined if smoke would affect the performance of erasable-programmable read-only memory (EPROM) and static random access memory (SRAM). These tests compared chip performance for different amounts of smoke. They also measured the leakage currents for a given voltage application and the voltage level for current injection. The EPROM chips were preprogrammed with data, and the data were read and checked to determine performance. The SRAM chips both recorded and read data. Non-volatile SRAM chips with internal lithium batteries were also tested in the smoke.

An eighth set of tests determined if smoke would interrupt hard disk access in the presence of smoke. The disks were used for both reading and writing while in the smoke environment. Hard disks were tested because hard disks are essential equipment in most computers, and they can cause severe interruption in computer performance if they are faulty.

Throughout the smoke tests, electrical measurements of surface insulation resistance, conductance of freestanding parallel plates and other effects of smoke on circuits were measured. These measurements were performed because we needed a basic understanding of how smoke would effect an electrical circuit in general. Early tests also included a metal loss measurement and chemical analysis. The literature review indicated that metal loss was an important measure of the effect of smoke on equipment and that the amount of chlorides deposited indicated the likelihood of failure. These measurements were discontinued because they were not direct measures of electrical problems that were likely to cause failures.

The equipment tested ranged from entire computers to component packages. This range of complexity allowed analysis of the reaction of a system to smoke and determination of individual causes of failure. The networked system tests identified likely system failures, while the component and functional board testing allowed determination of the causes of failure modes. The results of these tests are summarized in Sections 2.3 and 2.4.

2.2.3 Smoke Measurements

The smoke conditions were measured using physical means; optical extinction coefficient, fuel mass loss, mass of smoke in the air, and the density of soot deposited on flat surfaces were measured. These measurements were useful in determining the smoke and other environmental conditions of the test. For example, the smoke density, how much fuel was burned how much smoke was deposited on surfaces, temperature and humidity. Because of test-to-test variability with the same initial conditions, these smoke measurements allowed us to compare results for equivalent conditions. Sometimes smoke tests with the same initial test conditions result in different smoke measurements and in different electrical outcomes. Chemical analysis of the soot was performed before the LDRD program started and has yielded some chlorides and sulfates as standard ionic byproducts of the burning cables. No chemical analysis was followed up after the coating tests because of the limited scope of the program.

Fuel mass loss

Fuel mass loss indicates how completely a fuel is burned. In general, the higher the heat flux, the faster and more completely the fuel burned. The fuel mass was tracked by two methods, the fuel in a tray was weighed before and after each test, and a low-resolution measurement was made during the test using a load cell. A drawback of the load cell method was that the load cell was temperature sensitive so measurements during the flaming period, when the lamps were on are not very accurate.

Optical extinction coefficient

The optical extinction coefficient was measured with a He-Ne laser system. The laser beam was split and part of the laser light was monitored with a silicon photodiode detector while the rest of the laser light is collimated onto a fiber optic bundle. The fiber bundle directed the laser light through the smoke enclosure and then a second fiber optic bundle directed the light back to a silicon photodiode detector.

The transmission through the chamber was measured by comparing the signals from the monitor detector and the transmission detector. Since the objective was to measure the smoke in the air, nitrogen gas was used to purge the smoke from optical surfaces in the smoke chamber. The extinction coefficient, D_0, was then calculated using the Lambert-Beer law:

$$D_0 = -\ln(I/I_0)/t.$$

The ratio of I/I_0 is the ratio of the transmission while the smoke is in the chamber to the transmission before the smoke is added to the chamber and t is the distance the beam passes through the smoke (10 cm).

Mass density

Comparisons between the optical extinction coefficient and the mass density help ensure that the amount of smoke is known and can be compared with fire modeling codes. During the smoke exposure, four samples of air were drawn through silver 0.8 μ mesh membrane filters to measure the smoke mass density. The air samples were drawn directly above the optical extinction coefficient measurement. The filters were weighed before installation and again after the smoke exposure. Figure 9 shows the smoke collected on the silver membrane filter. The amount of air that was filtered was determined by measuring the airflow through the filters before and after the smoke test. Each sample was drawn for 30 s at rates that were less than 10 L/min (0.166 L/s). The optical extinction coefficient was proportional to the mass density as shown in Figure 10. Table 3 compares the ratios of optical to mass density for different cable fuels in this program.

Figure 9. Smoke was filtered from smoke chamber to determine the smoke density.

Table 3. Ratio of Optical Extinction Coefficient to Smoke Mass Density

Cable Fuel	D_0/ρ (L/mg-cm)
PVC	0.038
Ground mixed (see Table 2)	0.026
Brand rex	0.022

C08

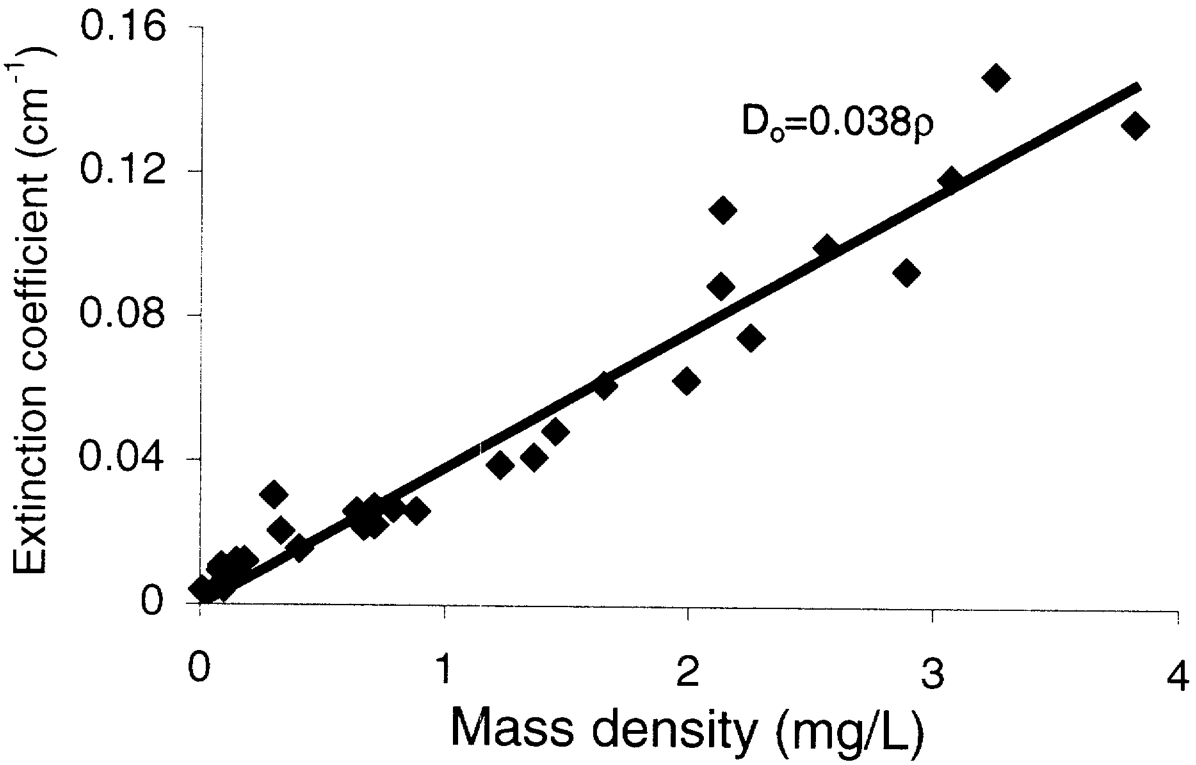


Figure 10. Optical extinction coefficient Vs Mass density for PVC smoke

Mass deposition

The mass of surface deposited soot was measured with a quartz crystal microbalance. A quartz crystal, patterned with gold contacts was connected to an oscillator circuit that drives the crystal at its resonant frequency. When smoke deposits on the surface, the resonant frequency decreases (as in mass loading of a spring), and the mass can be measured as the test is run. The disadvantage of this device is that temperature changes affect the resonant frequency of the crystal; therefore, corrections must be made for temperature changes. Although the quartz crystal is cut to reduce the frequency dependence on temperature, temperature changes also affected the oscillator circuit, changing the resonant frequency. Also, soot does not deposit on all surfaces equally, temperature and surface polarities are known to influence soot deposition. Hence measurements on these quartz/gold surfaces may not be indicative of how much smoke deposits on other types of surfaces, such as printed circuit boards.

2.2.4 Humidity measurements

The conductivity of soot is highly dependent on the relative humidity (RH) in the smoke chamber. The SNL smoke exposure tests have been performed with no control over the humidity other than the beginning and the end of the smoke test. Since conductivity depends on humidity and is a major concern in the reliability of electronics, humidity can be an important parameter to measure during a test.

Near the end of the program, small RH gages were included in the smoke chamber, one near the electronics and one near the mass vs. conductivity measurement boards. These gages included a platinum resistance temperature detector (RTD) so that both RH and temperature can be measured and other measurements of humidity can be derived. Figure 11 shows the RH/temperature gage that was placed in the smoke chamber to give readings throughout the smoke exposure. RH is the ratio of the mass of water vapor in the air to the mass of water vapor in saturated air (if the air is saturated, it contains the maximum mass of water vapor for air of that temperature). The mixing ratio is the ratio of the mass of water vapor to the mass of dry air and is independent of temperature of the air.

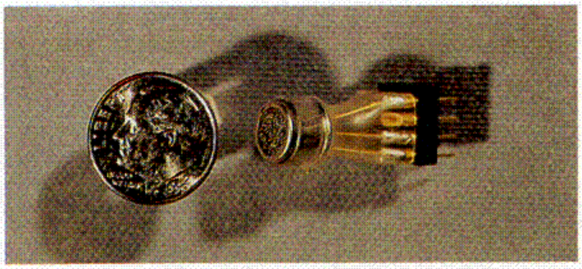


Figure 11. Humidity/temperature gage included in the smoke exposure chamber.

At the beginning of the smoke test, the humidity level was controlled by the environmental chamber, which surrounds the smoke exposure chamber, to approximately 75% RH. As the radiant heat lamps are turned on, the air in the smoke chamber was heated (Figure 12). The RH decreases with increase of air temperature because hot air can sustain more water vapor than cool air (Figure 13). Dry nitrogen was also added to the air near the smoke opacity measurement throughout the test. Dry nitrogen was used to sweep smoke from the optics of the smoke opacity measurement and prevent lenses from darkening from soot.

After 30 seconds the fuel began burning in the smoke chamber. Burning fuels that contain hydrogen (most fuels) creates water because the hydrogen molecules from the fuel material combine with oxygen to form H_2O. After 15 minutes, the lamps were turned off and the temperature of the smoke chamber dropped. At this point the RH increased slightly due to temperature effects, but because the nitrogen was added, the RH does not recover the original level when the temperatures return to the starting temperature.

C09

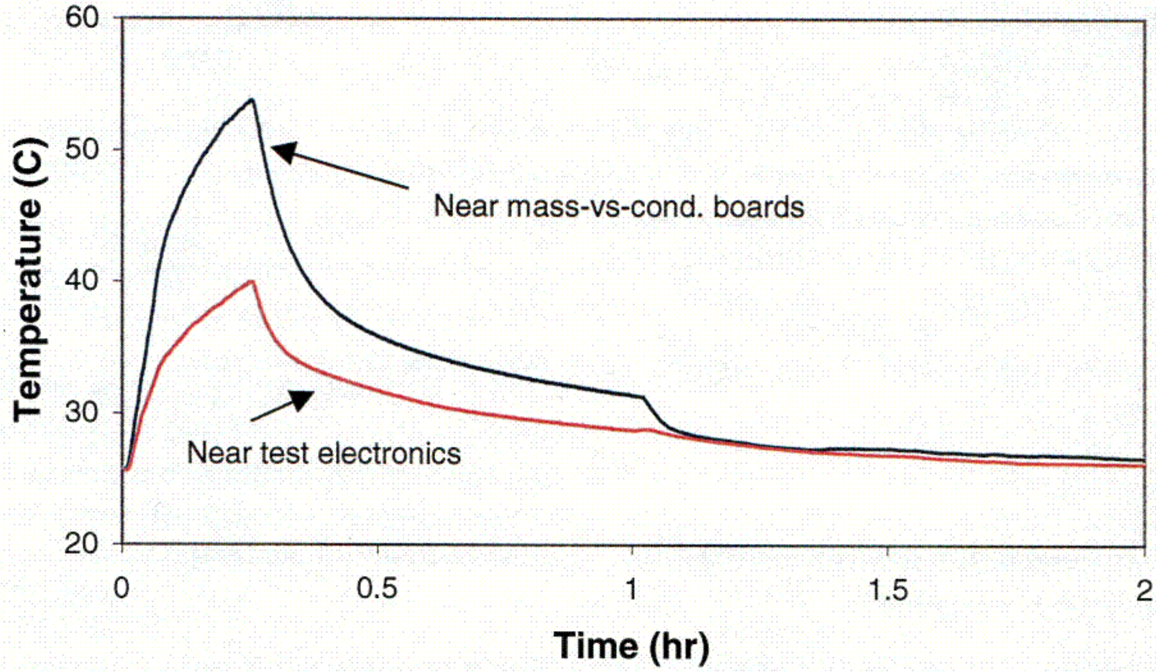


Figure 12. Temperature of the humidity probes was higher near the mass vs. conductivity boards than near the test electronics.

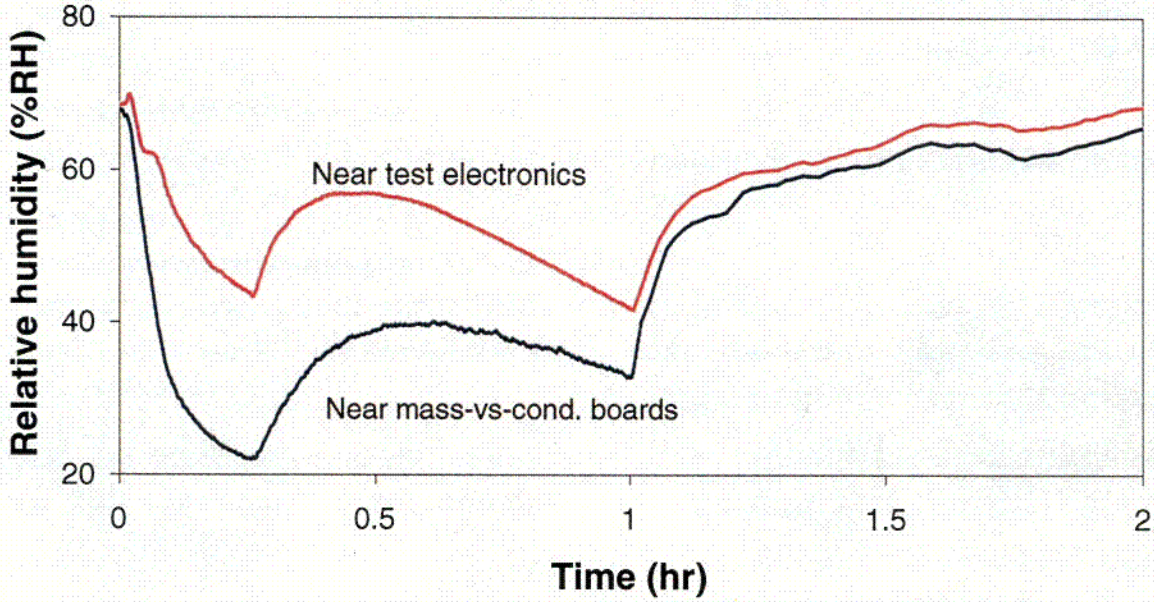


Figure 13. Relative humidity in two locations in the smoke chamber

C10

One hour after the lamps were turned on, the smoke chamber was vented. Smoke was exhausted from inside of the smoke chamber to outside of the building with a hood and moist, 75% RH air replaced the smoke. Venting with high humidity air overcomes the dry nitrogen purge and the RH in the chamber returns to the RH of the environmental chamber. Most of the soot has precipitated from the air and has now attached to surfaces within the smoke chamber (including the surface of the RH sensor.)

Relative humidity is the ratio of water vapor to saturation water vapor. The mixing ratio is the mass of water vapor compared to the mass of dry air. The mixing ratio (Figure 14) is dependent on the temperature and pressure, since the air pressure determines how many kg of dry air is in a volume.[22] The mixing ratio shows the effect of increased water vapor by burning and diluting the water vapor by adding nitrogen. The mixing ratio was calculated by estimating the ambient air pressure in the laboratory (approximately 1800 m above sea level) and calculating the mixing ratio of saturated air. Note that the humidity gage closest to the nitrogen feed by the mass-vs.-conductivity boards drops faster after the lamps are turned off and remains lower than the gage that was further from the nitrogen feed until venting at 1 hour.

Conductivity of soot-laden boards depends on both the suspended soot and the humidity. When the lamps are on and the optical extinction coefficient was high, the conductivity was dominated by smoke that is landing on the circuit boards. Later, after most of the smoke has deposited on the surfaces, changes in RH determine the changes in the conductivity measured by the mass vs. conductivity boards. Figure 15 shows the conductivity of the 500 V dc biased board. The initial peak occurs while smoke was being generated and was in the air. After the initial peak, the conductivity decreases as the smoke in the air settled, and the RH decreased due to the addition of dry nitrogen. The nitrogen feed was located directly above the conductivity boards. After 1 hour, plastic plates were placed over these boards to protect the soot from being cleared by venting the air and the smoke chamber was vented. The increases in conductivity at this time could be due to the increase in RH. Thus, the conductivity boards reacted to both the changes in humidity and the smoke density.

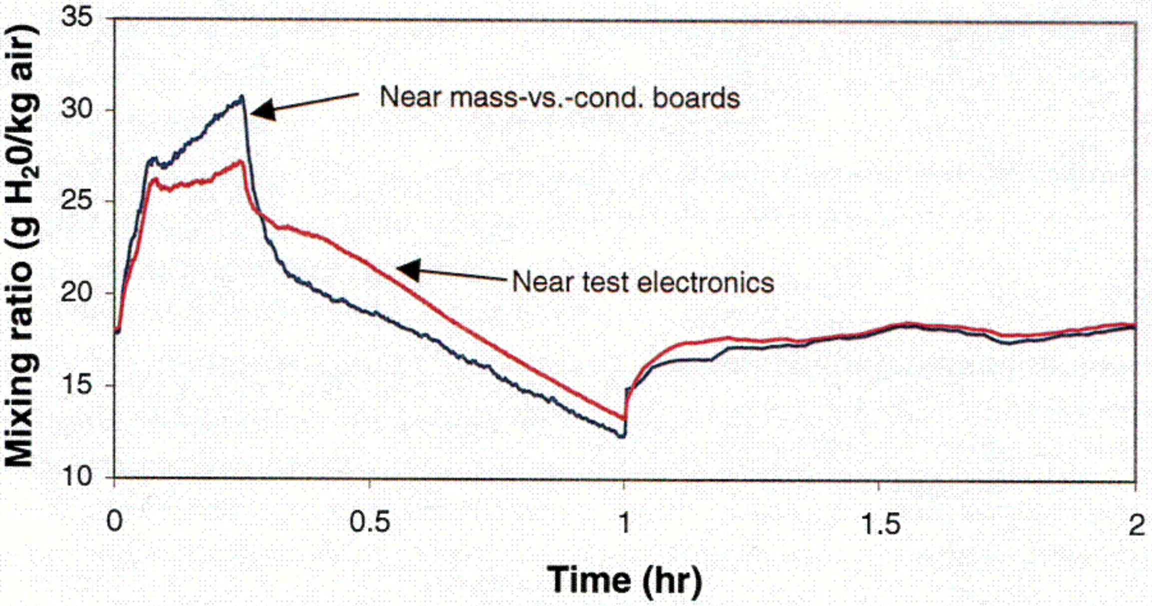


Figure 14. The mixing ratio decreased as dry nitrogen was added to the smoke chamber between the time that the lamps were turned off and the chamber vented (0.25–1.0 hr).

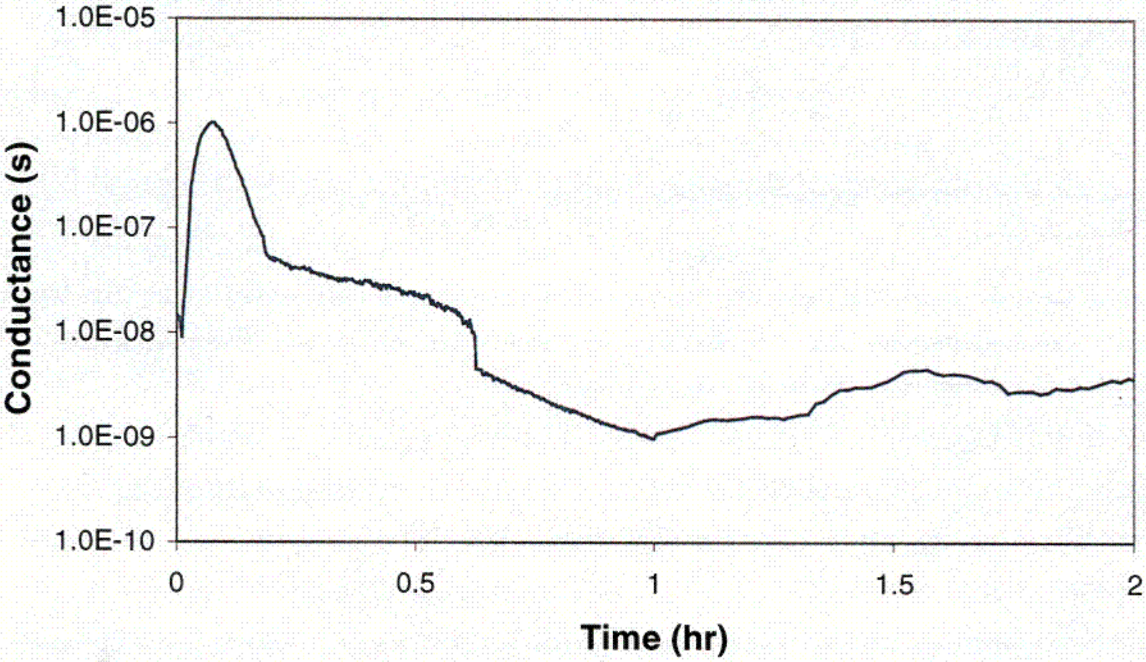


Figure 15. The conductance of the 500 V dc biased mass vs. conductivity board increased slightly after the chamber was vented (>1.0 hr).

C11

2.2.5 Temperature measurements

The temperature and humidity of the smoke chamber were controlled before and after the smoke exposure, but during the fire and for 45 minutes after the fire while the smoke is contained in the chamber, the temperature and humidity are uncontrolled. The temperature of the air within the smoke exposure chamber is measured throughout with type K thermocouples. The thermocouples were located in various positions inside of the smoke chamber and three outside of the chamber. Figure 16 shows the measured temperature from the tests from some of the thermocouples.

2.2.6 Chemical Analysis

The burned mixed cable fuel, soot, and smoke were chemically analyzed during the early stages of the program. When the fuel was burned, some of it becomes gaseous; some deposits as soot on surfaces of the smoke chamber, and some remains as ashes. In general 50% of the mass of the fuel is lost as either gaseous products or soot. Section 2.2.1 reported the byproducts of the fuel. The ashes were analyzed for metals

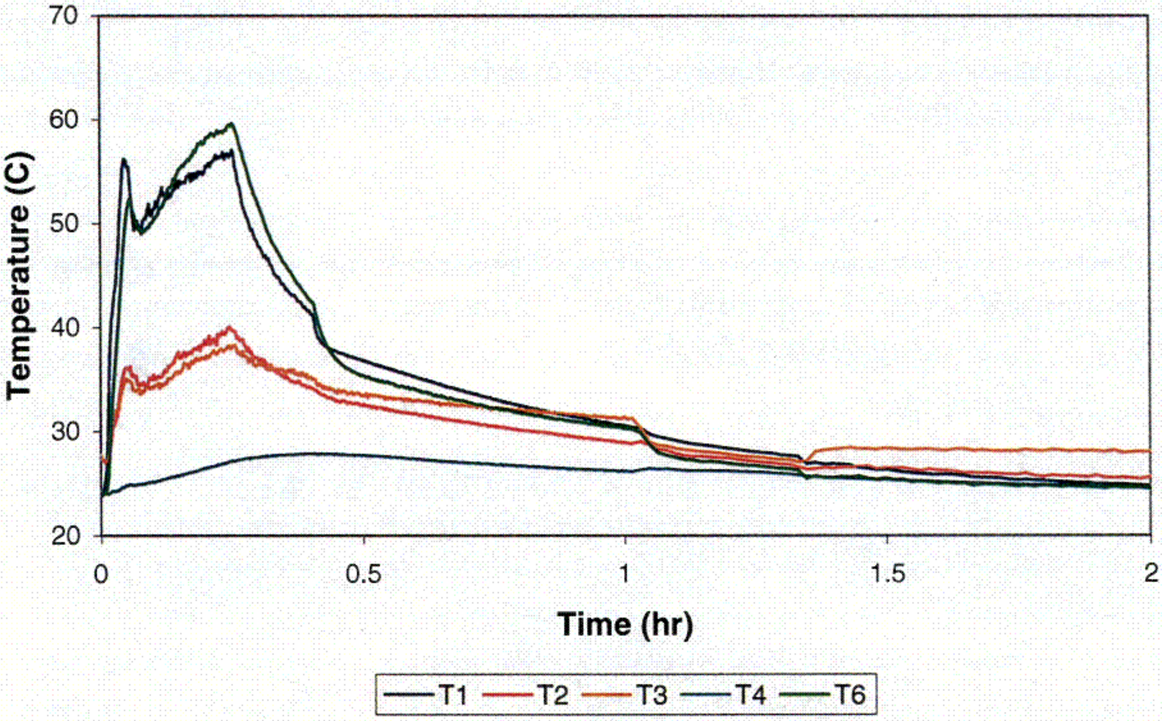


Figure 16. The temperature in the smoke chamber varied with position, T1-T3 are near the top of the chamber, T4 is at the bottom, and T6 is midway between top and bottom of chamber.

C12

semi-quantitatively. The predominant metals were silicon, titanium, lead, iron and magnesium.

Soot was collected in the smoke chamber by placing ashless filter paper on the floor of the smoke chamber. The filter papers were analyzed for halide and sulfide content, ionic compounds that have been found to increase the conductivity of insulators. 7.6 µg/cm^2 of chloride, 19 µg/cm^2 of bromide, and 31 µg/cm^2 of sulfate were measured from the soot samples taken during the coating tests where 40 g of fuel were burned in the flaming mode in the small, 200 L smoke chamber. Soot deposits can vary in an actual fire—cold surfaces attract more deposition and hot surfaces repel soot. Surface charge can also increase deposition. When the fuel was burned in a flaming mode, less chloride was These filters were burned and analyzed using ion chromatography to determine how many Cl, Br, and SO_4 ions were deposited at these sites. As shown in Table 4, the Cl and Br ion levels were fairly consistent deposited in the soot than when burned in the smoldering mode. This effect is shown in Table 4 taken from the functional tests. When the flux level was 25 kW/m^2, the fire was smoldering rather than flaming, as in the 50 kW/m^2 heat flux fires. There was an unexplained presence of fluoride, a third halogen that was detected in the chemical analysis, on the unexposed filer.

One of the standard measurements for smoke corrosivity has been the amount of chloride ions deposited on the electronics. To get some idea of how much smoke was available for deposition, filter papers were placed on the bottom of the smoke chamber on two sides of the functional boards: between the boards and the chimney (the front), and on the other side of the boards from the chimney (the back). throughout the tests, but the SO_4 measurements varied widely. It is unclear if this is a result of poor analysis or actual differences in each burn.

Table 4. Chemical analysis of filters placed in smoke chamber (µg/filter).

Fuel level (g/m^3)	Flux leve (kW/m^2)	Chloride	Bromide	Fluoride
3	25	95.5	2.1	0
3	50	24	5.5	0.25
25	25	92.6	96.6	0
25	50	73.0	66.9	1.45
50	25	147	181	1.25
50	50	95.4	165	0
Unexposed filter		3.9	0	0.7

Gas samples were obtained by evaluating a vacuum tight bottle and allowing gases from the chamber to flow into the bottle during the fire. Gas samples were analyzed for argon, CH_4, CO, CO_2, O_2, and N_2. The CO and CO_2 levels increased and N_2 and O_2 fractions decreased as more fuel was burned as would be expected from burning a carbon based fuel. Typical levels for CO_2 were 2–3% and 1% of CO, depending on the burning mode. Smoldering fires produce more CO.

Sorption tubes obtained samples of ionic compounds in the smoke in the component tests. Smoke was drawn through sorption tubes that were specifically developed to absorb ionic species. Chloride, bromide and sulfate were detected in the sorption tubes, all species that are known to increase leakage currents on circuit boards.[12]

Table 5. Ion Chromatography Results (μg/cm²)

	Front			Back		
Test no.	Br	Cl	SO_4	Br	Cl	SO_4
1	22.2	10.4	3.2	22.9	11.8	13.6
2	19.4	9.0	48.8	20.0	9.3	58.6
3	32.0	13.1	1.1	31.4	13.2	9.6
4	18.0	6.9	61.5	19.1	7.2	5.1
5	19.7	5.9	113.1	21.7	6.4	2.3
6	21.5	8.3	18.5	24.0	9.8	1.4
7	17.7	7.3	0.6	19.4	8.0	18.8
8	17.1	7.8	ND[a]	19.4	8.9	5.9
Average	20.9	8.6	35.2	22.3	9.3	14.4
STD	4.8	2.3	42.0	4.1	2.3	18.8

[a] ND = not detected

2.3 Summary of Previously Reported Smoke Exposures

This section summarizes results that were reported in reference 3, 7, and 8 on the digital system tests, component testing, and functional board testing.

2.3.1 Digital System Tests

The digital system tests were smoke exposures of microprocessor-based systems—either a computer or a board connected to a computer—and included digital communication between computers or microprocessors.

Multiplexer Tests

Multiplexing is one of the primary advantages of a conversion to advanced digital safety systems. Multiple control and sensor signals can be transmitted on a single cable. Three preliminary smoke exposure tests were performed on Analog Devices model 6BP04-2 multiplexer boards that were connected to a computer by a serial port (RS232 connection). The multiplexer boards consisted of circuit board back planes, which contained mounting slots for different plug-in units that could convert digital-to-analog (D/A) or analog-to-digital (A/D) signals. The back planes used serial ports to communicate between the multiple plug-in units to a computer that could control and log data from the different units. The multiplexing action results from transmitting several different signals from the plug-ins through the same serial port. This multiplexer model was chosen because this Analog Devices product contains many of the components that an advanced digital safety system might include, such as A/D and D/A units and an on-board microprocessor. This particular product was also simple to program and control with a personal computer and was small enough to be tested in our small smoke chamber.

A schematic of the multiplexer test setup is shown in Figure 17. DC current signals generated on a D/A plug-in unit located on a multiplexer board outside of the smoke chamber were transmitted through a pair of conductors to a 50 Ω resistor on a multiplexer board located inside of the smoke chamber. The A/D plug-in inside of the smoke chamber converted the DC analog current into digital signals. The multiplexer board inside of the smoke chamber transmitted the digital signals out through its serial port back to the computer located outside of the smoke chamber. For each test, either Brand Rex XLPE, Anaconda Flameguard, or Belden PVC cables were burned for a total of three different burns. Each test was performed at a high smoke exposure level of 75 g of fuel/m^3 of air. Humidity was expected to lead to failures by increasing circuit bridging and metal loss. Unfortunately, in this experiment, the humidity level was difficult to control since the humidity was added by means of a portable steamer, as the environmental chamber was not yet available. The humidity could not be controlled better than 15% in this manner.

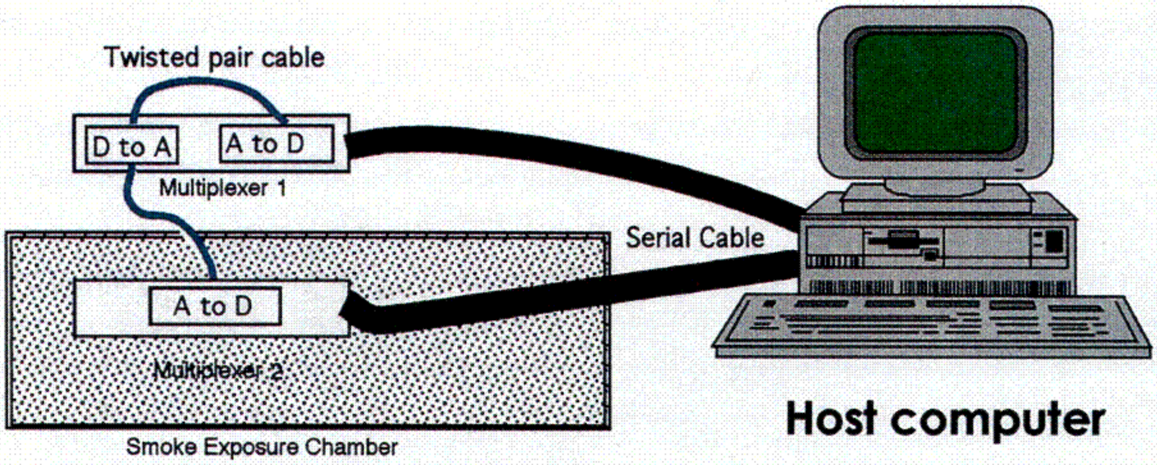


Figure 17. The host computer controlled two multiplexer backplanes for the multiplexer tests.

Of the three cables burned, two tests did not show any failures, but the PVC cable caused intermittent failures. The multiplexer board that was exposed to PVC smoke failed intermittently twice—once while the cables burned and once when humidity was being added after the exposure. When the board failed, the program that controlled and logged data from the boards stopped and could not be restarted until the personal computer was re-booted. Thus, the amount of time that the board was malfunctioning was not known.

The tests showed that smoke could cause failures in digital electrical equipment during the first 24 hours of exposure. It was hypothesized that intermittent shorts from soot that bridge conductors caused the failures in the circuits. Circuit bridging is the most likely cause because the failures were intermittent and most other failure modes, such as metal loss, would be expected to be continuous rather than intermittent.

These tests contributed to the general knowledge of smoke testing and indicated likely failure scenarios. Few of the physical and chemical measurements from this test showed significant differences between conditions that caused failure and those that did not cause failure. The only measurement to show an outstanding difference between the PVC smoke and the other exposures that did not cause failure was taken with the Rohrback probe, which measures metal loss. These tests indicated the need to improve software for the next experiment on the experimental digital safety system because the test program stopped when the failures occurred. A better testing program would accumulate data and record it even if the communication was temporarily interrupted.

ORNL Experimental Digital Safety System

Digital safety systems for nuclear power plants have the potential to be radically different from the present analog systems. For example, the digital safety system is expected to convert data from the analog transducers in various locations in the power plant to digital signals, and relay the signals back to the control room, where decisions on plant control can be made. The digital signals can be multiplexed so that all transducer signals may be transferred back to the control room on the same network cables instead of using separate cables for each signal. One concept that may not change is the idea of multiple-channel (e.g., two out of four) voting to determine if the plant should be tripped.

Because of functional and technological differences from analog systems, digital safety systems as a whole were studied to determine what environmental conditions could cause failure in an example system. ORNL assembled an experimental digital safety system from COTS parts that duplicated some of the features of advanced digital safety systems. The COTS parts included personal computers (of an industrial variety), fiber optic modules (FOMs) and the same type of multiplexer boards as used in the first test series, the Analog Devices boards with D/A and A/D units. This system was exposed to various environmental stressors and the results were reported in Reference 3. The environmental stressors included high humidity, electromagnetic interference, high temperature, and smoke.

The smoke exposures were performed at SNL. Subsystems of the experimental digital safety channel were subjected to various levels of smoke that approximated credible control and general room fire scenarios (a control panel fire and a small in-cabinet fire) while the system was in operation. These levels ranged from a low of 3 g/m^3 to 200 g/m^3. Before, during, and after each of these tests, the system was monitored to check that it worked. Several fire suppression simulations were included in the tests. This included the addition of humidity in the form of steam and CO_2 from a fire extinguisher. The monitoring period extended for up to 18 hours after the start of the exposure because this is a reasonable period to assess post event survivability.

It is noteworthy that the computers under test exhibited no permanent failures or serious upsets such as processor lockups resulting from deposition of smoke particles, although soot was spread throughout each chassis by the computer's fan. However, communication link errors were observed at all levels of smoke density, ranging from a few network retransmissions at low smoke densities to serial communication time-out errors at higher smoke densities. The FOMs were enclosed in a plastic case and when exposed to smoke in this manner did not have any failures, but when the FOMs were opened and their printed circuit boards exposed, the FOMs were found to be vulnerable to smoke deposition. Figure 18 shows the FOMs before the smoke exposure and Figure 19 shows the FOMs after the smoke exposure.

The severity of the communication link errors generally increased as the smoke concentration increased. The results of the high humidity (85% RH) tests showed that humidity may be an important factor in creating temporary shorts, and its adverse effect on digital boards is likely to increase with the severity of the smoke exposure. The CO_2 had very little effect on the equipment, although the temperature in the chamber dropped drastically.

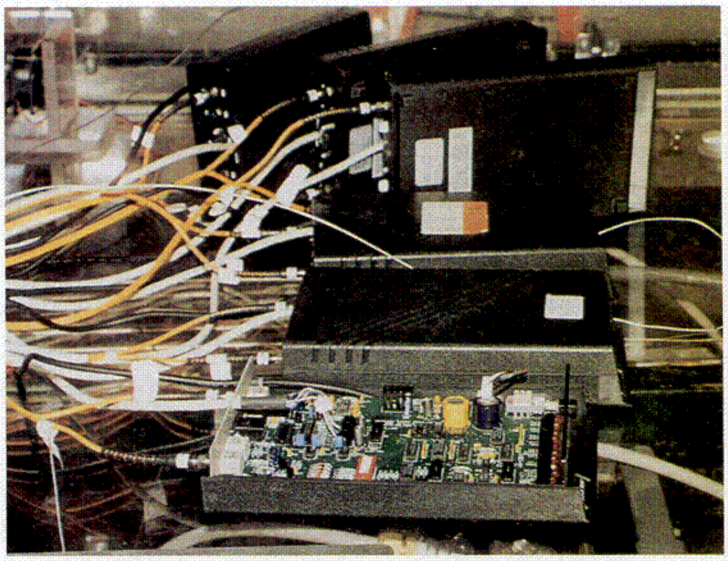


Figure 18. Fiber optic modules were tested in different orientations.

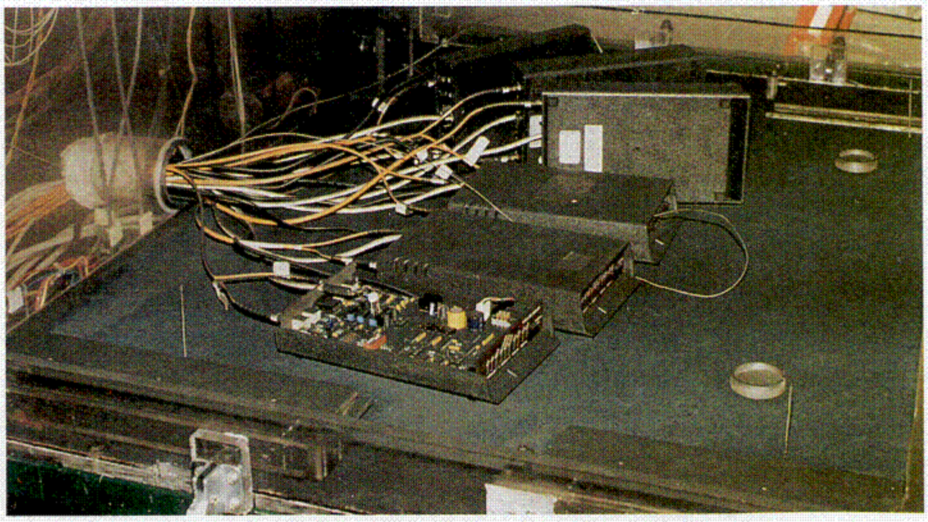


Figure 19. The fiber optic module that was open failed.

Once the system was exposed to smoke, the system tests in a nonsmoke environment were no longer free of communication link errors. This occurred even after the computer was cleaned with a Freon-based electronics cleaner. This behavior underscores the potential difficulty of thoroughly ridding a previously exposed board of all residual smoke particulates through cleaning and may point to the need to replace all exposed circuit boards after a fire as a matter of policy. These computers were cleaned with a halogenated cleaner similar to Freon. This may not have been the optimal method for cleaning. Cleaning is discussed further in Section 4.

Conclusions from the system tests

In summary, the experimental digital safety system was more smoke tolerant than the multiplexer boards because of its use of networked communication rather than serial communication. The networked communication system included more error checking and the ability to re-send the data if the data was not received correctly. The effect of the smoke on the network was to delay communication at the low levels of smoke and cause serious time-out errors at the higher smoke concentrations. Plastic cases provide smoke protection of the printed circuit boards for the FOMs, but without these cases the FOM printed circuit boards are vulnerable to smoke. High humidity and high smoke concentration increases the likelihood of failure, and electrical circuits cannot be adequately cleaned with a Freon-based cleaner after a smoke exposure.

2.3.2 Component Packaging and Circuit Bridging

The digital system tests showed that smoke could cause intermittent failures of electronics. Circuit bridging was suspected to cause these failures, but, because of the complex nature of the system tests, this suspicion could not be proved. To pinpoint the cause of intermittent failures in smoke, the component tests were designed to measure short-term smoke effects such as circuit bridging in typical component packages and under varied environmental factors to determine which factors were most significant in increased circuit bridging (i.e. shorts). The factors that were studied can be divided into three categories: smoke generation factors, component technology and packaging, and circuit board protection with coatings or enclosures. Measuring leakage currents and converting those currents to resistance in ohms tested the likelihood of circuit bridging. Loss of surface insulation resistance can cause problems in many components and circuits; for example if the resistance between the supply voltage and input signal drops, a false signal may be received by the device input from the voltage supply.

Test Component packages and circuit boards

Discreet components are packaged for two methods of mounting on circuit boards, plated through hole (PTH) and surface-mounted technology (SMT).

For PTH components, the circuit board must be drilled for the leads, the component leads inserted into the board, and the leads soldered to the underside of the board. For SMT components, the component package is soldered directly to the front side of the board. In large scale operations, this is accomplished by adhering all of the components to the face of the board, then passing the board through a wave solder machine, which heats the solder pads on the boards and makes contact to the component. The older PTH mounting results in larger component packaging than the SMT for the same device as shown in Figure 20. Mass produced boards are more frequently populated with SMT components because they are faster to build on a large scale and can be packed more densely, resulting in smaller circuit boards.

A test circuit board was designed for use with empty chip packages to measure the effect of bridging of leads and traces on circuit boards by smoke (Figure 21). Both PTH and SMT components were placed on these boards to compare the effect of lead spacing and density on circuit bridging by smoke. Adjacent leads were biased with either 5 V dc or grounded, and the leakage currents between the leads were monitored. Surface insulation resistance measurement boards, designed by the IPC, were included in these tests to measure the effect of circuit bridging for printed circuit traces also by measuring leakage currents for a range of bias voltages (Figure 22). These boards included 4 identical interdigitated comb patterns. Alternating traces on the IPC surface insulation resistance boards were either grounded together or biased with 5, 50 or 160 V dc. Leakage currents were measured for the biased patterns and the leakage current for the grounded pattern was measured for with a 5 V dc bias.

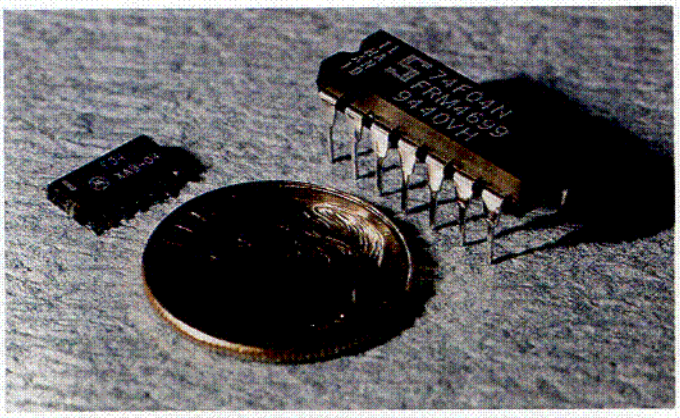


Figure 20. SMT chip packages are much smaller than PTH chip packages for the same type of device.

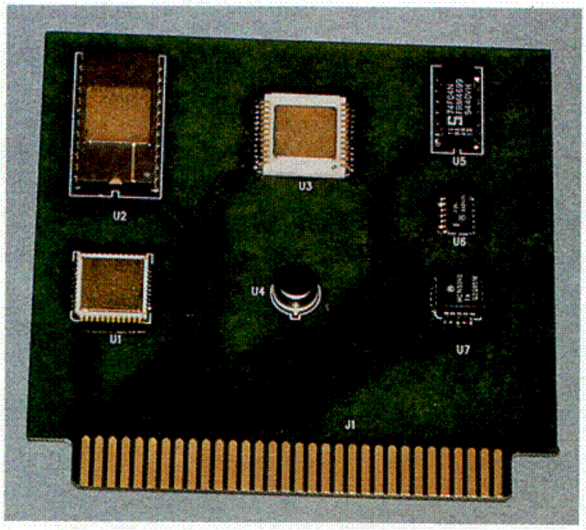


Figure 21. The component packaging tests featured both PTH and SMT component packages.

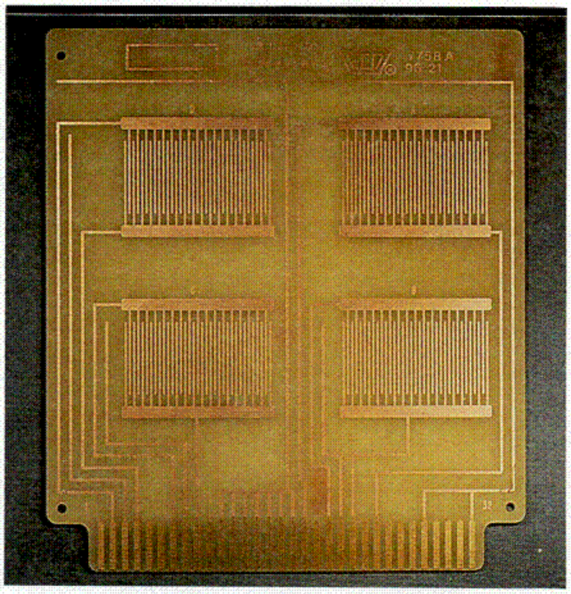


Figure 22. Surface insulation resistance was measured on an interdigitated comb pattern, IPC-B-24, developed by the Institute for Interconnecting and Packaging Electronic Circuits.

Two chips with functional components were included in these tests, optical isolators and 16K memory chips. The role of the optical isolator is to provide a directional gate that allows pulses to pass from input to output, but not from output to input. They also limit the voltage of a pulse that is passed through the gate. The optical isolator performs this function by converting electrical input to an optical signal, then converting the optical signal back to an electrical signal all within a small chip. A square wave pulse was transmitted through the optical isolator and the rise time, delay and amplitude of the transmitted pulse was measured.

16 K memory chips in both hermetically sealed ceramic packages, and plastic packages were tested in these smoke tests. The 16K memory chips were biased with 5 volts, but no signals were applied to the chips. These were tested before and after each test to measure functionality.

Component packaging test setup

Many factors determine a fire environment and the smoke it produced, such as the availability of oxygen, fuel, humidity level, and fire size. To determine which were the most significant, 27 tests were run, and some factors were varied. The humidity levels that were compared were between 30% and 70% RH. High and low fuel loads were compared. The high load corresponded to burning 100 g/cm^3 and low fuel loads to 3 g/cm^3. Two burning modes were compared, flaming (at 50 kW/m^2) and smoldering (at 25 kW/m^2). The burn mode 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. The fuel mixture was varied slightly, some of the fuel included 5% PVC because of the great concern regarding PVC and metal loss failures of electronics. CO_2 in the form of a fire extinguisher was added to some of the tests as well as galvanized metal to determine if galvanic salt solutions would form and drip on electronics.

For each of the 27 tests, 4 chip packaging boards and 4 SIR boards were tested using different configurations to determine the effect of circuit protection. These configurations included: inside of a PC chassis with a fan, face up in the smoke chamber, face up in the smoke chamber with a sprayed on acrylic coating, and outside of the smoke chamber (Figure 23). Leakage current measurements from all of the chips on the boards and the SIR patterns were collected every 3 minutes. The memory chips and optical isolators were placed inside of the smoke chamber, but were not protected with either coating or chassis.

Results of component packaging and circuit bridging

Resistance between leads on the component packages dropped when exposed to smoke as shown in Figure 24. To further analyze this data, the leakage current measurements were averaged over two periods: (1) the period when the smoke was in the chamber and (2) after the smoke was vented. Equations were derived to model the resistance as a function of the different factors. Factors that

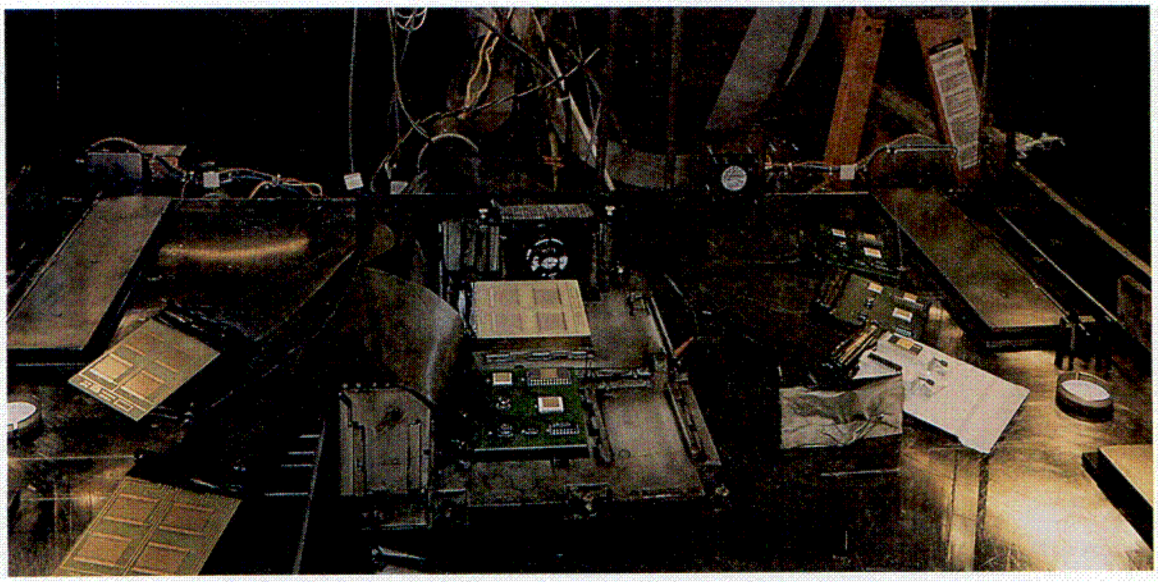


Figure 23. The component packaging tests were performed in the large smoke chamber.

C17

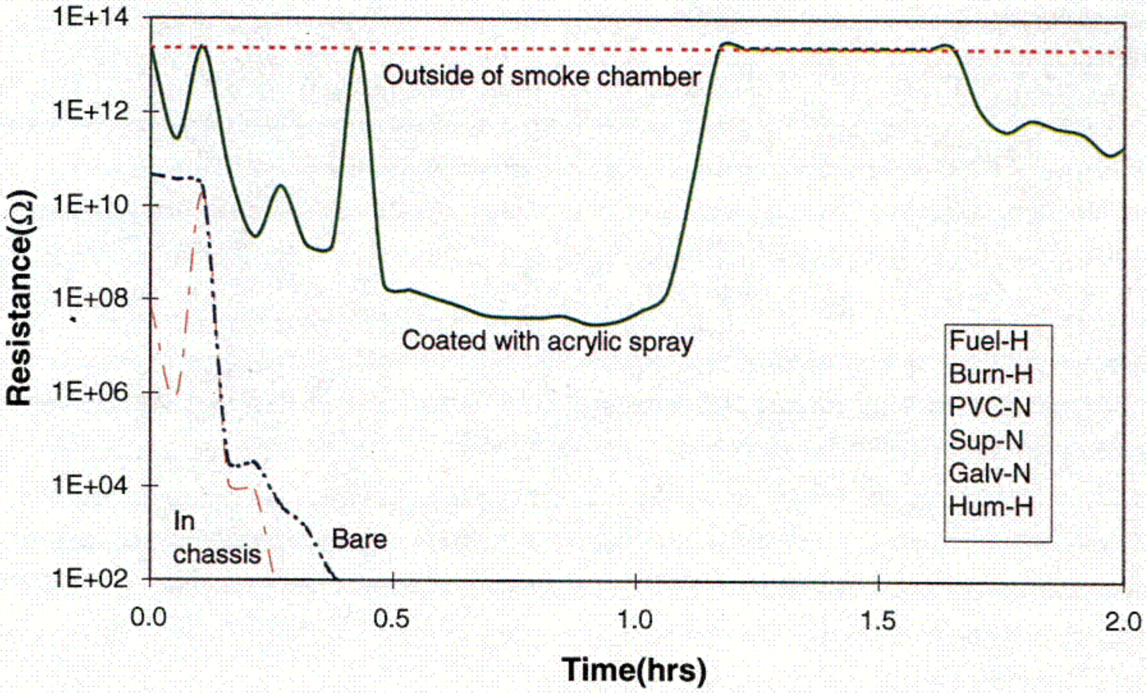


Figure 24. Resistance between leads of surface mounted ceramic package during a smoke exposure.

were most significant were determined by their frequency of occurrence in the equations. The most significant factors were humidity, fuel level, and burn mode.

The tests showed that the synergistic effects of smoke and humidity are higher than for humidity alone. 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 burning mode (flaming vs. smoldering) did not affect the resistance as much as the humidity or fuel amounts; however, the flaming mode did cause the components to short slightly faster. Soot analyses for Cl, Br, and SO_4 show a low correlation with burn mode. The amount of fuel burned is determined by both fuel and oxygen availability. If a large amount of fuel was burned by smoldering, only 20% of the fuel was consumed (80% of mass left after burning), while if a small amount of fuel was burned in either mode or a large amount of fuel was burned by flaming, approximately 40–50% of the fuel was burned. The large fuel load did not seem to have enough time to be consumed if smoldered since the lamps were on for only 15 minutes. Smoke deposited a film on the surface of the electronics, which was black and powdery if the fuel was burned in the flaming mode with adequate oxygen and was white and oily if produced by smoldering. If so much fuel is burned that the flame extinguishes due to lack of oxygen, the film is black and oily. Nowlen [23] reports that on large-scale cable fire tests, black oily deposits are common.

The insignificant factors that were tested included presence of PVC, addition of CO_2 as a fire suppressant, and inclusion of galvanic metal in the smoke chamber. PVC smoke has been found by other researchers to be a significant cause of metal loss, but metal loss is not a significant electrical failure mechanism unless the loss is significant as in equipment exposed to the smoke and soot for an extended period (months). Only a small proportion of the fuel was PVC in the high fuel load 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 deposits. These findings are also supported by tests on the effect of CO_2 on computers.[24]

Galvanic metal was included in the smoke test because earlier reports showed that it could cause additional failures of electronics by combining with smoke and humidity to create galvanic salt solutions, which then drip on electronics.[25] Galvanic metal is often used in electronic enclosures. The Zn in the metal will combine with Cl in the smoke to produce $ZnCl_2$. $ZnCl_2$ readily combines with humidity and forms a thick liquid. 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.

Resistance measurements on the comb patterns indicate that patterns are more affected by smoke if the applied voltage is higher. At higher voltages, comb patterns have higher leakage rates before the smoke is applied and continue to produce more leakage current throughout the exposure. Visually, soot tends to accumulate more around the high voltage patterns. The 160-V pattern was observed to be arcing during the smoke exposure.

Comparison of the functionality of the 16-K memory chips showed that the ceramic packages were more robust than the plastic packages in a smoke environment. The higher failure rate of plastic packages may be due to penetration of the plastic by humidity rather than shorting outside of the packages because the spacing between leads is similar in the plastic and ceramic packages tested. 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.

Since high fuel load, high humidity, and a flaming fire are the most difficult conditions for maintaining high resistance among leads, the results of the tests performed with these conditions were investigated further. For many components, smoke exposures with these conditions resulted in interlead resistance below the recording levels considered reliable ($<10^3\ \Omega$). The amount of time required to reach a resistance level less than $10^3\ \Omega$ was averaged for four tests, all of which had high fuel load, high humidity, and a flaming fire and are presented in Figure 25. The longer it takes to short the component, the more smoke tolerant it is. Packages with larger lead spacing tended to take longer to short than closely spaced lead packages. Comparisons of the bare chip packages showed that the transistor outline can (TOC) takes the longest to short, while

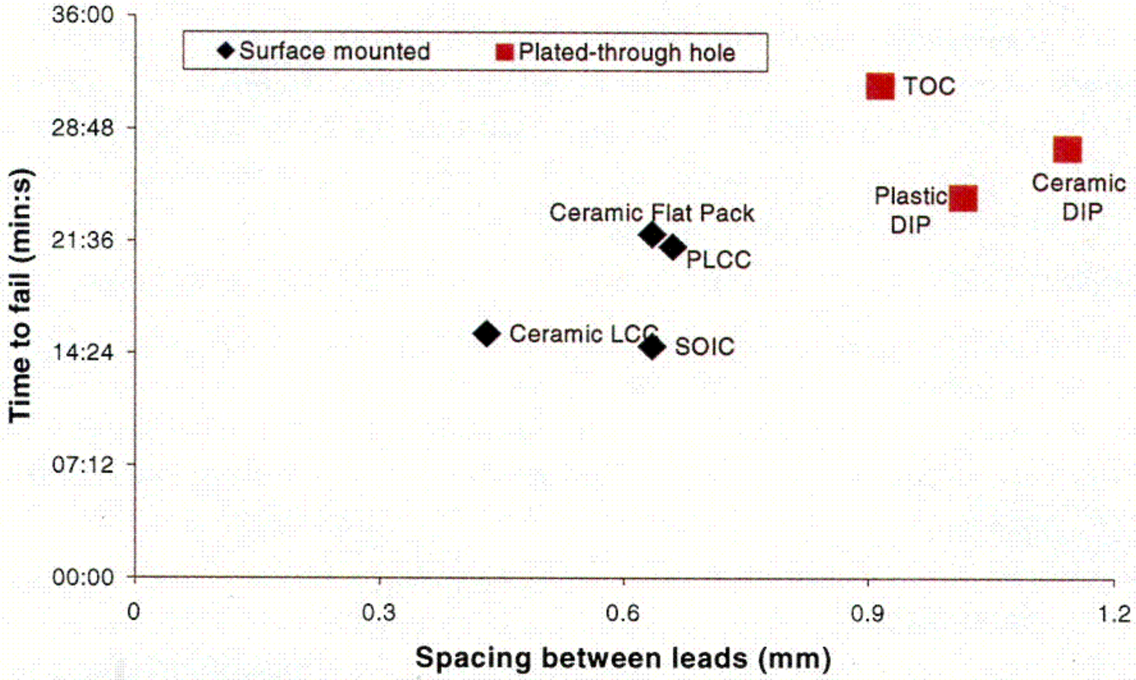


Figure 25. The time of failure increased with the spacing between leads for different components.

C19

the small-outline integrated chip package shorted sooner. The spacing between leads for these packages can be compared in Figure 25. Both the lead spacing and separation of the TOC are larger than those of the small-outline integrated chip are. In general, surface-mounted technology SMT packages were more closely spaced than PTH packages, and PTH packages were better able to maintain a high resistance.

Figure 26 compares different protective treatments—an acrylic coating* and enclosure in a fan-ventilated chassis—on different types of component packaging. The acrylic-coated ceramic leadless chip carrier and the chassis-enclosed ceramic dual-in-line package (DIP) were not included because the instrumentation wires to these components broke. In general, acrylic-coated chip packages took longer to short than either the bare or chassis-enclosed packages. The chassis-enclosed packages shorted in less or equal time than the bare packages, except for the ceramic leadless chip carrier. The acrylic coating improved leakage resistance somewhat and hence performance. Bare components exposed directly to the smoke performed the same or better than bare components inside a fan-ventilated chassis. The fan tended to collect soot into clumps and fling them onto the boards. The bare boards in the chassis were coated with larger clumps of soot than the bare

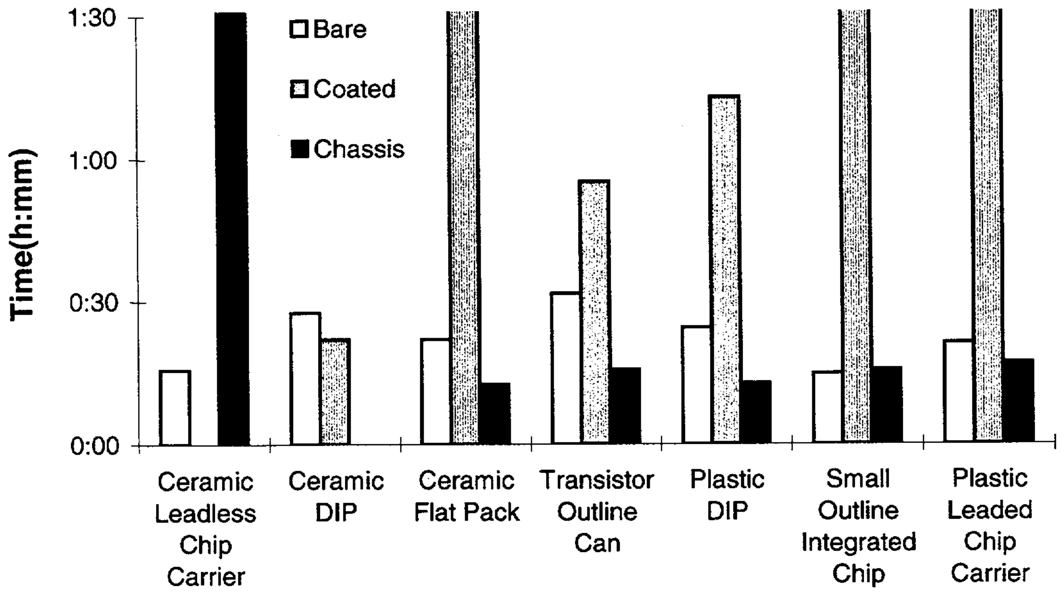


Figure 26: The time to failure due to smoke exposure is longer for acrylic-coated boards than uncoated or chassis housed boards.

boards outside of the chassis, which were coated with a more even layer of soot.

Conclusions from the Component Tests

Several conclusions can be drawn from the results of these circuit-bridging tests. They 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.The most significant factors that affect circuit bridging are the amount of smoke, humidity level, and burning mode. Other factors such as the use of CO_2 as a fire suppressant and the presence of small amounts of PVC are not as important. The test for galvanic metal was not of adequate scale to provide conclusive results.

3. Although surface deposits cause some circuit bridging, the leakage is highest while smoke is in the air.

4. Failure thresholds from circuit bridging are dependent on type of circuit, device technology, chip packaging, and circuit layout.

5. Smoke can randomly short or partially short the contacts of a component, and the component reaction depends on the impedance of the input or output of the device and which contacts are shorted.

6. Conformal coatings add some protection to circuits against bridging due to smoke.

7. Mechanical protection may also protect circuits, but the presence of a ventilation fan may negate this effect. A fan may draw more smoke into the electronics and cause more smoke bridges

2.3.3 Chip Technology Tests

The component packaging tests showed that smoke causes circuit bridging, which results in increased leakage currents. Increased leakage currents can cause digital failure by shorting a high to a low output, and thus transmitting the wrong signal through a circuit. As smoke is neither a perfect conductor, nor a perfect insulator, the effect of the smoke is more like a resistor placed in the circuit rather than a good conductor.

In-situ measurement of resistance changes in smoke was difficult because of the wide range of values during a smoke test. Typical clean circuit boards maintain resistances of approximately $10^{12}\ \Omega$ between traces. When smoke is added the resistance values may drop below $10^{3}\ \Omega$, but typical values were in the range of $10^{6}\ \Omega$. We found that measurements of resistance ranges from 10^{12} to $10^{2}\ \Omega$ to be difficult during our smoke tests because of time limitations. Although test equipment can be used in autorange mode, this mode is significantly slower and peak smoke measurements were lost. As our early measurements showed that most of the resistance measurements were greater than $10^{3}\ \Omega$ the later measurements were limited to values above $10^{3}\ \Omega$.

The amount of leakage current needed to cause digital failure depends on the type of logic component. The chip technology tests measured the amount of conductance (in terms of resistance) that would cause false data in different types of logic chips. Rather than exposing the logic chips to smoke, the effect of increased conductivity that the smoke would have caused was simulated using a variable shunt resistor.

Test chips selected

A variety of logic chip technologies were chosen to test for their vulnerability to increased leakage currents. At the time of the tests (1996), two types of transistor-to-transistor logic (TTL) were widely available and were tested: Fast Schottky (FAST) and Low Power Schottky (LS). The advantage of TTL chips is that they are fast and simple to use in circuits. (Ground is a low state, 4.5 V and higher is a high state, and the chips are biased with 5 V). At publication time of this report the LS version is still available, but the FAST is no longer widely manufactured. A wide variety of complementary metal-oxide semiconductor (CMOS) gates were also available at the time: standard metal gate (MG), high-performance silicon gate (HC), and advanced CMOS (ACT). The advantage of these chips is their small size and low power usage. The CMOS gates can be biased at different DC voltages and their high states vary according to the bias level of the chips. These CMOS chips are still available. The fastest chips that were widely available were the emitter-coupled logic (ECL) chips, which at the time were available in the 100K or 10H models. Other varieties of ECL chips are now available. The advantage of ECL chips is their speed, but they use more power than the CMOS and are more difficult to install in a circuit than the TTL chips. A list of chips that were tested is included in Table 6.

Test setup for chip technology tests

For simplicity, a steady-state test was designed to determine the critical surface insulation resistance below which a logic gate would provide faulty logic values. Motorola logic AND and OR devices, packed 4 to a package were tested on a prototype board. Figure 27 shows a sample circuit diagram where the outputs of two gates are shorted with a variable resistor. The resistance was started at a high value, and the value was reduced until the output of the circuit changed. The resistance value that resulted in a change of output was determined to be the critical resistance below which the circuit would fail.

Results

The results are shown in Table 6. The components that tolerated the lowest resistance had the highest output drive current. Components with a high tolerance to resistance loss are more tolerant of smoke. The components with high tolerance included the FAST (TTL) chips. Higher supply voltage on the HC (CMOS) chips improved smoke

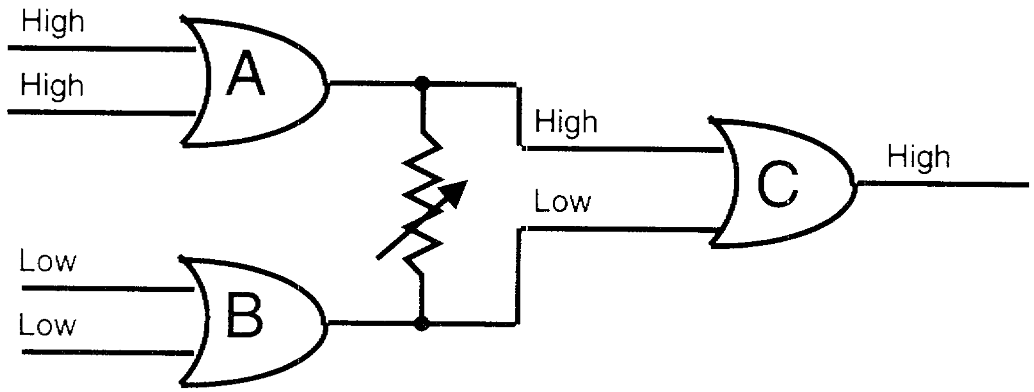


Figure 27. The chip technology test circuit introduced a variable shunt resistance into a logic circuit to simulate the effect of smoke.

tolerance. Standard CMOS components were the least tolerant to a decrease in resistance, especially at low power supply voltages. Resistance values of 10^3 Ω would definitely cause faulty logic for CMOS gates. Other gates such as TTL and HC would be more resistant to smoke. Although only Motorola components were used in these tests, the specifications from other companies indicate that similar technology families should react in a similar fashion to smoke.

Chip technology conclusions

The failure resistance varied between chip technologies and was highly correlated with the output current drive. This is especially evident for the standard CMOS, where the drive current changes with supply voltage. Gates with higher current drives can better supply the current necessary to maintain a voltage level despite a shunt. For the CMOS family, higher supply voltages correspond to higher drive current and lower input impedance. CMOS gates with higher supply voltage will be more resistant to the effects of smoke. The circuit-bridging smoke exposure tests only measured down to a resistance of 1000 Ω; this level of resistance would cause metal gate CMOS failure, but other components would not be likely to fail. The circuit bridging tests can be viewed as providing conservative estimates of smoke levels that would cause errors in logic circuits.

Note that in these experiments, measurements were made using steady state values. The effect of smoke on fast switching circuits was not taken into account. The increased conductance of circuit boards by smoke can slow switching, because some of the current can be drained from the normal circuit path and thus logic changes that are expected to occur when a particular voltage level is attained would be slower. If a range of conductance of the circuit board were defined as likely to cause failure, this test would show an absolute upper level. Any circuit containing these types of chips that were exposed to smoke to cause these levels of conductance would always fail.

Table 6. Critical Resistances for Failure from Smoke

Logic family	Supply voltage (V_s)	Output drive current (mA)	Critical resistance (Ω)
LS(TTL)	+5	-0.4/8	100
FAST(TTL)	+5	-1.0/20	31
Standard CMOS	+5	+/-0.88	1220
Standard CMOS	+10	+/-2.25	605
Standard CMOS	+15	+/-8.8	490
HC (CMOS)	+2	+/-0.02	120
HC (CMOS)	+4.5	+/-4.0	68
HC (CMOS)	+6	+/-5.2	56
FACT (CMOS)	+3	+/-12	30
FACT (CMOS)	+4.5	+/-24	30
FACT (CMOS)	+5.5	+/-24	25
100K (ECL)	-5.2	50-Ω load	105
100K (ECL)	-5.2	50-Ω load	107

2.3.4 Functional Circuits

The component packaging and chip technology tests showed that circuit bridging is a likely mode of digital circuit failure for standard CMOS circuits. Although most of the logic and decision making circuits of an advanced digital safety system would be primarily CMOS or TTL type components, the rest of the circuit, especially the sensors or actuators, could be very different. The functional circuit tests compared the effect of smoke on very different simplified circuits. The test target was a circuit board designed by the Low Residue Soldering Task Force (LRSTF) to study the effects of no-clean solders. These tests showed (1) the predominant effects of smoke on electronics, (2) which types of circuits are most vulnerable and (3) the conditions under which circuits are most affected. The advantage of exposing simplified circuits is that the effect on each circuit is easier to determine than if the circuit had more functions and components.

Test boards for functional circuit tests

Smoke may cause three different, immediate effects on electrical circuits: (1) it may lower resistance by acting like a shunt; (2) it may increase resistance by attacking solder joints or adding debris to connectors; and (3) it may increase stray capacitance. These effects were tested on the functional circuit board designed by the LRSTF (shown in Figure 28). The LRSTF designed this board to test extremely different types of circuits and measure how these circuits react to different levels of cleanliness. Since the physical differences between PTH and SMT components are significant, both of these types of components are included on the boards. As smoke exposure can be considered an extreme case of soiling a printed circuit board, the LRSTF test board was adopted for this smoke program to compare the effects of smoke on the different circuits.

The high-voltage low-current (HVLC) circuit, leakage current measurements, high-frequency transmission line (HFTL), and high-speed digital (HSD) circuits determined effects of smoke as an added shunt. Both the HVLC circuit and the leakage current measurements were on circuits with high (>50 MΩ) resistance. When smoke acts as a shunt in these circuits, overall impedance drops and current through the circuit increases. The HFTL consists of two parallel transmission lines whose cross talk from one transmission line to the other is measured. For a clean circuit board there is high impedance to any cross talk, but when smoke is added, the impedance can be lowered and more cross talk results. The HSD circuit consists of a series of NAND gates that propagate a signal pulse. The action of a shunt resistor can add a delay to this signal. The technology of these gates are TTL (FAST), however, and as shown in Section 2.3.4, are not expected to be very vulnerable to smoke.

The high current low-voltage (HCLV) circuit indicated the effect of increased resistance. This circuit had very low initial resistance (<3 ohms) and was good for measuring any increases in resistance.

The low-pass filter (LPF) determined the effect of stray capacitance. This circuit contained both capacitors and inductors and is designed to cut off frequencies higher than 1 GHz. In reality, the PTH circuit cuts off at 4 GHz, and the SMT circuit cuts off at 8 GHz, even though they contain the same component values. The PTH circuit has a lower cut off frequency because the components are larger and the stray capacitance is larger. Smoke might also increase capacitance and increased capacitance should change the cut-off frequency of the filter.

Functional circuit smoke test conditions

The functional circuit tests were performed in the small smoke exposure chamber. Four functional boards were tested at one time, one coated with an acrylic spray and one uncoated board were placed inside the smoke chamber and one coated and one uncoated board were placed outside of the smoke chamber as controls. Since the component packaging tests showed some smoke effects although they were outside of the smoke chamber, the control boards were wrapped in plastic to protect them from stray smoke that escaped the smoke exposure chamber. Six smoke exposure conditions were tested as shown in Table 7, where the fuel indicated is ground mixed cable in grams of fuel provided for the small 200-L smoke exposure chamber. All smoke tests were conducted at a starting humidity of 75% as that was the worst case found in the previous component packaging test conditions.

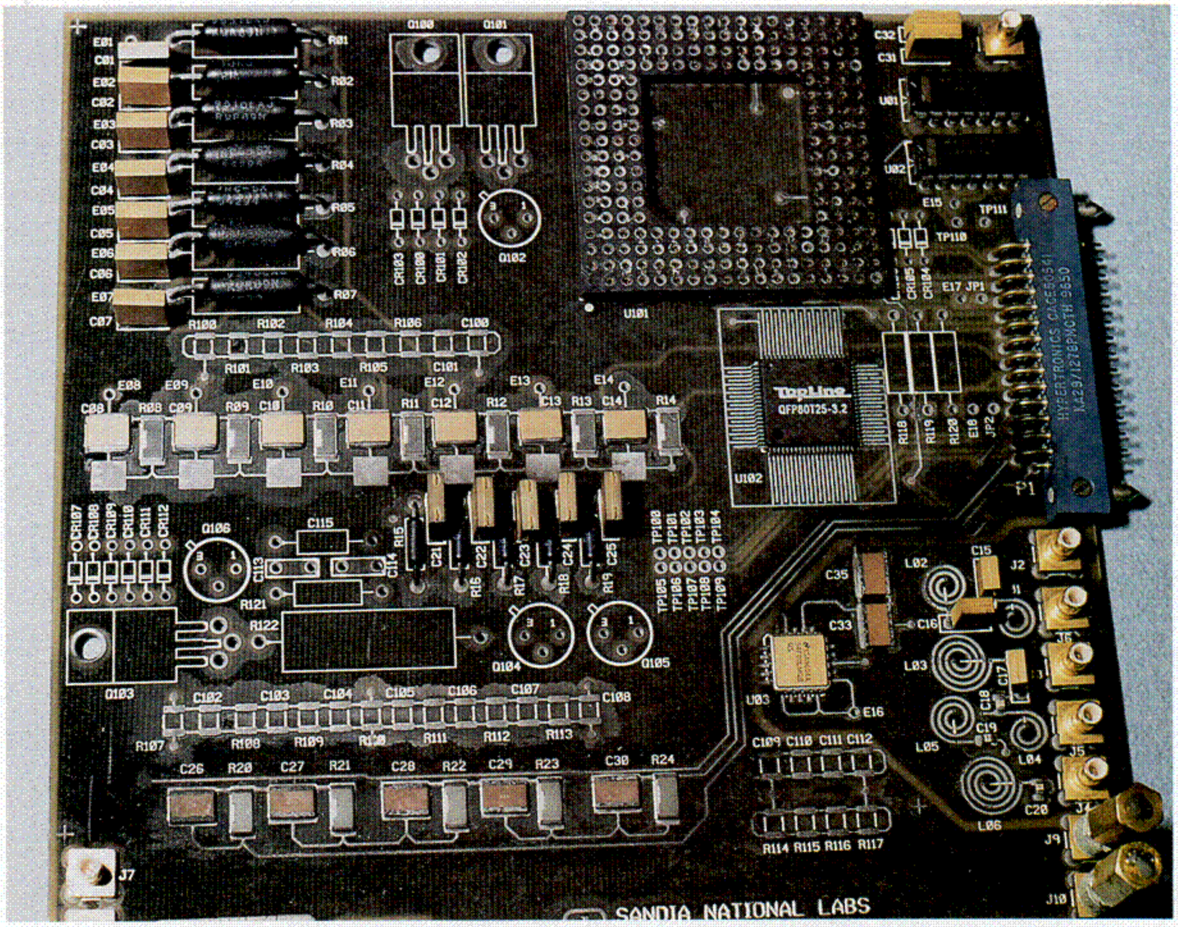


Figure 28. The functional board tested various types of circuits to determine their relative vulnerability.

C20

All of the circuits were individually measured before and after the smoke test. The fuel was placed in the combustion chamber and the humidity was increased to 75% RH. The lamps were turned on to the required heat flux for 15 minutes, and then the boards were allowed to sit in the smoke for 45 minutes with the lamps off. The smoke was then vented and the boards were allowed to continue to be monitored for 23 hours. Throughout the smoke test the boards were monitored every 3 minutes using a computer controlled process.

Functional circuit test results

The high fuel load and high heat flux levels caused the most smoke effects. Smoke effects that resulted from increased conductance of smoke were highest during the smoke exposure and fell after the smoke was vented from the chamber. Smoke effects that resulted in increased resistance increased throughout the monitoring period. These results are summarized in Table 8. More details on these tests and comparisons between the control, coated and uncoated boards can be found in reference [8].

Table 7. Smoke exposure conditions for the functional circuit tests.

Fire Scenario	Condition	Fuel /air ratio (g/m^3)	Heat flux (kW/m^2)
Large cabinet fire in control room	1	3	25 (smoldering)
	2	3	50 (flaming)
General Area fire	3	25	25
	4	25	50
Equipment in small cabinet fire	5	50	25
	6	50	50

Table 8. Summary of uncoated functional circuit worst case results.

Circuit	Smoke effect (greatest change)	LRSTF failure criteria
HVLC PTH and SMT	R changed from 50 MΩ to < 1 M Ω	ΔR>5 MΩ
HCLV PTH	No change	ΔV > 0.365 V
HCLV SMT	Voltage needed to produce 1 A changed by 0.034 V	
HSD PTH	Fall time changed from 2.9 to 3.2 ns	Fall time >7 ns
HSD SMT	Fall time changed from 3.7 to 4.3 ns	
LPF PTH and SMT	No change	Change > 5 db
HFTL	Increase of 23 db	Change >5 db
PTH solder pad leakage	R changed from 10^{13} Ω to 10^{7} Ω	R< 5 × 10^{5} Ω
SIR	R changed by 10^{3}	Comparison only

Conclusions from functional circuit tests

The predominant smoke effect was lowered resistance (increased conductance), and the most vulnerable circuits were those that had high input impedance. Clean printed wiring boards have resistances higher than 10^{12} Ω between traces. When smoke lowers electrical resistance in the vicinity of a circuit, the relatively low impedance of the smoke will bridge a high-impedance circuit. Thus, the circuits that were most affected were those that reacted to reduction in surface insulation resistance (i.e., added shunt current paths), such as the HVLC circuit. For the HVLC circuit, virtually all of the current was transmitted through the smoke and soot deposits instead of through the circuit when the fuel level was higher than 25 g/m^3. However, smoke did not affect the HSD circuit; the shunt resistance was not low enough to affect the FAST (TTL) logic chips in the HSD circuits. FAST (TTL) chips have a high tolerance to smoke because they have low impedance and high output current. If the HSD circuit contained a CMOS chip instead, it might have been damaged just as the memory chips in the earlier component tests were, because CMOS chips have lower output current drive.

The increased conductance induced by smoke was highest during the smoke exposure and was reduced by venting. Therefore, smoke and not just surface deposition causes increased conductivity by orders of magnitude. Values of resistance for the smoke can be estimated to be in the MΩ range and hence are significant for high impedance circuits and insignificant for low impedance circuits. Results from tests earlier in this program showed that a fuel level greater than 100 g/m^3 caused increased conductivity that remained after the smoke was vented. This implies that for higher smoke densities, the increased surface deposition will cause lingering effects. The tests showed that a polyurethane coating helped considerably to prevent smoke from increasing conductance or damaging solder joints. The polyurethane acts like an insulator, keeping the smoke from shorting the components.

The resistance of an uncoated HCLV SMT circuit increased by 1 to 2% when it was exposed to fuel levels of 25 g/m^3 or greater, but the PTH circuits and all coated circuits remained stable. For these low impedance devices, smoke did not lower resistance around the circuit enough to cause circuit bridging. Instead, smoke increased the resistance by corroding solder joints. These types of changes are more apparent in low-impedance circuits. Venting the smoke did not decrease these effects; however, they made relatively small changes in circuit performance—less than 2% in the worst case. Smoke did not cause any obvious change in the low-pass filter circuit, indicating that there was little change in stray capacitance.

2.4 Recent Smoke Test Results

This section describes tests that were not previously published in this NUREG/CR series,[7,8] the conformal coatings, digital throughput, memory chip and hard disk drive tests.

2.4.1 Conformal Coating of Functional Circuit Boards

Conformal coatings are plastic materials that are either sprayed, brushed, or vacuum deposited on electronic circuit boards to protect them from contamination. During component package tests, an acrylic conformal coating on the boards significantly reduced the adverse effects of smoke. The study with functional circuits coated with polyurethane also showed that conformal coatings can add considerable protection to circuits. This section describes a series of smoke tests on the functional board to compare the performance of five types of coatings.

Types of coatings tested

While the conformal coatings available on the market number in the hundreds, there are five major categories of coatings: acrylic, epoxy, parylene, polyurethane, and silicone. One representative from each of these five coating categories was included in these tests as shown in Table 9. Choices of coatings to be used for a product are usually based on the ability to rework the board, thermal conductivity, electrical characteristics, cost, and ease of application.

Table 9. Coating Types

Coating types	Brand	Product	Application thickness (mils)	How applied
Acrylic	Humiseal	1B-31	2.5	Dipped
Epoxy	Envibar	UV1244	2.5	Dipped
Parylene	Union Carbide	Type C	0.75	Vacuum deposited
Polyurethane	Conap	CE-1155	2.5	Dipped
Silicone	Dow	3-1765	5	Dipped

Test setup

A selection of different coatings was applied to LRSTF functional circuit boards before smoke exposures under high-fuel, high-humidity conditions to determine how different conformal coatings compared. A single product from each category was applied to the boards. The coatings were supplied by Specialty Coating Inc.,* who suggested which coatings would best represent each category.

The acrylic coating, Humiseal 1B-31, is a single-component; fast drying coating that can be cured at room temperature. This coating was deposited by dipping the board in the acrylic liquid and allowing it to dry. The epoxy coating, Envibar UV1244, is also a single-component coating. This coating was applied by dipping, but it was cured under UV radiation (it does not cure unless heated to 160 °C). Parylene, Union Carbide type C, was the most difficult and expensive to apply because it is vacuum deposited onto the boards, but it has the advantage of being a very tough coating for the application thickness. Vacuum deposition creates a very even coating because the deposition is not dependent on gravity or on the direction of a spray, but is like a cloud. Conap polyurethane is a single-component liquid that can be applied by dipping and air-dried. The polyurethane used in the coatings tests was a different brand than that used in the functional board tests discussed in Section 2.3.5.

The Dow Corning silicone is a one-part self-vulcanizing elastomer that can be applied by dipping. Silicone can be applied thicker than any of the other conformal coatings and remains flexible after curing. The silicone-coated boards had a tacky feel.

Thermal conductivity and application thickness determine how much heat will be dissipated through the conformal coating and are important considerations in the design of a system. All of the conformal coatings have high volume and surface resistance. The values of electrical and physical characteristics of these coatings are presented in Table 10. The coating manufacturer provided these characteristics.

---

* Specialty Coating Systems, 5707 West Minnesota Street, Indianapolis, IN, 46241

Table 10. Coating Properties

Property	Acrylic	Epoxy	Parylene	Poly-urethane	Silicone
Dielectric constant at frequency	2.5 at 1 MHz	2.30 at 1 MHz	2.95 at 1 MHz	3.5 at 100 MHz, 3.21 at 1 MHz	2.53 at 100 Hz
Dissipation factor at 1 MHz	0.01	0.0139	0.013	0.0162	
Dielectric strength for given thickness		5500 V/mil for 2-mil film	5600 V/mil for 1-mil film	3000 V/mil for 2 mil film	1100 V/mil.
Moisture vapor transmission (g-mil/100 in^2-d)		2.96	0.21		
Volume (bulk) resistivity (Ω-cm)		7×10^{15}	8.8×10^{16}	1.18×10^{16}	1.0×10^{15}
Surface resistivity (Ω)	800×10^{12}	4×10^{16}	10^{14}	5.66×10^{14}	
Dielectric breakdown voltage	7500 V at 2 mil		400 V at 1 mil		
Dielectric withstand voltage	>1500 V			1500 V	
Thermal conductivity (W/m/°C)			0.08		0.13
Water absorption			<0.1%		0.0539%

Coating Test Conditions

The conformal coatings were expected to provide some protection for the LRSTF functional circuit boards; hence the boards were exposed to more aggressive rigorous testing than in functional circuit tests. Therefore, a large amount of fuel, 40 g, was burned in the small exposure chamber. The fuel load was 200 g/m^3. The humidity level before and after the exposure was 75% RH. Because of limitations in multiplexer channels, only four boards could be exposed and monitored at one time. Figure 29 shows the four boards in their vertical orientation for the smoke test. To account for variations among tests, uncoated boards were used as controls. For each test, at least one board was uncoated. The testing plan is presented in Table 11. Because the smoke tests were variable, we included 12 bare "control" boards in the test plan. No two boards coated with the same material were tested at one time, and the placement of the boards on a particular data channel was varied in case the data channel had problems (for example, soot can get into the connection or a connector can fail). All of the 29-pin connectors were protected with black electrical tape.

The smoke tests were conducted using the same measurement setup as the functional board tests. Nine active measurements as well as four leakage measurements were monitored for each coated or bare board. Two surface insulation resistance (SIR) boards were included in each test, one in a horizontal position and one in a vertical position. Of the four combs on each SIR board, two were biased at 5 and two at 30 V dc. The leakage currents from these boards were determined by measuring the voltage drop across a ballast resistor.

Table 11. Coating Board Test Plan

Test No.	Channel 1	Channel 2	Channel 3	Channel 4
1	Bare	Parylene	Acrylic	Bare
2	Polyurethane	Silicone	Bare	Bare
3	Epoxy	Bare	Parylene	Bare
4	Bare	Bare	Parylene	Acrylic
5	Acrylic	Polyurethane	Silicone	Bare
6	Parylene	Epoxy	Bare	Polyurethane
7	Epoxy	Bare	Polyurethane	Silicone
8	Bare	Acrylic	Silicone	Epoxy

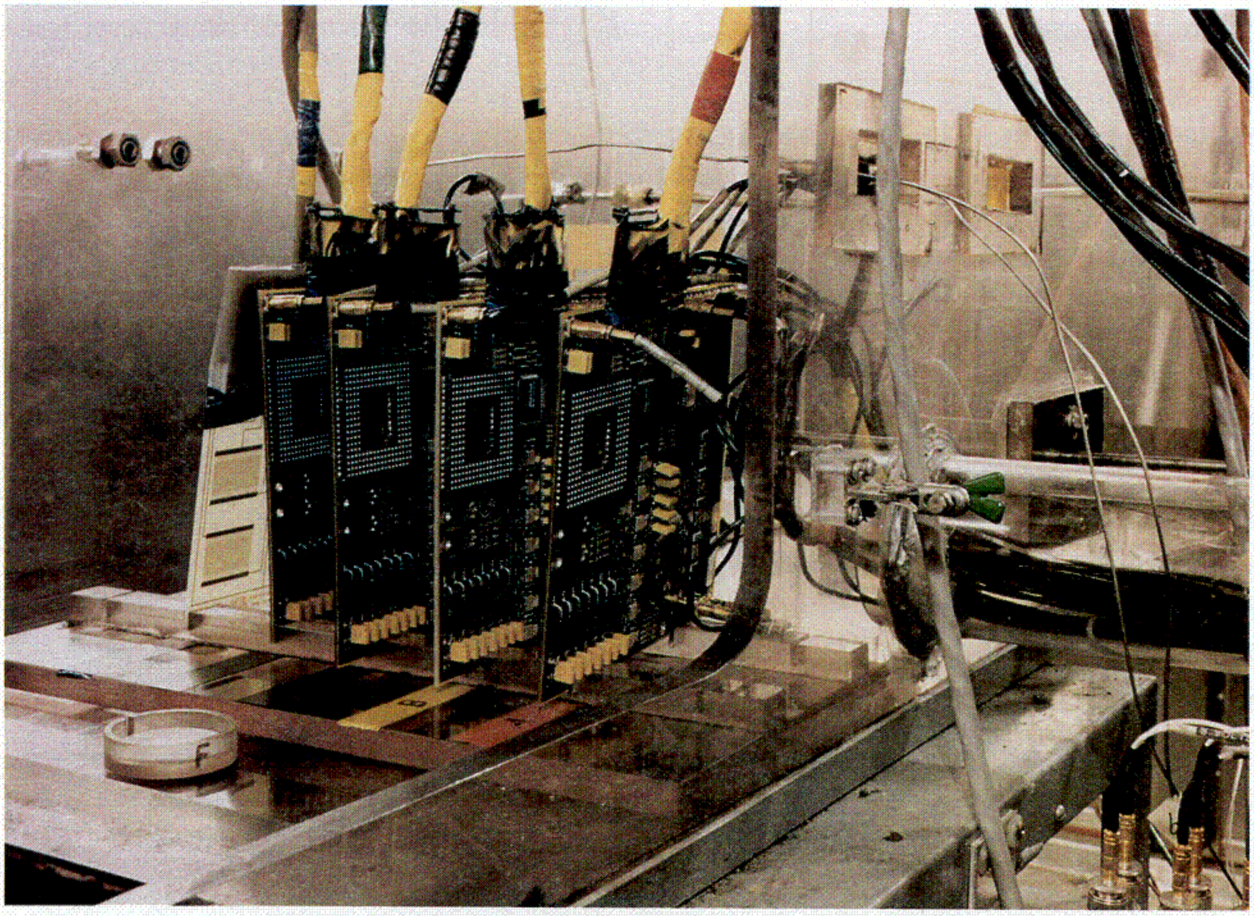


Figure 29. The small smoke chamber was loaded with four functional boards and an IPC-B-24 board for the coating tests.

Before each test, the circuits were measured to determine a baseline value using the manual measurement box (pretest). The boards were then connected to an automatic measurement system and measurements taken every 3 minutes throughout the smoke exposure. For analysis, the automatic measurements were separated into four time periods: before the fire started (preburn), while the lamps were on (burn), after the lamps were turned off, but before the chamber was vented (soak), and after the chamber was vented until the end of the 24-hour data-taking period (vent). The boards were then placed back into the manual measurement box and a final manual measurement made (post-test).

Results of coatings tests

The HVLC test measured the resistance across a 50-MΩ, high-resistance circuit with a 300-V dc bias. The data were analyzed by averaging data from the four time periods as well as the manual measurement taken before and after the test. All measurements were converted into resistances. The HVLC circuit reacted in two ways to smoke. For most of the control boards, the measured resistance dropped as a result of the smoke providing alternative current paths between the 300 V dc applied to the circuit. However, the resistance of some of the PTH circuits increased during the burning phase, as shown in Figure 30. This did not occur for the SMT circuit (Figure 31), so this must indicate a difference between how SMT and PTH components are constructed or connected to the circuit rather than how close the traces are placed, because these distances were closely matched in the two designs. The PTH circuit showed two different failure modes, one in which the resistance increased (open-circuit fault) and one where it decreased (short-circuit fault). After the test, many of the control board circuits recovered almost back to normal.

The HCLV circuit on the functional circuit board is a low-resistance circuit (1.5 Ω) designed to study corrosion of solder joints and traces. Smoke increased the resistance of the uncoated HCLV SMT circuits, but did not affect the PTH. This effect has been observed during the functional circuit tests on HCLV circuits. All of the coatings did a very good job of protecting the circuits from this failure mechanism. Typical data are shown in Figure 32.

The HSD circuit was a series of NAND gates built with SMT and PTH components using FAST TTL technology. TTL technology uses more power than CMOS technology and also has more output current drive. A square wave pulse was passed through a series of gates to determine if the smoke would cause the pulse to be shorted or delayed.

Because of the higher smoke exposures, the HSD circuit failed in tests 3 and 5 with the bare boards, whereas they had not failed in previous tests. The increased leakage currents caused a drop in the output from the 5-V dc power supply that drove the HSD circuits. Test 3 was unusual because the plug for the

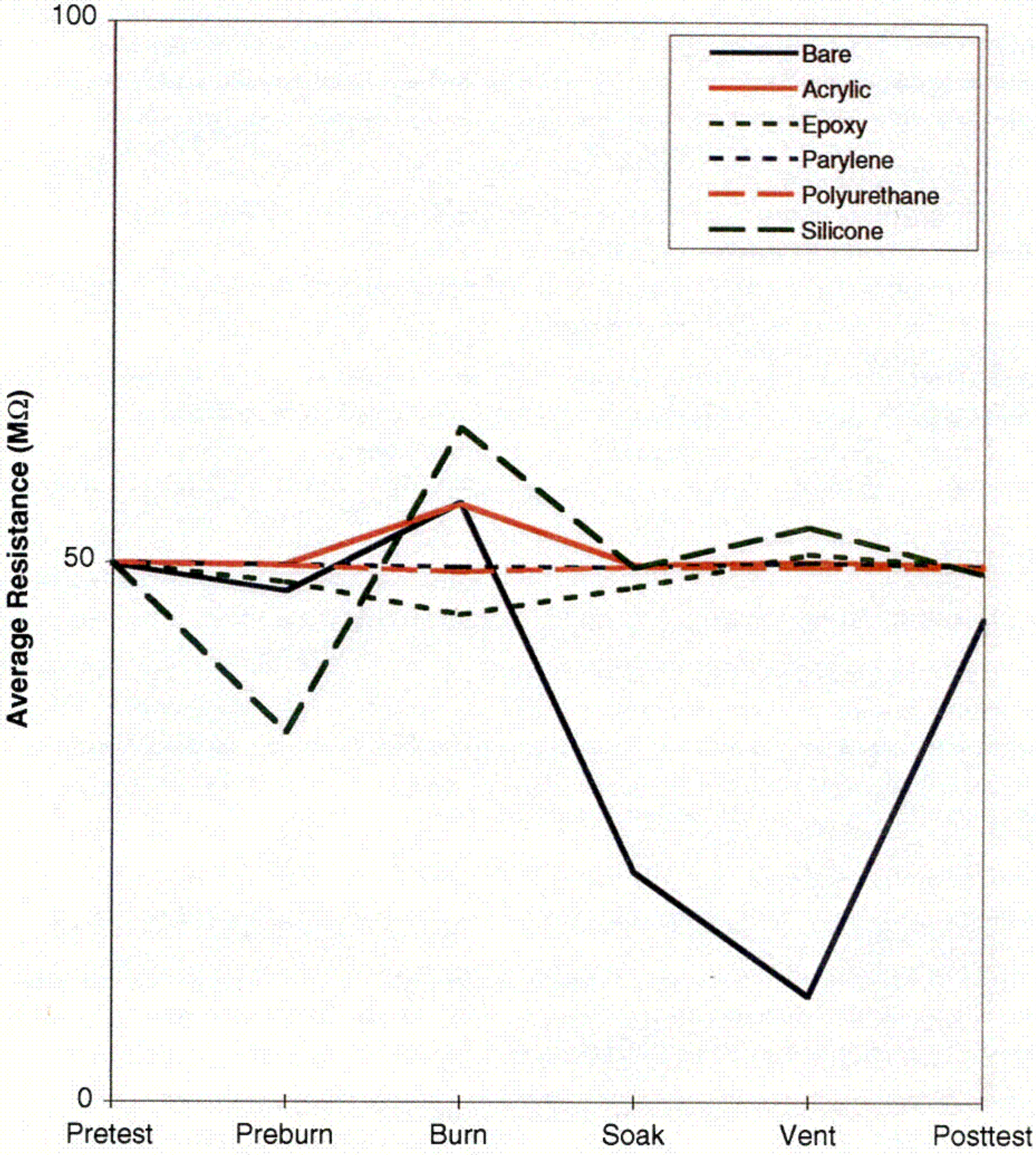


Figure 30. For the PTH components in the HVLC circuit, parylene and polyurethane were the best coatings.

C22

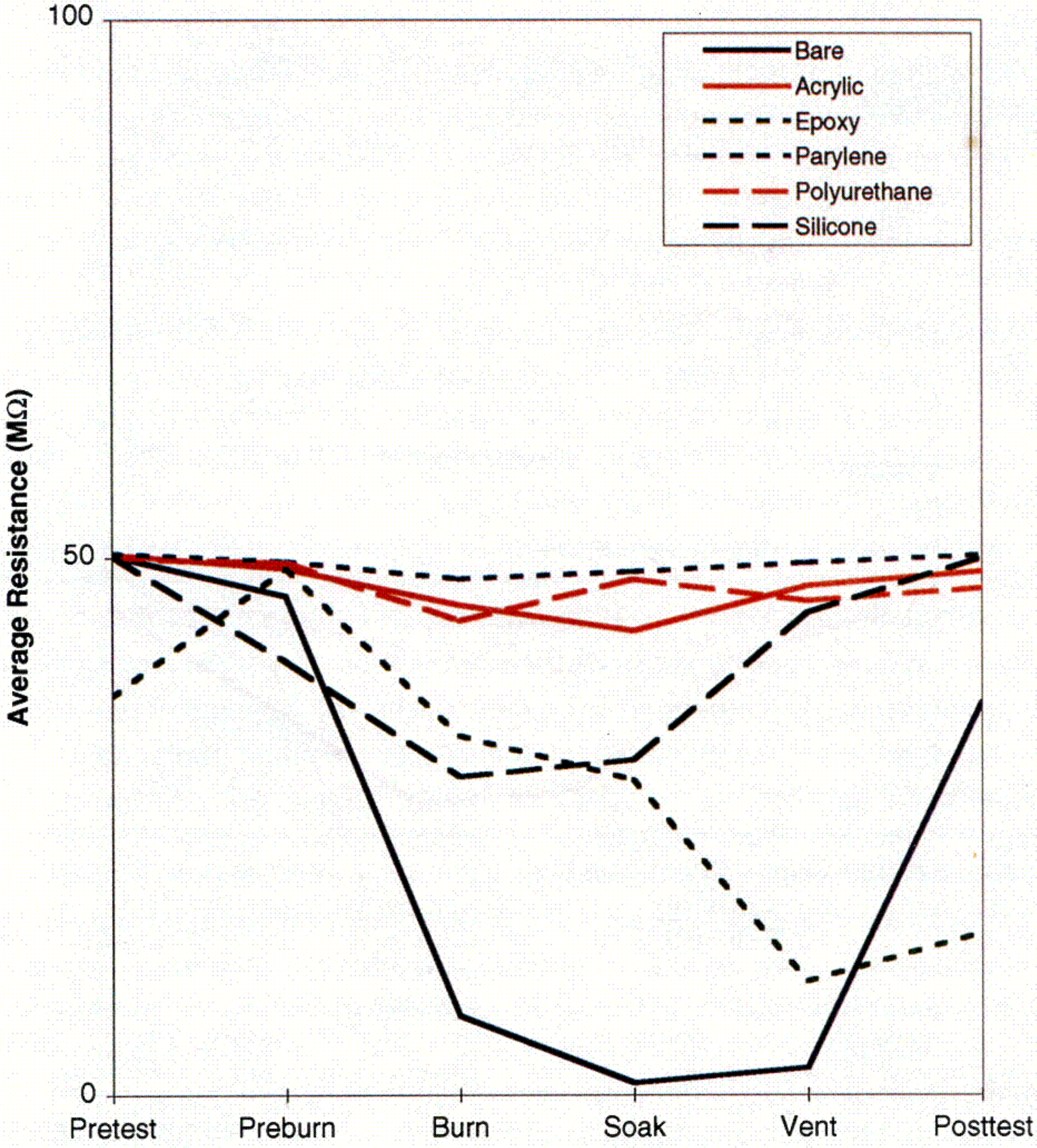


Figure 31. The parylene, acrylic, and epoxy coatings worked best on the HVLC circuit with SMT components.

C23

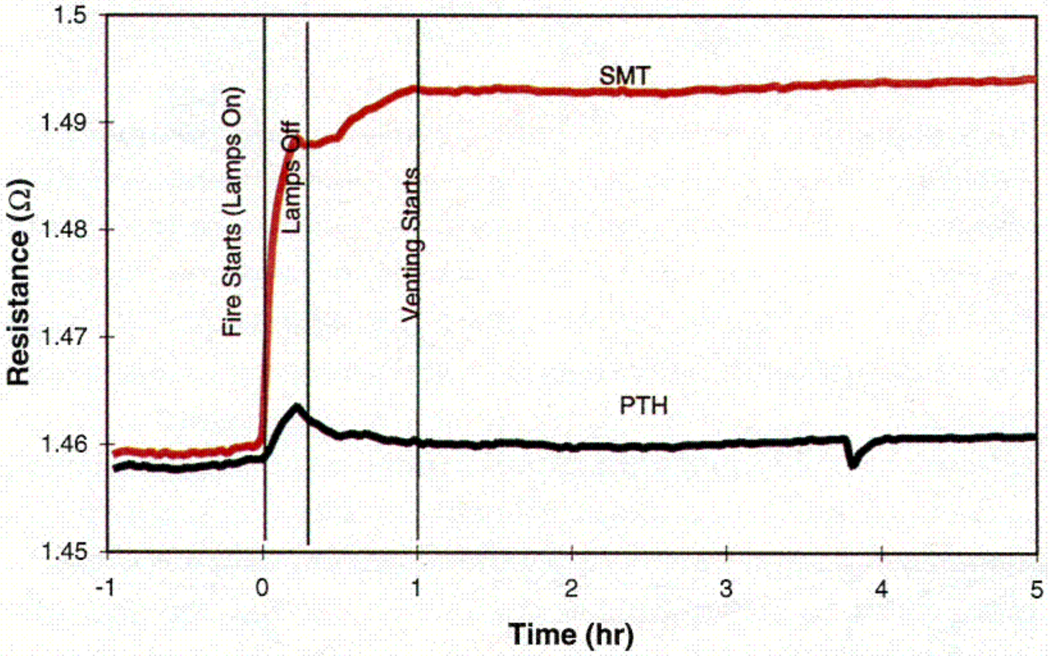


Figure 32. Resistance of the HCLV circuit. The SMT circuit resistance increased when smoke was added, but the PTH remained unchanged.

combustion chamber fell out and as a result the burn took place at a higher oxygen level than before. The reason test 5 was different is unknown. Because all of the HSD circuits were connected to the same 5-V dc power, all of the data from the HSD for the two tests were eliminated because we cannot be sure if the anomaly was a result of the control board causing the short or a coated board. Comparisons between the automatic and manual measurement systems are not valid for this circuit because of differences in cable length.

Two types of changes can be observed in the HSD circuits: catastrophic failure of the HSD circuit where the circuit quits pulsing, and a more subtle increase in the fall times of the circuit. Besides the tests that we eliminated because of power supply problems (which can also be considered catastrophic failures), catastrophic failures occurred in the control PTH circuits. These mostly occurred in the vent period, but were momentary in nature. Table 12 shows the momentary failures that occurred in the remaining 9 bare boards.

Table 12. Momentary Failures (out of 9 boards)

Time Period	PTH	SMT
During fire	0	0
After fire	7	1

C24

Comparisons of the PTH fall times between pretests and post-tests (manual measurements) show that fall times increased from 1.6 ns to 2.2 ns. The SMT control fall times measured at pre- and post-tests were almost unchanged. The SMT seemed to be a more rugged component and not as susceptible to failure. The conformal coatings tended to protect the circuits very well.

The transmission line coupling was measured at three frequencies: 50 MHz, 500 MHz, and 1 GHz. Of these three, the most understandable reaction to smoke is exhibited by the 50-MHz data. When transmission lines are coated, the coupling between them tends to decrease. When smoke is added to uncoated transmission lines, the 50-MHz coupling increases, as shown in Figure 33. This is not the case for the other frequencies; instead, the coupling decreased when the smoke was in the chamber. The coated transmission lines were unaffected by smoke, and the coatings worked very well for the transmission lines

The high-frequency low-pass filter measurements showed a slight effect of the smoke on the control boards, but very little on the coated boards. The high-frequency-filter throughput at 250 MHz drifts down during the smoke exposure on the uncoated boards.

All coatings protected the pads and gull wing areas of the board. Pin grid array (PGA) sockets could not be compared because they were not

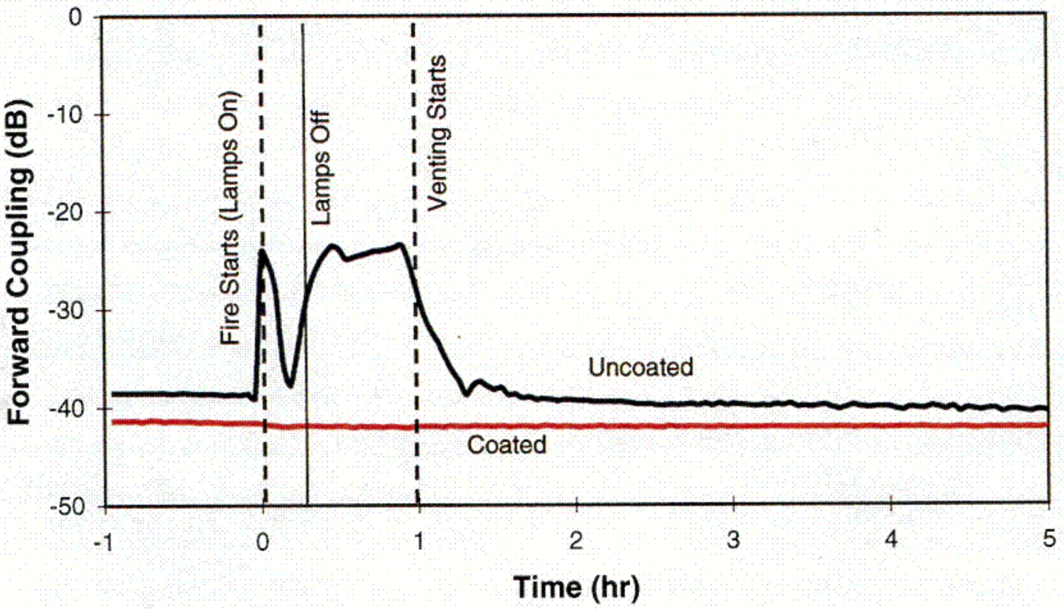


Figure 33. The coupling increased between transmission lines while smoke was in the chamber, but the coated board remained constant at 50 MHz.

C25

uniformly treated with a conformal coating. The parylene coating worked very well. This measurement is similar to that for the HVLC because it is a measurement of leakage current, but since it is performed at a lower voltage, this does not differentiate the good coatings from the bad as well as the HVLC.

Conclusions from coatings tests

Overall the coatings did a very good job of protecting circuits from smoke, especially for failure by increased leakage currents. This was not true, however, for the HVLC circuits. Sometimes the HVLC PTH circuit failed by increasing (open circuit) rather than decreasing (short circuit) resistance, as was expected. For this failure mode, the coating had very little effect. As with earlier functional board tests (Section 2.3.5), HVLC was the most affected. This was the circuit that separated the effects of coatings. The two best coatings were parylene and polyurethane, followed by acrylic, silicone, and epoxy. The epoxy coating did not seem to recover after testing as the others did.

Overall, the coatings protected the boards against decreased resistance; however, for the PTH circuit, some of the coated boards showed increased resistance, just as they had for the uncoated PTH circuits. These coatings included the parylene, acrylic, and silicone coatings. The least benefit was provided by silicone, followed by the epoxy coating.

At pretest, the epoxy-coated SMT circuit had a lower resistance than normal. The epoxy coating could have required a longer cure time, for during the preburn period these circuits returned to normal. During the burn and soak stages, the silicone and epoxy coatings again were the worst coatings, followed by the acrylic coating. After the vent period and after the test, the epoxy was the worst coating.

Because more smoke was added than for the functional board tests, new measurement problems occurred. In particular, the HSD circuit failed on tests 3 and 5. The same power supply was being used for all HSD circuits and when it shorted on one of the boards, it caused all other HSD circuits to fail because the voltage was not high enough to power the HSD chips. It is assumed that the power supply was shorted on one of the uncoated control boards. On test 3 this seems to have caused permanent damage on all of the chips, but it did not damage the coated boards in test 5.

In general, the coating tests at 200 g/m^3 caused significantly more failures of the uncoated functional boards than the earlier functional circuit tests at a maximum of 50 g/m^3. This was especially apparent in the HSD circuits. The HF TL circuit still recovered after the smoke was vented. Thus, the smoke in the air is much more significant than deposits for transmission line coupling.

2.4.2 Digital Throughput

Types of digital connectors tested

The connectors typically used for serial signal transmission, parallel signal transmission, and Ethernet transmission for standard personal computers are the D-subminiature 9-pin (DB-9), the D-subminiature 25-pin (DB-25), and the network modular (RJ-45) connectors, respectively. To test these connectors, signals from a personal computer were routed through connectors placed in the smoke exposure chamber. A printed circuit board was manufactured that would wire three pairs of connectors (a pair of each type) so signals entering from one connector would be transmitted straight through to its pair. All of the connectors were through-hole-soldered connectors. The printed circuit board was placed in the smoke chamber so those through-hole pins were uppermost, exposing the contacts to the most smoke deposition. Figure 34 shows the digital throughput board with the D-subminiature 9 and 25 pin, and the RJ45 connectors.

Test Setup

To test the connectors, appropriate digital signals were transmitted through the connectors in the smoke chamber. For serial communication, a bit-error rate test was performed on a serial communications port on a personal computer. To test parallel communications, an IOMEGA Zip drive was placed at the end of a parallel port connection after the connecting cable was passed through the smoke chamber. Data were written to and read from the Zip drive, located outside of the smoke chamber. To test Ethernet communications, the network communications between two computers were monitored as data was transmitted between computers.

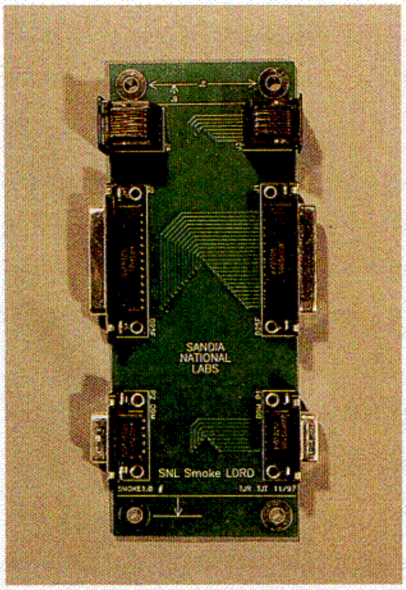


Figure 34. Throughput boards tested digital transmission.

Results of digital throughput tests

A total of 19 tests were made on the digital throughput connectors. The fuel used for the tests varied, PVC, Douglas fir, and jet fuel were burned through the various tests. The fuels were varied because other smoke measurements were tried during these tests including optical extinction coefficient and conductance between vertical parallel plates with a DC bias. These tests were the first conducted after we assembled a new computer and acquisition system, so some of the recording problems could be attributed to the problems of the acquisition system. The throughput boards were unaffected by smoke. A simple test with a variable resistor indicated that the resistance between leads had to drop below 200 ohms before any of the throughput signals would be interrupted.

The surface insulation measurements (with 5 V dc bias) have been inconsistent as have the 5Vdc biased parallel plate. These voltages may be too low to attract soot. The AC biased plates have shown some changes in admittance at frequencies above 3 MHz.

Conclusions of digital throughput tests

Although the digital connectors were exposed to some of the highest levels of smoke in our series of tests, none of the digital connectors failed. An evaluation of the likelihood of failure using a variable resistor in place of smoke showed that the conductance through the smoke must be very high, about 10^{-2} S, before the typical connector fails with this application. This level of conductance is approximately the same value as the admittance of typical cables. For example, a typical coaxial cable has impedance of 50 Ω. The admittance of such a cable is 1/50 Ω or 2×10^{-2}. Since most of our measurements of smoke conductance indicate that a typical value with a high level of smoke is about 10^{-6} S, the smoke levels would not be expected to cause failure of the digital connectors.

2.4.3 Memory Chips (SRAM, EPROM and Non Volatile)

Digital systems contain many different components, but a common component is the memory chip. These chips store both programs and data. Memory chips are often based on CMOS technology because CMOS technology draws little power and has high noise immunity. CMOS has also been shown to be more vulnerable to smoke than other technologies because it has a low output current drive. When digital circuits are exposed to smoke, the current is divided between the intended circuit and alternative circuit paths created by the smoke. Because the current is split, the chip switches more slowly or may not switch at all. The lower the current drive, the more slowly the chip switching will take place.

CMOS memory chips were tested in two separate series. First, Static Random Access Memory (SRAM) and Erasable Programmable Read Only Memory (EPROM) were tested in a smoke environment. At a later date the non-volatile SRAM was tested. Different smoke concentrations were used to determine a tentative failure threshold and failure mode. The previous tests had shown that digital equipment could fail when the smoke concentration is high, and then recover as the concentration drops. Therefore, it was important to detect failures during a fire, rather than after the smoke has settled or vented as we had for the 16 K memory chips during the component packaging tests. This information could be used to help estimate the failure threshold of digital systems because memory chips are assumed to be one of the most vulnerable components in a digital system.

Types of memory chips tested

Memory chips have evolved by increasing the amount of data they can store while decreasing in physical size and power requirements. Three standard memory chips in use today are the static random-access memory (SRAM), the dynamic random-access memory (DRAM), and the erasable programmable read-only memory (EPROM). SRAMs can store data as long as power is supplied. If the power is removed the data is lost. To supply power continuously, the non-volatile SRAM contains a lithium battery so that data can be stored for 9-10 years without an outside power supply. DRAMs (commonly used as random access memory—RAM--in personal computers) also require a power supply to store data, but their data must also be refreshed at regular intervals. DRAMs are slower than SRAMs, but also less expensive. EPROM's, another form of non-volatile memory can store data even though the power supply is removed. However, they can only store and be read with the power on. Some EPROM's can only be written to one time, but others may be reprogrammed after exposure to UV light. The advantage of EPROM's is that they can be used to store the start up program for a microprocessor so that it could be restarted after it is powered down.

There were many choices of memory chips to test, but decisions were made by determining what kinds of chips are being used in designs of advanced safety systems and what kinds and capacity of chips could be tested with the equipment on hand. Korsah[3] suggested that certain EPROM's and SRAM's would be common in advanced safety systems such as AP600 (Westinghouse), the ABWR (General Electric), and the System 80+ (Combustion Engineering) systems. Project mangers at the NRC who found that these chips were likely to be installed in digital safety systems suggested the non-volatile SRAM.

The number of pins in a random access memory chip is determined by the amount of memory addresses and how many bits of data are stored per address. For example, if 8 bits of data are stored per address, 8 pins are required to either input or output the data. Each bit of data is either a logical 1 or 0. Pins identified as DQ serve as both the input and output data connections. Two to the power of the number of address input pins (A) determines the number of memory addresses. Hence, for a 128K X 8-bit memory chip (one megabyte), the number of memory addresses is 17 $(2^{17} = 131{,}072 = 128 \times 1024)$. In addition to these pins to select an address and input and output data, each memory chip needs an input power supply pin (V_{cc} or V_{dd}), a ground pin ($\overline{V_{ss}}$), chip enable ($\overline{E}$), write enable ($\overline{W}$), and output enable ($\overline{G}$).

The chip must also have power on the supply pin (V_{cc} or V_{dd}) and be grounded through V_{ss} to operate. If the power or ground is disconnected, the data will be lost. To read data from a particular address, the correct voltage is placed on the address pins (A_0, A_1, …A_n), the chip enable pin ($\overline{E}$) is set to a low state (because of the overbar sign, enabling this pin is done by setting the logical value to 0), the output enable pin ($\overline{G}$) is set to a low state, and the data is read off of the DQ pins. To write data to a particular address, the correct voltages are placed on the address pins, $\overline{E}$ is set to a low state, $\overline{W}$ is set to a low state, and data, in the form of various voltage levels, are applied to the DQ pins.

In the first series of memory chip tests, two-one Mbit SRAM's (128K X 8 bit) were tested, the MCM6226BB and the MCM6926A, both manufactured by Motorola. The MCM6226BB operates on 5V while the MC6926A operates on 3.3V. These two standard voltages are typical of SRAM's, but more equipment is now being designed to use the lower 3.3V because there is less power used and the temperatures of the equipment can be lower. These two chips had similar packages, surface-mounted plastic-bodied with J-shaped leads common known as SOJ packages. Each package had 32 pins, in the case of the MCM6226BB chip, two pins had no connection and two pins are connected to chip enable, $\overline{E_1}$ and E_2. The MCM6926A chip has two pins connected to V_{ss} and V_{dd}.

The Advanced Micro Devices EPROM, AM27C256, was tested also in the first series of tests. This chip comes in 28-pin dual-in-line (DIP) and 32-pin plastic-leadless chip carrier (PLCC) packages. This chip is a 256 kb memory chip (32,768 x 8 bit), thus it contains 15 address, 8 data, 1 output enable, 1 chip enable, 1 voltage supply, 1 ground, and 1 program voltage input pins. The AM27C256 came in two different packages, the 28-pin dual-in-line (DIP) package, and the 23-pin plastic-leadless chip carrier (PLCC). Both packages were tested. The EPROM chips were programmed prior to installation on a printed circuit board. The SRAM and EPROM chips are shown in Figure 35.

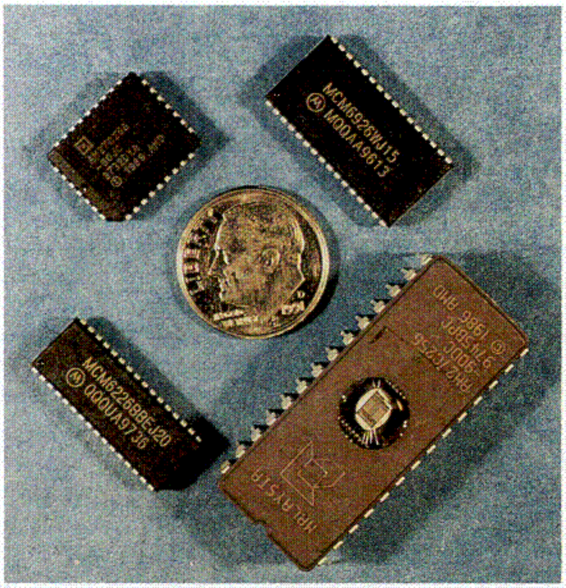


Figure 35. SRAM and EPROM memory chips were tested.

The SRAM's and programmed EPROM's were individually mounted on printed circuit boards as shown in Figure 36. The chips were soldered on the board rather than mounted in a socket so that the circuit board would be similar to a board in a computer. The printed circuit board traces connected the pins on the memory chips to a connector for testing. The printed circuit board was designed to accept all of the memory chips, although they used four different chip packages. Because of the general features of the board, when one memory chip was mounted, other solder pads were unoccupied. Potentially, the unoccupied solder pads could short. To reduce shorting of the unoccupied solder pads, they were coated with a polyurethane conformal coating that had been tested earlier in the program and shown to be very protective.

In the second series of memory chip tests, a Dallas Semiconductor 8 Mbit non-volatile memory chip was tested, DS1265Y. This chip was packaged in a 36-pin DIP package with a minimum 10-year lithium battery to supply power to store data. Similar to the SRAM's tested in the first series, these chips have 8 data input/output pins, 20 address pins, one chip enable, one write enable, one output enable, power and ground. The normal operating bias is 5 V. These chips were not preprogrammed and were mounted on a separate printed circuit board than the ones designed for the first series of tests.

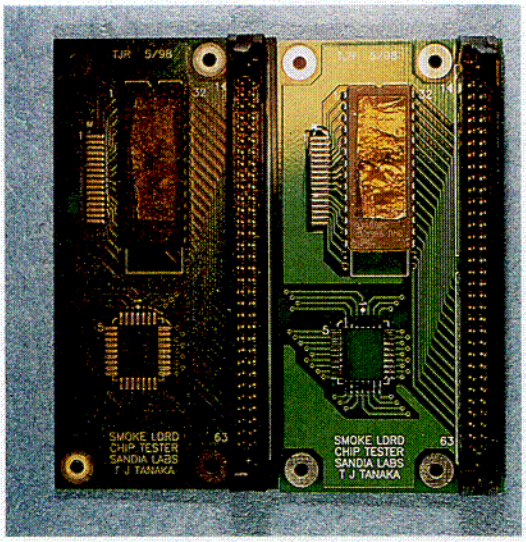


Figure 36. The EPROM on the left was exposed to smoke; the EPROM on the right has not been exposed to smoke.

Test setup

In the first series of tests two types of tests were performed on the chips in the smoke chamber: "functional and timing tests" and "parametric measurements." The functional and timing tests measure if the chip can record and output data from all cells in the memory chip without errors and indicate how long the chip takes to make data available. Parametric measurements test to see if certain parameters change as the chip is exposed to smoke. The parametric measurements include a standby current measurement (current drawn by the supply voltage pin), a current leakage measurement (a standard voltage is applied to the pin and the current measured), and current injection test (a standard current is injected and the voltage level measured). Two chips were exposed to the smoke at a time, and all of the chip tests were repeated at 30-s intervals.

The HP 82000 chip tester was programmed to measure the performance, access time, and voltage and current specifications. For the SRAM, a pattern of 1 and 0 states was written into all the addresses and then read out to determine functionality. For the EPROM, the pattern was only read, as the pattern was programmed in prior to testing. The parameters of

C28

Table 13. Parameters measured for first memory chip test series.

Parameter Symbol	Parameter Description
V_{OH}	Output HIGH Voltage
V_{OL}	Output LOW Voltage
I_{LI}	Input Load Current
I_{LO}	Output Leakage Current
I_{CC1}	V_{CC} Active Current
t_{CE}	Chip Enable to Output Delay

the memory chips were then tested. Typical parameters are listed in Table 13. The chip tester can test up to 64 connections at one time. Each test exposed two EPROM or two SRAM chips. The functionality test frequency depends on the load time for the chip tester and is approximately 30 seconds to test two chips. Each test was performed for 2 hours; for the first hour the chips would be immersed in smoke, and the next hour the smoke was vented. To test for the worst case, the boards were mounted with the solder pads up as in Figure 37.

For the tests of the non-volatile SRAM, a logic analyzer was used to write data to the memory chip. The data was then read from the memory chip to determine if the smoke would cause any errors. The power was then turned off for 1 second and the data was read again to determine if the battery back up was working properly.

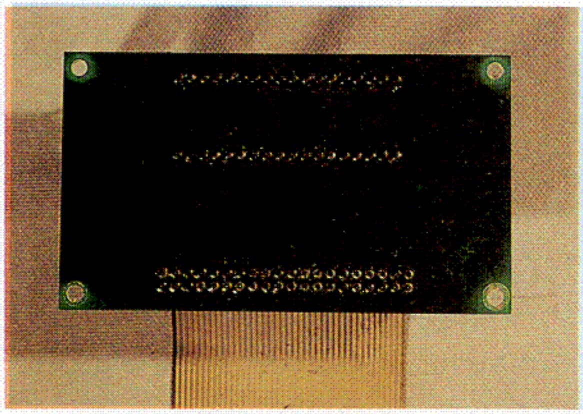


Figure 37. This memory chip board is darkened by smoke.

A mixture of cable material was burned at 50 kW/m^2 to create different levels of smoke density. The staring humidity level was 75% RH, but the heat of the fire and the addition of N_2 to purge the laser optical measurement system decreased the RH during the test. The RH was restored to 75% upon venting.

Results of memory chip tests

The smoke caused the memory chips to fail functionally. As shown in Figure 38, the 3.3V SRAM chip failed each of the four times it was tested with more than 10 g of fuel burned, but did not fail for when less fuel was burned. The 5 V SRAM failed half of the time when more than 10 g of fuel was burned, but not for less fuel. The EPROM's failed once each at low fuel levels, but did not fail for higher levels. All of the chips were tested outside of the smoke chamber several weeks after the smoke exposure, and

C29

they all performed well. The failure of the memory chips was a temporary failure that occurred during or immediately after exposure to smoke.

Failures occurred at different times during the tests depending on the type of chip. A majority of the failures occurred after the smoke was vented. When the smoke is vented, the test samples have a coating of soot on them, but no more is being deposited, the environment is held at 75 °F and at 75% RH, and air is circulated inside of the smoke chamber. Measurements taken in the second series of memory chip tests indicated that RH drops significantly during the test while the lamps are on and nitrogen is used to purge the laser optics. As the failure seems to occur during those times that both smoke is high and the humidity is high, we believe that both conditions must occur to cause failures in the 3.3V SRAM chips.

The failures for lower smoke levels for the EPROM's are suspect data. The failure of the PLCC EPROM only occurred 2 times out of the 800 or more functional tests performed during that test. The DIP EPROM failed more regularly, however, the first failures occurred before the smoke was added to the chamber, so the test setup may have been flawed to begin with. After this test where the DIP EPROM failed even before the smoke was added (the second test), new cables were used to connect each new set of chips to be tested. This eliminated the possibility of the cable

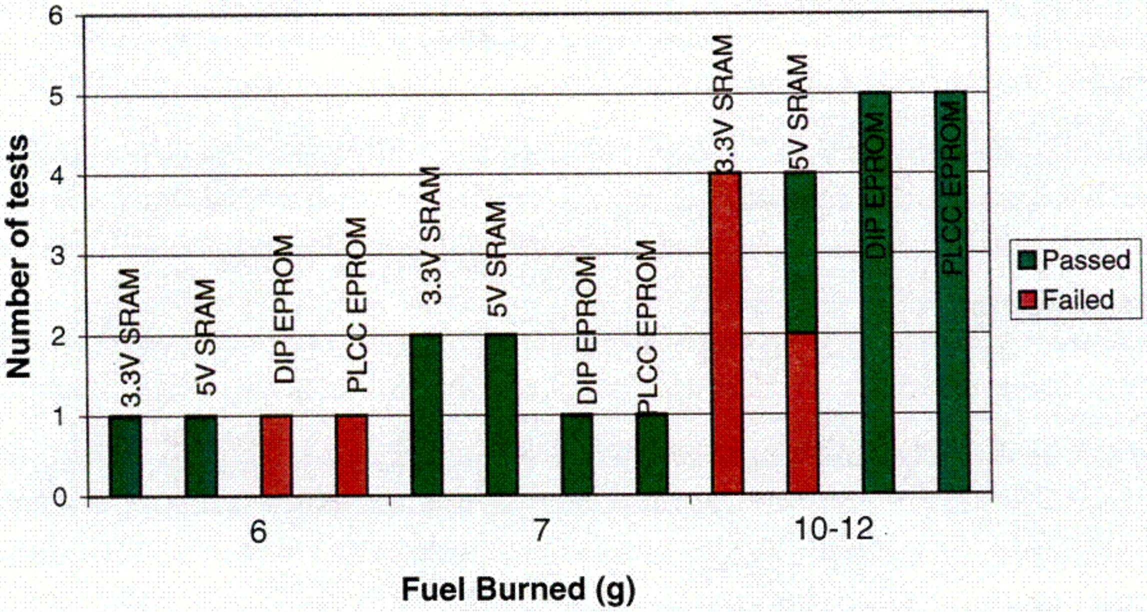


Figure 38. The 3.3V SRAM failed when 10 or more grams of fuel were burned.

C30

from a previous test influencing the outcome of the next test.

The parametric measurements did vary during the test, depending on how much smoke was introduced. As expected, leakage currents increased during the fire and were observed during the current leakage measurement. However, changes in leakage current did not correlate with most of the failures. Instead, the current on the supply pin varied drastically during chip failure. When the 3.3 V SRAM chips failed they tended to increase in current. The normal operating current was approximately 4 to 6 mA, but when these chips failed their supply current increased to greater than 10 mA. When the 5 V SRAM chips failed, their operating currents dropped to half of their normal value. As the EPROM's failed only once each, no trend has been assigned to when they failed.

The non-volatile SRAM's did not fail even though they were exposed to smoke created by 30 g of cable mixture in the 200 L small smoke chamber (150 g/m^3).

Conclusions from the memory chip tests

Low voltage (3.3 V) SRAM's were found to be the most vulnerable to smoke. Higher bias voltages decrease the likelihood of failure as was predicted by the chip technology tests. EPROM's and non-volatile SRAM's were very smoke tolerant. Failures of the SRAM's occurred when two conditions were present, high densities of smoke and high humidity. As the high humidity was present for only part of the test, the failures were intermittent; all of the chips that failed during the test recovered after enough venting. This behavior can account for the failures of the digital systems where there was also intermittent failure (Section 2.3.1).

2.4.4 Hard Disks

Purpose of hard disk tests and selection criteria

Hard disks are standard equipment in most personal computers, providing long-term storage of the majority of data on a computer. In normal operation the hard disk is accessed frequently, often several times a minute. When hard disks fail, the entire computer can halt, waiting for the hard disk to be accessed correctly. Thus, unimpaired hard disk performance is essential to computer performance.

Hard disks consist of a stack of magnetically coated disks mounted on a spindle. Each side of the disks is accessed by its own read-write head, which floats on an air stream above the swiftly rotating disk. The hard disk is operated at atmospheric pressure and it is the presence of air that allows for correct operation. Typical distances between the head and disk are only 0.0003 mm.[26] If dirt or smoke were to deposit on the disk, the heads could be easily fouled and the data could be destroyed. The air inside of the hard disk drive is heavily filtered to prevent destruction by dust particles, and the disk is sealed (typically with adhesive tape) so that outside air does not easily penetrate. Smoke exposure has the potential to disrupt the operation of the hard disk and thereby a computer system.

For a personal computer in 1999, there are two common types of hard drives, those that operate off of *enhanced intelligent drive electronics* (EIDE) buses, and those that operate on *small computer systems interface* (SCSI) buses. Since the EIDE bus is more prevalent at this time, this type of disk was selected for testing. A series of smoke exposures were performed on standard EIDE, 8.4 Gbyte hard drives,* a typical size for computers at the time of testing. Hard disk drives are rapidly increasing in capacity, however their physical design has not changed significantly.

Hard disk test setup

Five hard drives were exposed to different smoke conditions to determine if they would be susceptible to failure. Because only the hard drive was to be tested, not the computer, only the hard drive was placed inside of the smoke chamber. The computer was enclosed in a plastic bag outside of the smoke chamber to reduce the likelihood that smoke that leaked from the smoke chamber could cause any failures of the computer. The hard drive is shown in the smoke exposure chamber in Figure 39, and a close-up of the drive is shown in Figure 40. In later tests the hard drive was placed upside down from the standard orientation because more electronic circuitry would be exposed to the smoke in this orientation. The hard drive was connected with the computer by an 18" (45 cm) data cable and a power cable extension. The data cable was limited to this length because of specifications by the hard drive manufacturer.

The monitoring scheme was a simple read and write test. A string of text was stored on the hard drive and then recalled from the hard drive. The string that was read back from the drive was compared to the original string. The result of the comparison, a pass or failure to recall the same string as was written, was recorded. Preliminary experiments showed that if some of the data or power supply lines that were connected to the hard drive were shorted, the computer on which the hard drive was mounted would stop operating. If the computer that was recording the failures was directly connected to the smoke-exposed hard drive, smoke could have shorted some of the data or power lines and stopped the computer. In that case, hard drive failures could have prevented failures from being recorded. Thus, a second computer, located outside of the environmental chamber, but connected by an Ethernet network, both monitored and recorded failures, and transmitted data to write on the smoke-exposed hard drive. Data was written to and read from the hard drive over the network. The data read from the hard drive was compared to the data written to the hard drive to determine if the smoke caused any failures.

---

* Western Digital Caviar 28400 drive

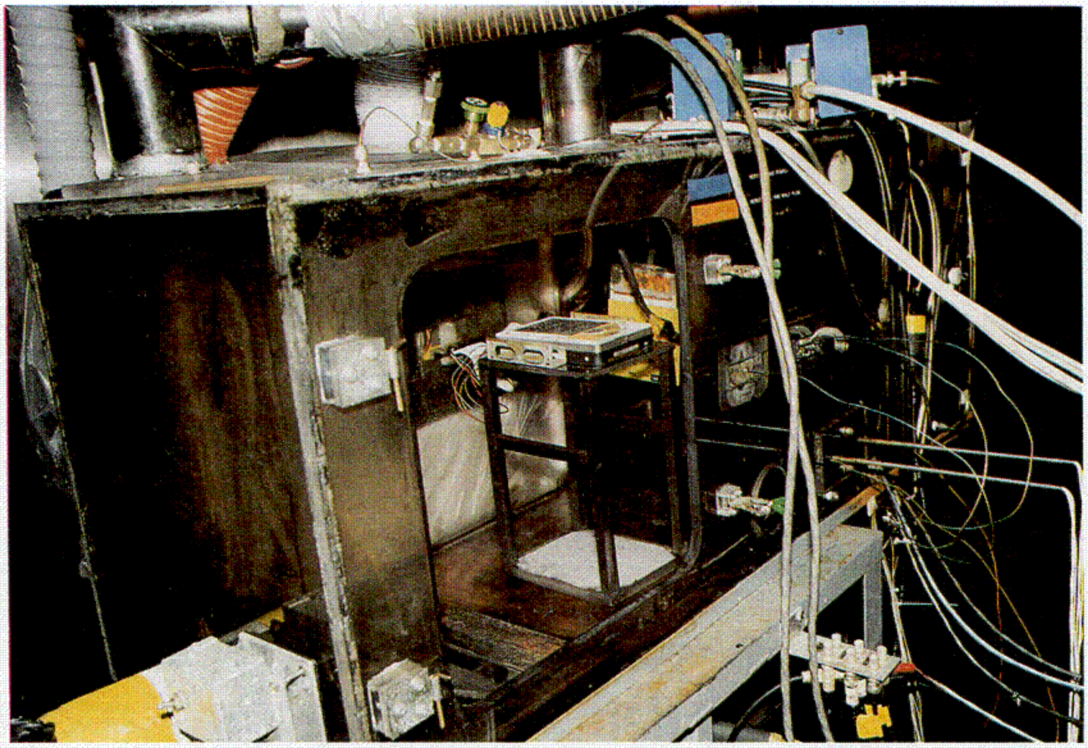


Figure 39. Hard drive test tested only the hard drive.

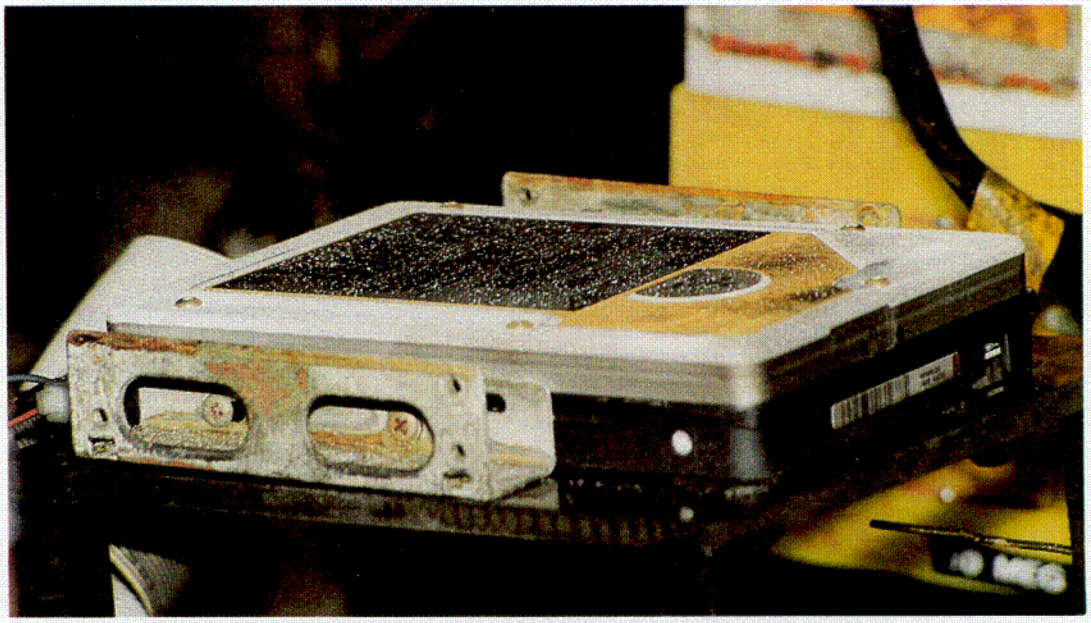


Figure 40. Hard disk drives showed some corrosion after testing.

Table 14. Hard disk test conditions.

Hard disk	Test Orientation	Fuel level to start	Nitrogen Purge
1	Upright/Upside down	15 g + 15 g (two exposures)	Yes
2	Upside down	15 g	Yes
3	Upside down	30 g	Yes
4	Upside down	30	No
5	Upside down	15	No

Six tests were performed with the hard drives. In the first test, the hard drive was placed in the standard configuration, aluminum side up, and 15 g of mixed cable fuel was burned at 50 kW/m^2 of heat flux. Since no failure occurred, the same disk was placed upside down from the standard so that the printed circuit surface of the disk was upward. This disk was then exposed smoke from 15 g more of mixed cable burned at 50 kW/m^2 of heat flux. Thereafter, each disk was exposed to either 15 or 30 g of fuel and with 50 kW/m^2 of heat flux as shown in Table 14.

The humidity before and after the test was maintained at 75% ± 5%. As mentioned in the section on the laser data, nitrogen was added to the smoke chamber during the smoke exposure to prevent smoke from clouding the transmission measurement optics. The added nitrogen as well as the increased temperature of the smoke chamber combined to reduce the relative humidity of the smoke chamber. To check the effect with the most severe smoke case possible, for some of the tests the laser system was turned off and no nitrogen was added to the smoke chamber. This resulted in higher humidity levels during the smoke exposure.

The hard disk was monitored with the read and write test for 2 hours, which included 1 hour of smoke exposure and another hour while the smoke was vented and humidity was restored to the chamber. After the smoke exposures the hard disks were scanned for errors using a commercial product, Scantest. Scantest checks hard disks for corrupted data sites and reports the results. Because the hard drives were large compared to the operating system of the computer it was attached to, Scantest took up to 6 hours to complete. This test was typically performed immediately after the smoke test or on the next day.

Results of hard disk tests

Results of the smoke monitoring test and Scantest are shown in Table 15. No hard disks failed during or within 2 hours of the smoke exposure. Only one hard disk failed by showing errors during Scantest.

Figure 41 shows four of the hard drives after smoke testing in the orientation that they were tested.

Figure 42 shows the inside of one of the tested drives. No detectable smoke was found inside of the drive.

Table 15. Hard disk results

Hard Disk	Fuel Burned	Active test result	Scan test result
1	22.2 g	Passed	Passed
2	18.4 g	Passed	Some errors
3	18.2 g	Passed	Passed
4	18.7	Passed	Passed
5	10.7	Passed	Passed

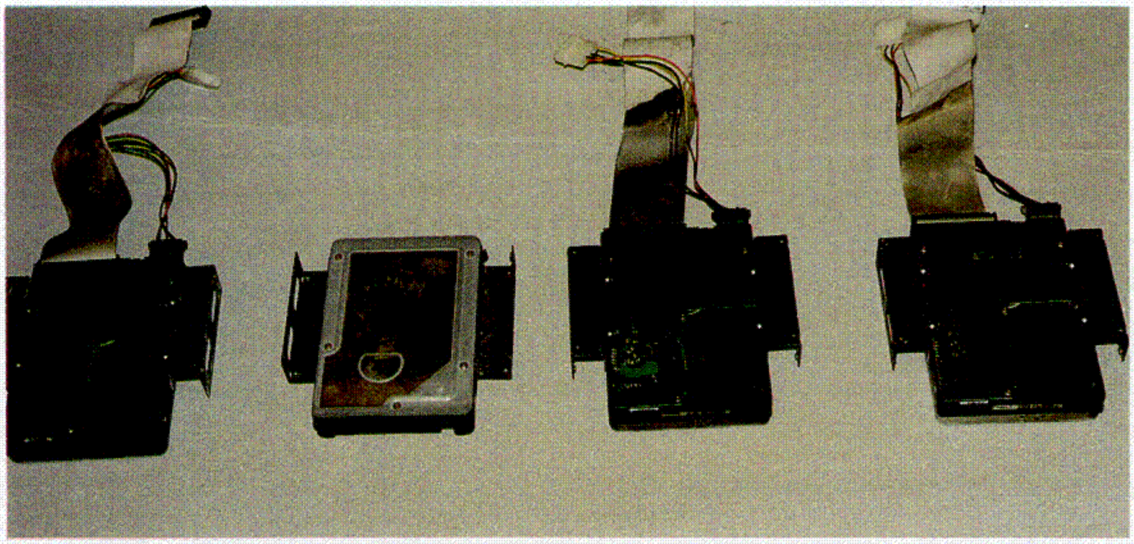


Figure 41. These disk drives did not fail during the smoke test.

C32

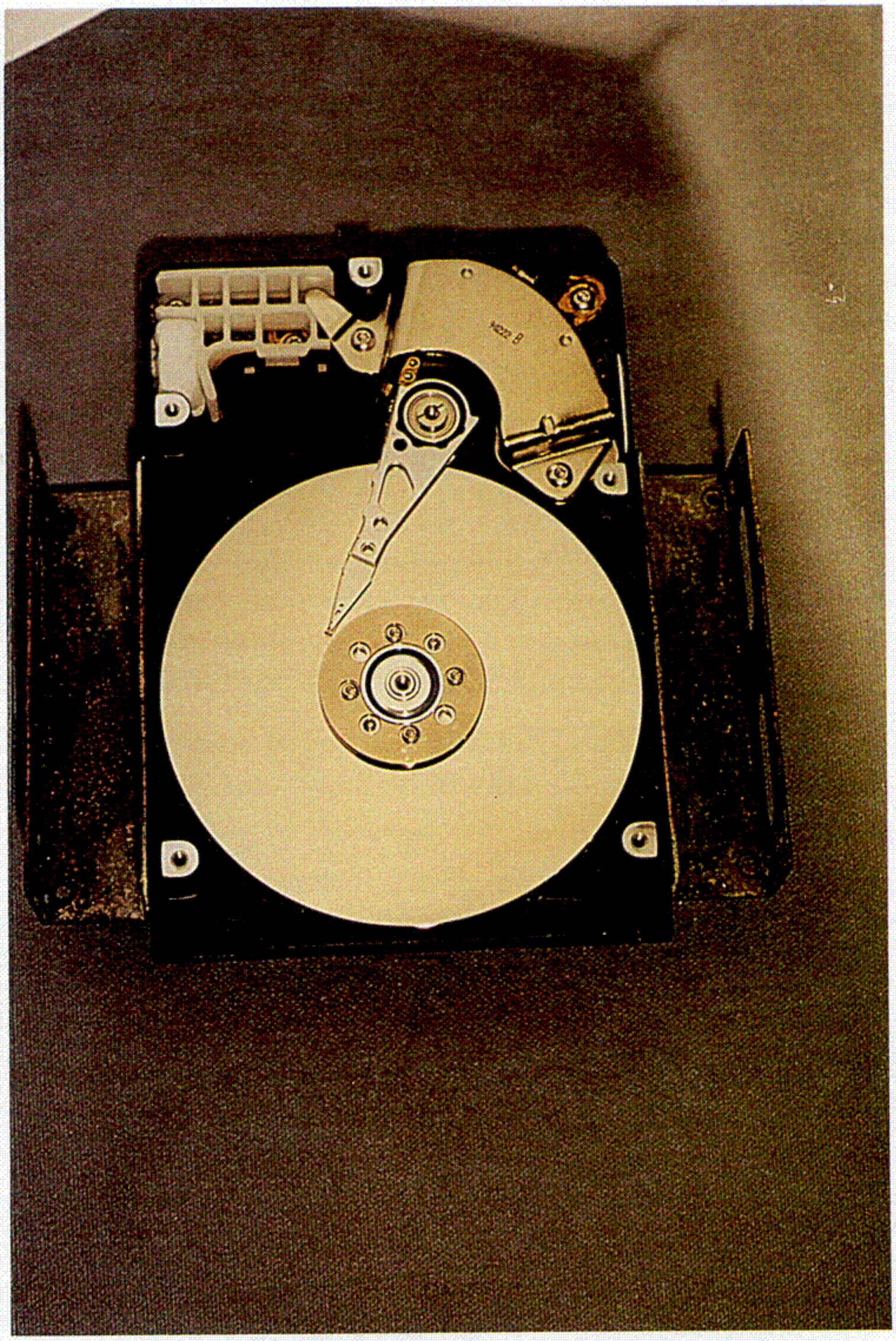


Figure 42. The inside of the disk drives remained clean.

Conclusions of hard disk tests

The hard disks were very smoke tolerant. The two failure modes predicted for hard disks, particulate contamination and electrical shorting, did not cause any failures of the hard drives. Although disk 2 did show some bad sectors after the smoke test as revealed by Scantest, these bad sectors did not cause any problems during the smoke exposure. If a fire were to occur near a computer, commercial hard drives that are typically installed in personal computers could be expected to survive the smoke exposure at least for a day after the fire and data could be downloaded from the disks. No tests were performed on these drives beyond one day after the smoke exposure, so long term use of smoke-exposed hard drives may not be advised.

2.4.5 Electrical Measurements

Parallel plates and interdigitated combs were included in the smoke tests to provide a simple geometry whose electrical field can be approximated and whose leakage currents can be measured. Items with simple geometry, such as these, can be more easily modeled to calculate field strengths that can be generalized for use with more complicated electrical equipment. The parallel plates model freestanding conductors, while the interdigitated combs model traces on surfaces of printed circuit boards.

Parallel plates DC and HF

Two types of leakage currents have been measured: the leakage between two freestanding vertical parallel plates and the leakage between interdigitated comb patterns printed on a circuit board. The parallel plate conductivity was measured to determine if the smoke in the air was causing the increased conduction. The plates were spaced 2.5 mm apart and were made of perforated stainless steel. The perforations allowed more transport of smoke between the plates, (Figure 43). Four pairs of plates were placed in the smoke chamber at a time, and each was biased with a different voltage, 500 Vdc, 50 Vdc, 5 Vdc, and 1 Vac. The plates biased with dc voltages were connected electrically in series with a resistive circuit that allowed for measurement of leakage currents across the plates. The ac-biased plates were connected to a network analyzer, which measured the admittance of the plates for a range of high frequencies between 0.5 and 30 MHz.

Parallel plates AC

AC voltage was applied to the same parallel plates as for the DC measurements. The steel plates spacing was adjust to distances between 3 and 25 mm apart for the tests. The plates were mounted near the top of the smoke chamber. 4.2 kV (RMS) was applied to the plates. Arcing was measured with a Pearson current probe on the high voltage conductor and the voltage measured

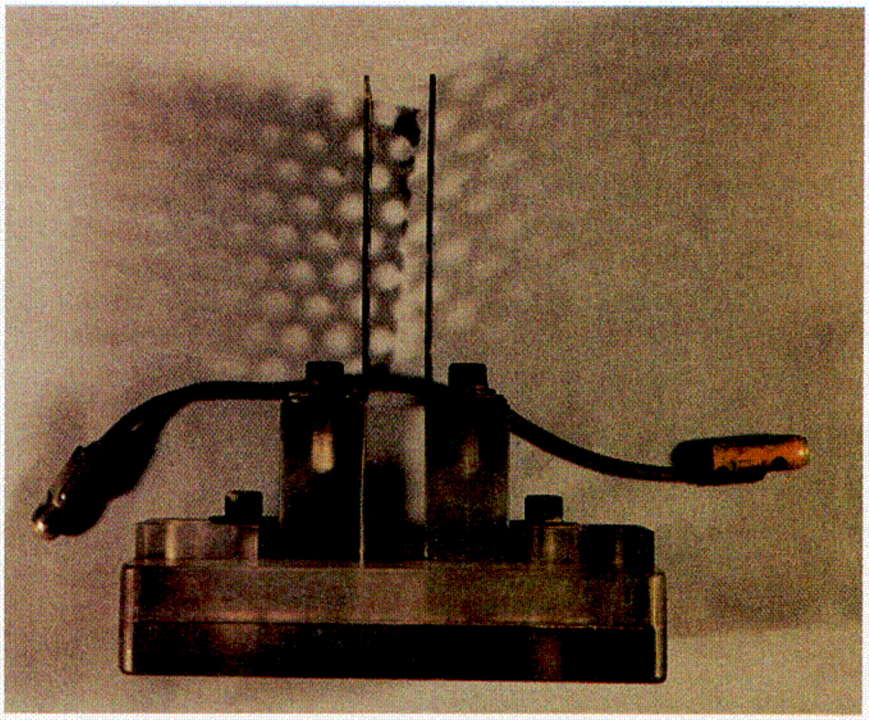


Figure 43. Perforated parallel plates were used to measure the effect of smoke between vertical plates with DC and AC bias voltages.

with a two-channel oscilloscope. Both the current and voltage waveforms were recorded when the plates arced. Some preliminary measurements of shorting voltage vs. humidity in the chamber showed little variation due to humidity.

Ideal parallel plates are infinite in extent and perfectly flat. For ideal parallel plates, the field between the plates should decrease linearly with increasing separation. In our tests, plate separation was a significant factor in likelihood of arcing, although the variation was not linear. To study this, the voltage was raised slowly until the plates began to arc, then another separation distance was selected and the voltage raised again. When the plates began to arc, the arcing tended to be continuous. The ac power supply could supply up to 40 ma of current on a continuous basis, but if required to provide more, the voltage would drop. The arc current was high enough to lower the potential across the plates. Nevertheless, the arcing continued once a path was established because the hot, ionized air provided an easier path for arcing than normal.

Results of the parallel plate experiments

A surprising result was that the conductivity between parallel plates remained high although the optical extinction coefficient in the smoke chamber dropped drastically, indicating that there was very little smoke in the air. This result is plotted in Figure 44 for a 500 Vdc-biased pair of plates. A video recording of the plates in the smoke chamber shows

C34

the mechanism by which this occurs. Four frames from this recording are shown in Figure 45 to 48. The smoke is attracted to high-voltage surfaces and builds up fragile bridges between the parallel plates. These carbonaceous bridges conduct current much like carbon resistors. If the air is forcefully vented from the smoke exposure chamber, the carbon bridges are destroyed and the conductivity falls. While smoke is in the air, air movement destroys some of the bridges, but more smoke is then attracted to the bridge formation. After the optical extinction coefficient drops, however, there is no more smoke to replace the bridges and the conductivity slowly falls.

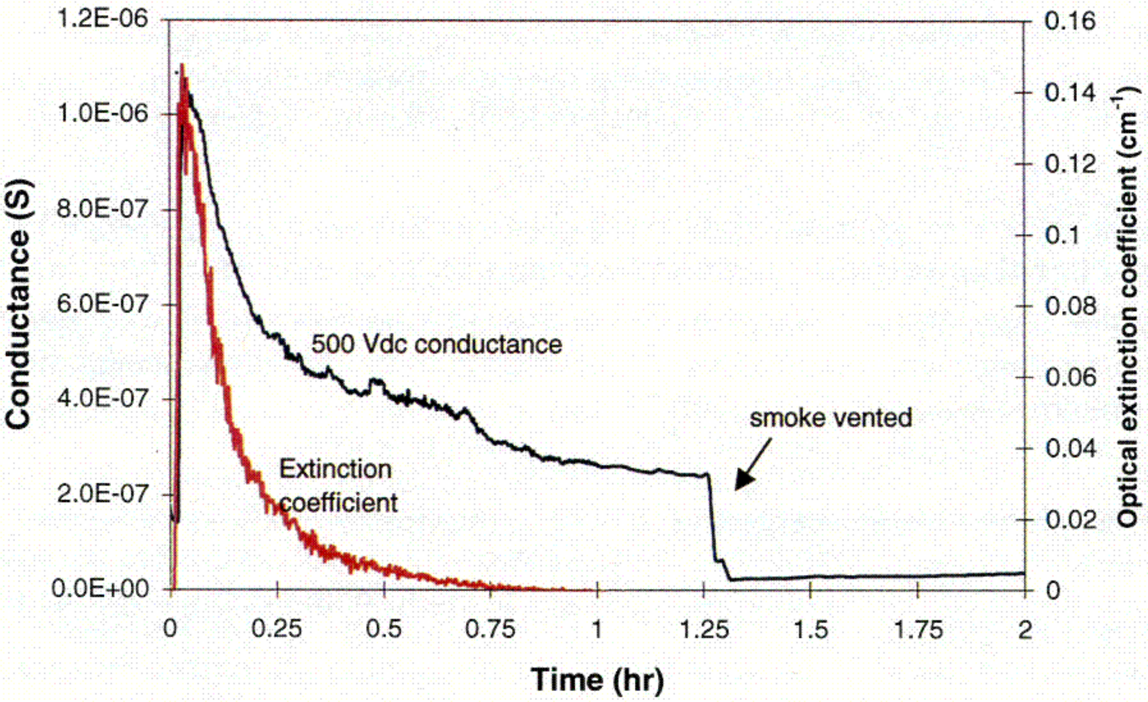


Figure 44. The optical extinction coefficient decreased after the fire more quickly than the 500 DC V conductance.

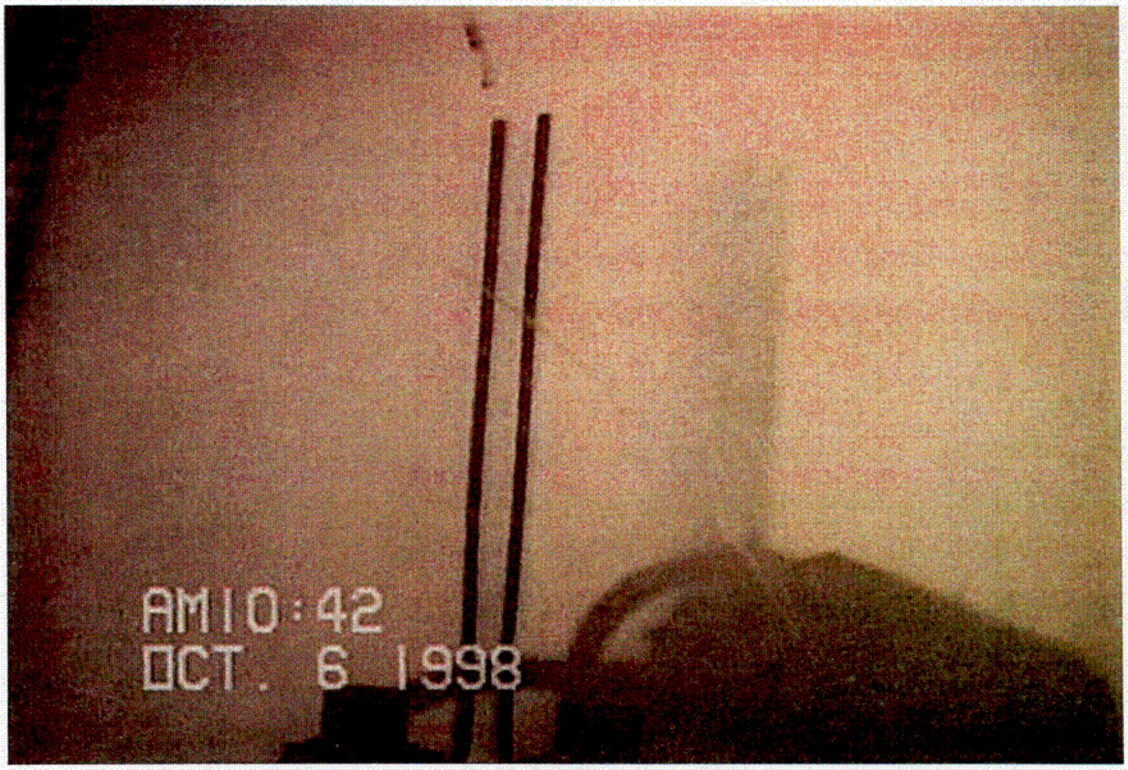


Figure 45. 500 DC V parallel plates at beginning of test are clean.

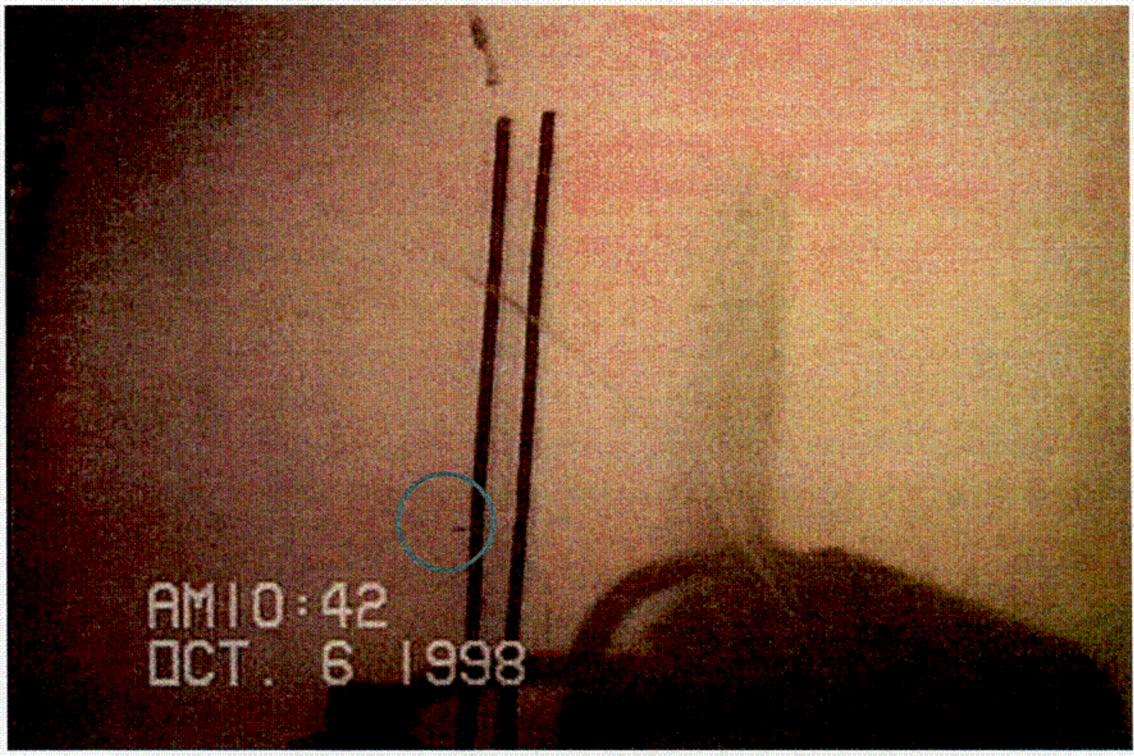


Figure 46. After a short time, the parallel plate starts to collect smoke, notice the encircled whisker of smoke.

C36

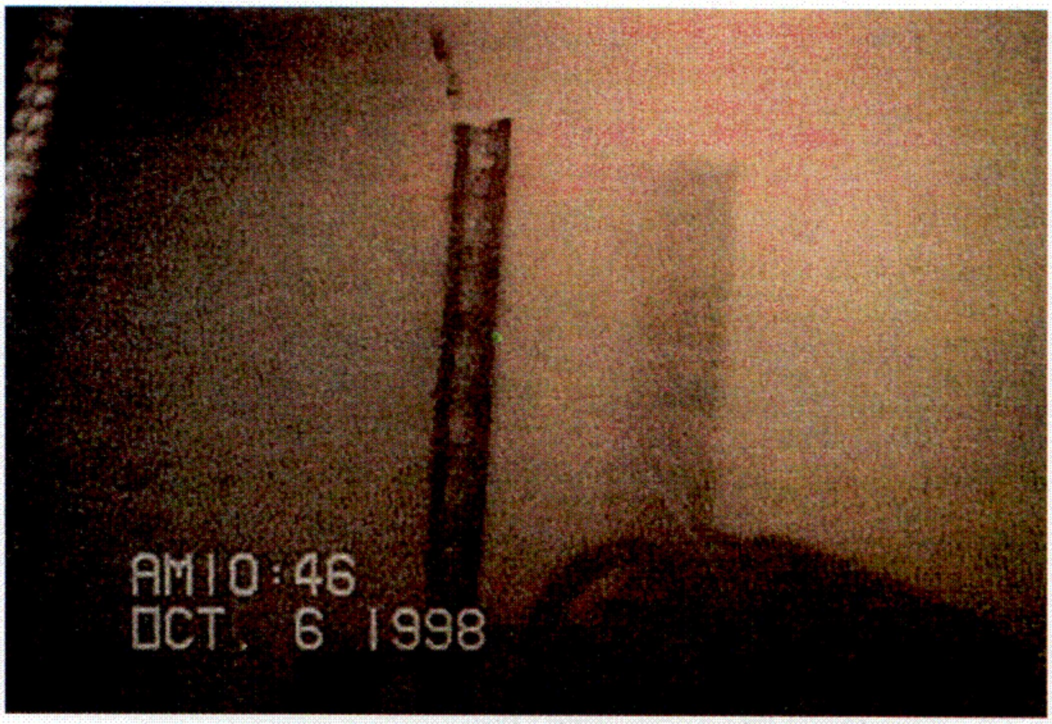


Figure 47. 4 minutes into the smoke test, a substantial amount of smoke has gathered on the parallel plates.

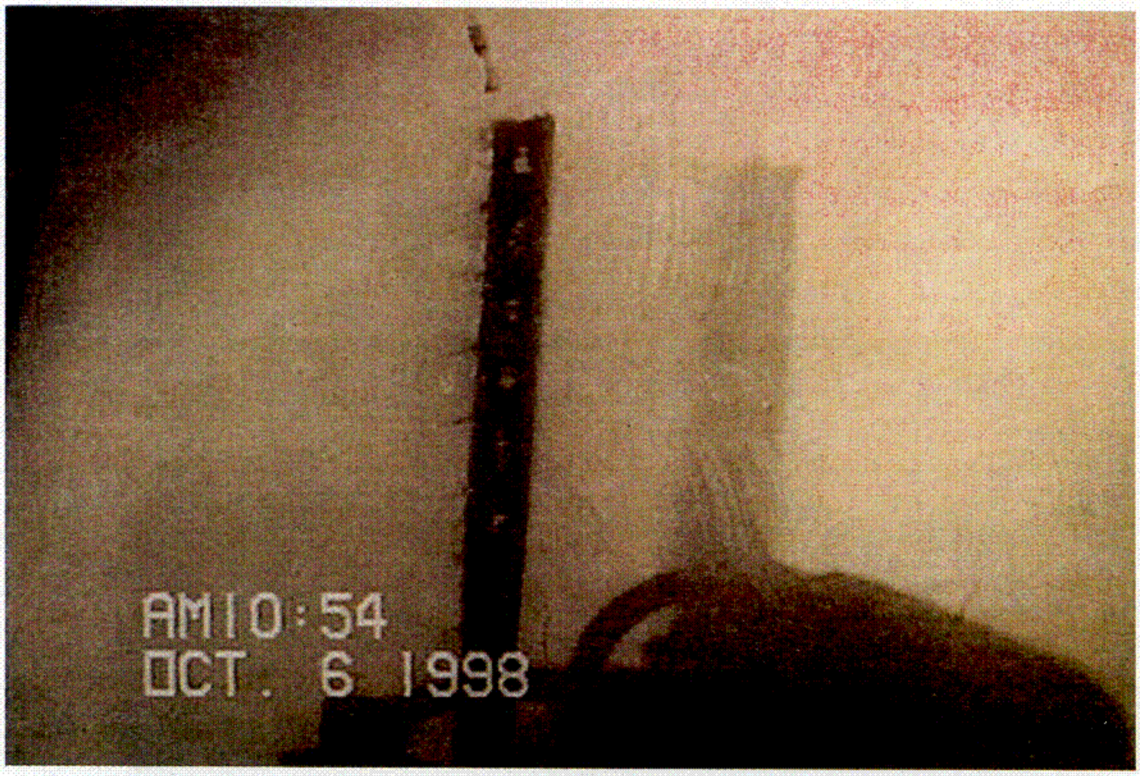


Figure 48. After 12 minutes, a thick bridge of smoke shorts the parallel plates together.

A lot of soot collects on these plates. They tend to act like electro-static precipitators and attract soot particles. The soot is probably not evenly distributed in the smoke chamber, because high potentials will attract so much of the soot. Further discussion of these phenomena appears later in the section on the mass vs. conductivity boards. In this case, smoke to the right of the pair of plates is subject to one polarization of the electric field and the smoke to the left of the plates to the opposite field. The field strength is large in the general area and smoke is attracted to the plates. More soot should be attracted to the parallel plates when the voltage is high.

The conductivity on the 500 Vdc-biased plates was no higher than that on the 50 Vdc-biased plates at the peak of the smoke output Figure 49); however, the 500 Vdc bridges were more robust. Higher voltages have more force to maintain the bridges, but since the plates were the same size, the peak conductivity is similar because a maximum volume of soot could be attached to each plate. The 5 Vdc-biased plates showed little increase of conductivity and probably did not have a strong enough field to attract soot and bridge the plates.

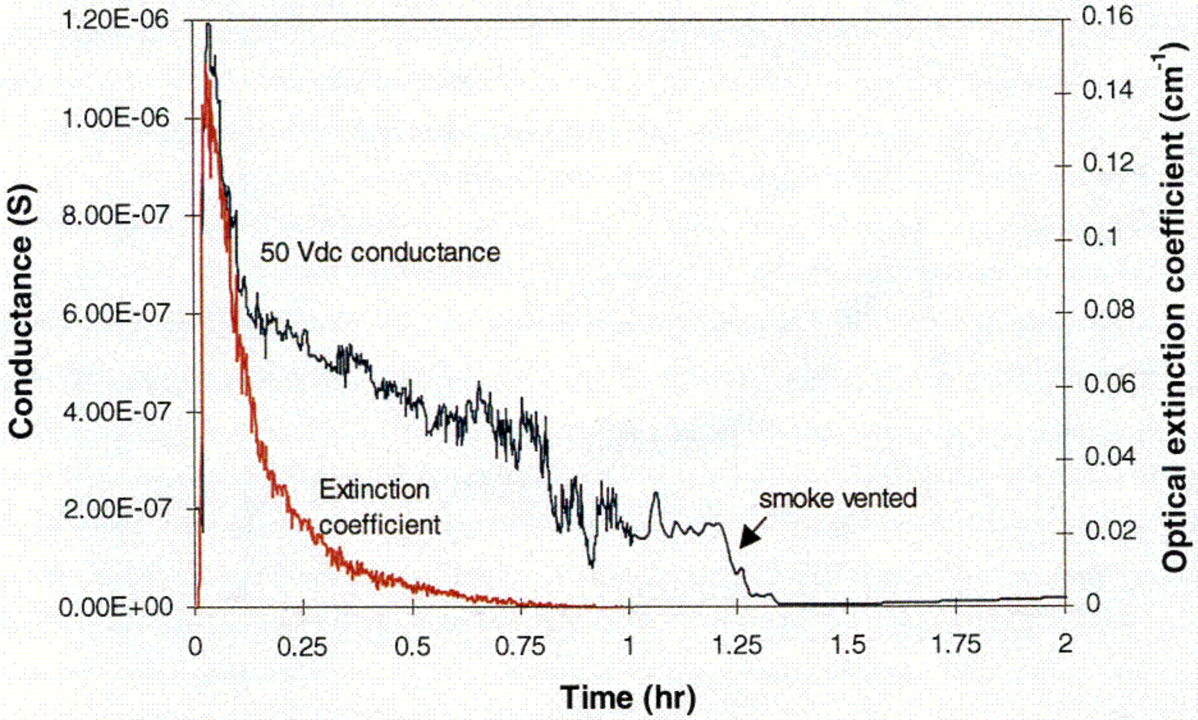


Figure 49. The conductance between the 50 DC V parallel plates also falls slower than the optical extinction coefficient.

C38

The high frequency measurements yielded a change in admittance as the smoke was added. At high frequencies the changes were larger than for low frequencies. Figure 50 shows the change in admittance as smoke was added for 30 MHz. The parallel plates were set 2.5 mm apart. Smoke particles are semiconductive so the response of the circuit to smoke should be similar to the introduction of dielectric material between the parallel plates.

For a parallel plate capacitor, the capacitance is expressed as $C = \varepsilon A/d$ where A is the area of the plates, d is the distance between plates, and ε is the dielectric constant. The resistance between two parallel plates is $R = d/\sigma A$, where σ is the conductivity of the air. These two formulas contain the geometric factor, A/d. Since the parallel plates used in our experiments are perforated, the electric field lines will not yield the standard values of capacitance and resistance. However, we can assume that the field lines will be equivalent for the two formulations and hence, a geometric factor, g can be considered to be the same for both, i.e., $C = \varepsilon g$ and $R = 1/\sigma g$.

The geometric factor can be determined when there is no smoke in the air. In that case, $\varepsilon = \varepsilon_0$ or the electrical permittivity of air, 8.85×10^{-12} F/m. Thus, for a given capacitance measured in the air, C, can be determined. If the parallel plate can be modeled as a capacitor and resistor in parallel, the current from such a circuit would be: $I = V/R + C\dot{V}$, where V is voltage and I is current. If we

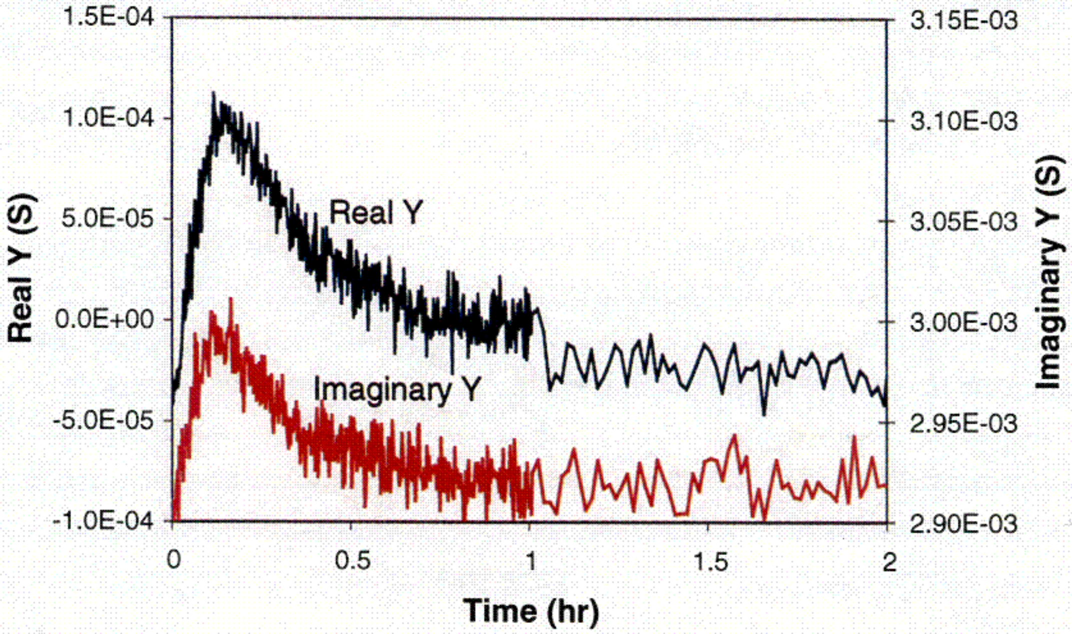


Figure 50. Both the real and imaginary parts of admittance at 30MHz are affected by smoke.

C39

assume that $V = V_0 e^{j\omega t}$, a sine wave, then $I = V/R + Cj\omega V$. Since the admittance, $Y = I/V$, then $\mathrm{Re}(Y) \equiv G = 1/R = g\sigma$ and $\mathrm{Im}(Y) \equiv B = C\omega = \varepsilon g\omega$.

Surface insulation resistance (SIR)

Interdigitated comb patterns were placed in the chamber either faces up and parallel to the ground or horizontal and perpendicular with the ground. The comb patterns, shown in Figure 22 were connected to a resistive circuit similar to the dc parallel plate circuits, biased with 5 Vdc, and leakage currents were monitored in these circuits. These patterns (IPC-B-24 boards), developed by the Institute for Interconnecting and Packaging Electronic Circuits, measure surface insulation resistance and are used by the IPC to monitor the accuracy of the printed circuit manufacturing process.[27] Better processing should yield higher SIR values. Smoke and other contaminants decrease SIR values. Humidity can influence contaminated boards.

Mass vs. conductivity measurements

An interdigitated pattern was designed for use as a surface to collect smoke for weighing and comparison to conductivity. The pattern has solder traces separated by 0.1" (0.25cm). The pattern is illustrated in Figure 51. Printed circuit boards with these traces were biased with 5, 50 and 500 VDC and leakage currents were measured as they were exposed in smoke. The substrate for these printed circuit boards were very thin so that the weight of the boards were below 1 g, but each printed circuit board had 30 cm^2 of surface area. The printed circuit boards were weighted before and after each smoke exposure to determine how much smoke would cause a given amount of shorting. All boards were placed in a horizontal position to get the maximum collection of soot possible. A board in its holder is shown in Figure 52.

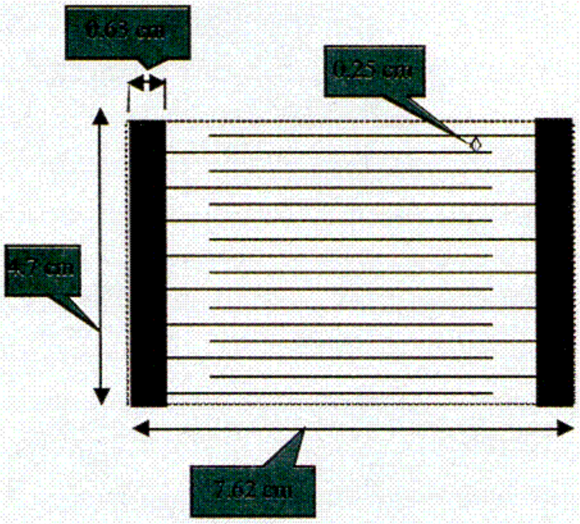


Figure 51. The mass vs. conductivity board was designed with an interdigitated comb pattern.

The pattern of smoke deposition on the mass vs. conductivity boards depended on the applied bias voltage. As shown in Figure 53, 500 V and 50 V biased boards collected soot around the conductors, while the 5 V biased board had a more even distribution. On the 500-V biased board, the area between conductors had little smoke deposition. Likewise, the 50 V biased board had a smaller area of little deposition. The higher the bias voltage, the more uneven the smoke deposition. The higher-biased patterns had stronger electric field strengths and the stronger the electric field, the more force on the smoke particles to flow toward the conductors. Hence, the higher-biased patterns had a more uneven deposition.

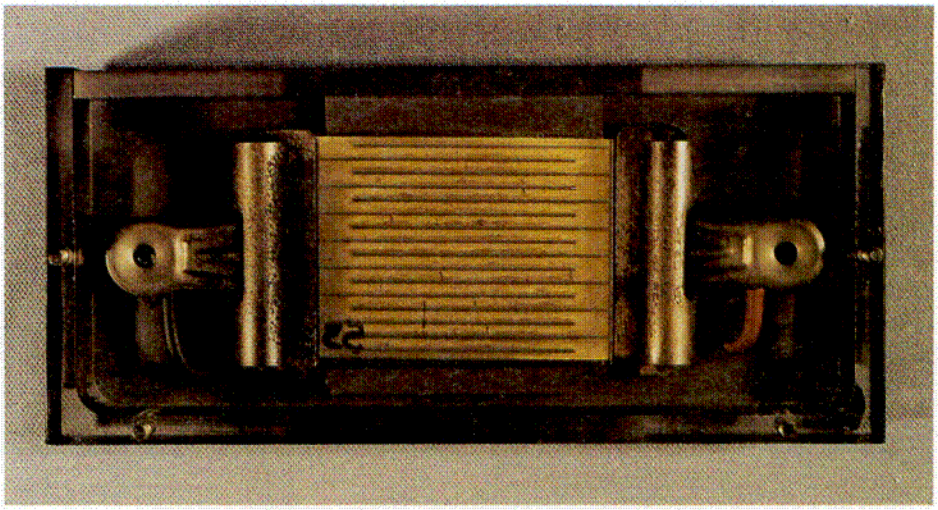


Figure 52. The mass vs. conductivity board was placed in a holder to provide bias and protect the board from air currents after smoke collection.

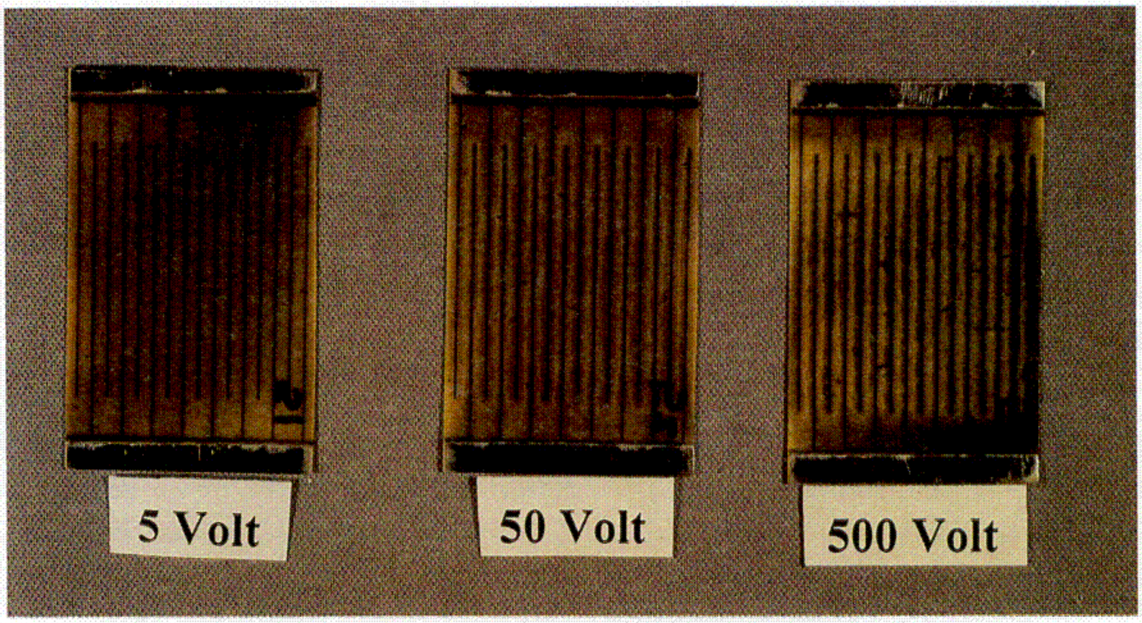


Figure 53. Smoke distribution on the mass vs. conductivity boards is more even on the 5 DC V biased board.

C41

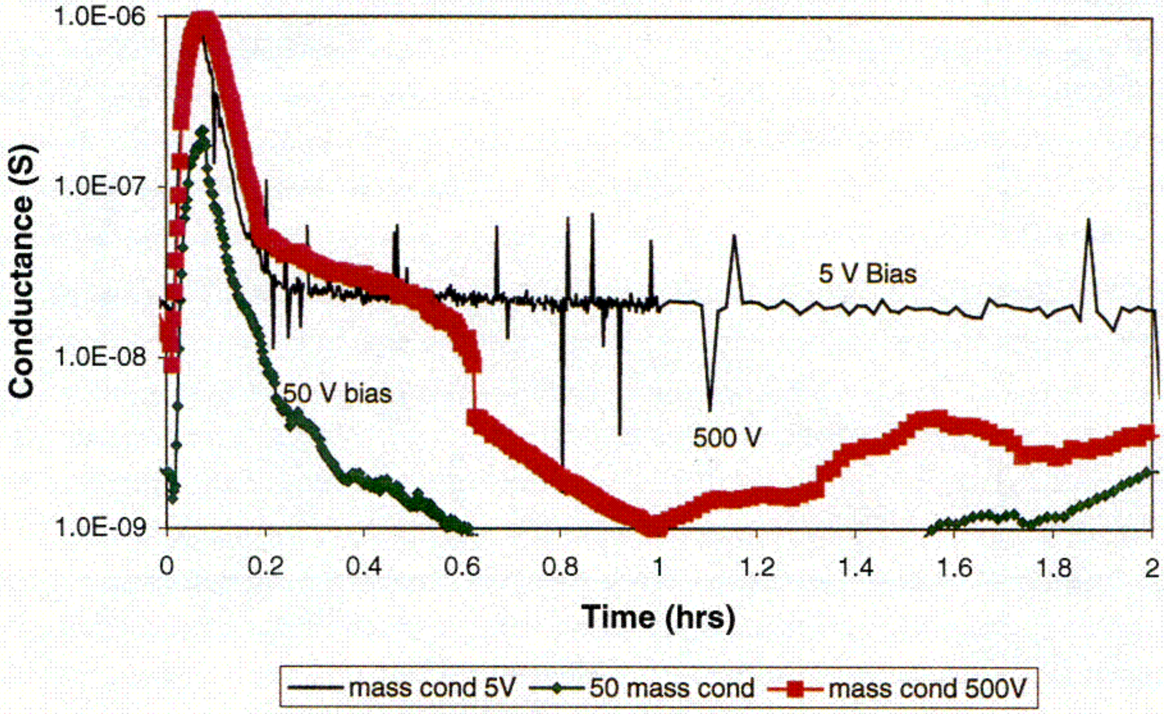


Figure 54. The conductance remains higher on the 5 V biased board that has a more even distribution of smoke.

The conductivity between traces varied throughout the smoke test as shown in Figure 54. The conductivity is highest when smoke is in the air, 3-4 minutes after the test starts. After most of the smoke has settled or vented, the conductivity drops the more for the 500 and 50-V biased boards than the 5-V biased board. The higher conductivity of the 5-V biased board after 1 hour (the smoke was vented from the smoke chamber by then) could be attributed to the more even distribution of smoke on that board.

Figure 55 compares the mass of deposition between boards for different amounts of fuel burned and at different bias voltages. The mass of smoke deposited does not vary significantly with the bias voltage. Although higher electric fields are present near the surface of the boards when the bias voltage is higher, far away from the boards, the effect of the stronger electric field is cancelled because there are an even number of traces on the circuit board. However, the smoke mass collected on the board varies with the amount of fuel burned. When more smoke is in the air, more smoke is deposited.

The mass of soot collected on the mass vs. conductivity boards related well to the amount of fuel burned, but not to the conductivity measured near the end of the smoke exposure. This may be attributed to dependence of conductivity on the relative humidity.

C42

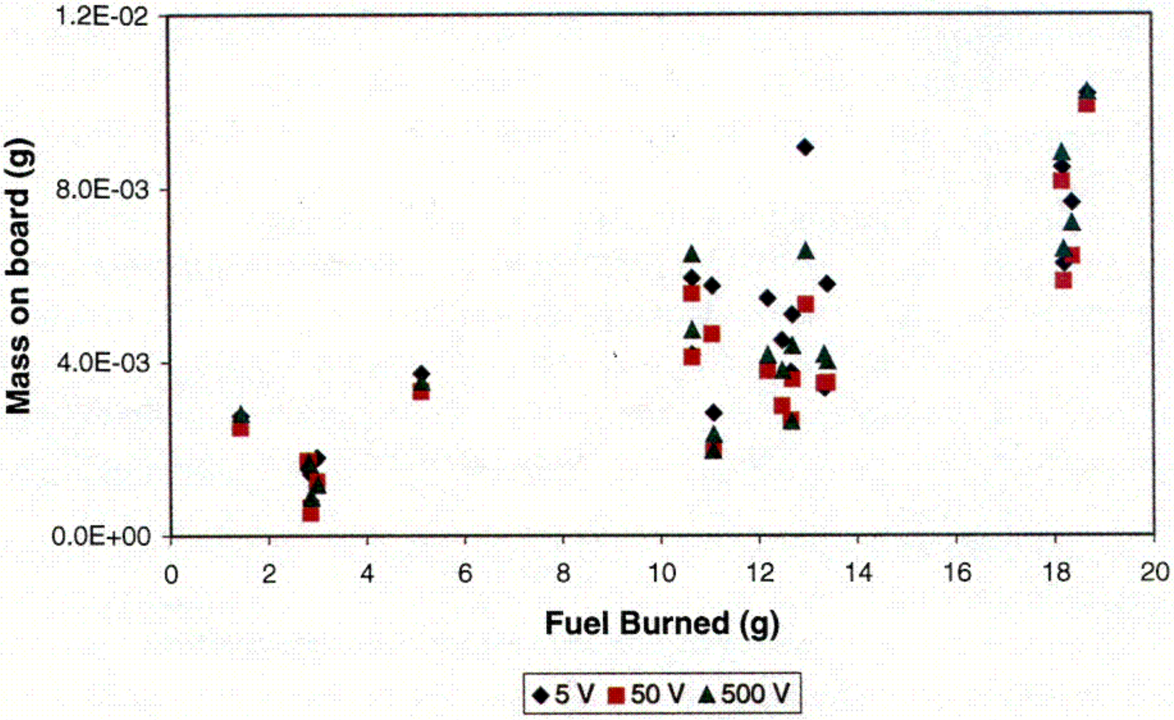


Figure 55. Smoke collected by conductivity board was roughly proportional to the amount of fuel burned and not very dependent on the DC voltage applied.

C43

3 FIRE PROTECTION AND THE MITIGATION OF SMOKE DAMAGE

3.1 Overview

There are a number of potential features of current fire protection practice that can be used or implemented to lend some additional protection against smoke damage. These include both direct features of physical fire protection, such as Appendix R (to 10CFR40) requirements, as well as predictive tools that can aid in assessing the level of smoke hazard associated with a particular installation and potential mitigation strategies. It is these measures that are the topic of this section.

3.2 Physical Fire Protection Features

3.2.1 The Classical Fire Protection Strategy

One of the most effective means of preventing or minimizing smoke damage is to minimize the potential for and magnitude of the smoke production. In general fire protection practice, this can be accomplished through the classical approach to fire protection; the implementation of effective programs and features to minimize the occurrence of fires, and to quickly detect and suppress those fires that will inevitably occur. The design of digital equipment should not neglect such concerns. While many of the fire protection features in this regard will be predetermined, the digital equipment design process may provide the opportunity to review and potentially enhance critical features of fire prevention, detection, and suppression practices.

For example, implementation of enhanced rapid-response smoke detection systems may provide a significant benefit. Testing has demonstrated that smoke detectors located inside an electrical panel can detect the very early stages of an incipient electrical fire much more quickly and effectively than can general area smoke detectors that respond only after the fire has reached a stage of significant smoke production. The implementation of such features to address specific potential fire threats could greatly reduce the likelihood that significant smoke production might occur. Similarly, implementation of enhanced fire suppression systems to address the most likely fire threats in an area would also minimize the potential for smoke damage.

3.2.2 Current USNRC Fire Safety Regulations and the Smoke Damage Issue

The primary source for current USNRC fire safety regulations is Appendix R to 10CFR50. While not all licensees are directly liable for compliance with the Appendix R requirements, all have implemented a fire protection program and the vast majority of these programs derive in large part from the Appendix R requirements. Hence, Appendix R will be used to represent the current "template" for fire safety regulation.

There are aspects of Appendix R that will clearly impact the design and routing of digital instrumentation and control systems. For example, provisions for a fire protection program (Section II.A in Appendix R), fire prevention (Section II.C), fire fighting (Sections III.A-F and III.H-I), administrative controls (Section III.K), and barrier qualifications (Sections III.M and II.N) will clearly reduce the fire hazard for digital systems just as they reduce the fire hazard for analog systems. However, it should also be recognized that Appendix R was not written with the explicit intent to address smoke damage. Rather, Appendix R was written with the view that fire damage was primarily a thermal problem.

The focus of Appendix R is to ensure that at least one hot shutdown path is protected from the effects of any given fire (see Sections I and III.G.1.a). Where this cannot be achieved, such as in the main control room, an alternate shutdown capability is to be provided (see Sections II.D, III.G.3 and III.L). (Separate and less restrictive requirements are set forth for cold shutdown equipment in Section I and III.G.1.b.)

Three acceptable means to protect one hot shutdown path are set forth in Section III.G.2; namely, (a) separation by 3-hour rated fire barriers, (b) separation by 20-feet of horizontal space free of combustibles with automatic suppression and detection, or (c) separation by 1-hour rated fire barriers with automatic suppression and detection. Any other measure found by the USNRC staff to provide an equivalent level of protection may also be accepted by exemption [10CFR 50.48 (c)(6)]. Presumably, digital systems will be subject to these same requirements.

The potential for direct thermal damage to digital components must be considered, and the separation criteria of Appendix R will provide some level of protection for the digital components in this regard. However, Appendix R will not ensure that smoke vulnerable components will not be threatened by the same fire, in particular, in cases where spatial separation has been relied upon to meet the Appendix R requirements. Note that the focus of the Appendix R requirement is placed on physical separation. The acceptable separation criteria noted above are not specifically intended to address smoke damage. Specifically, 20-feet of spatial separation has little or no significance with respect to smoke. While separation by a rated 3-hour or 1-hour barrier will provide some substantial barrier to smoke exposure, fire barriers are not specifically designed or tested for their ability to contain smoke. Rather, fire barriers are designed to prevent the spread of fire itself. Fire doors opened to allow access for fire fighting and open hatchways will allow for the spread of smoke to adjacent areas. Smoke may also be spread through ventilation systems to various plant areas. Overall, smoke can easily traverse substantial distances.

In other regards, Appendix R will clearly impact the digital system design. The requirement to maintain one hot shutdown path free of fire damage will still remain as a design criteria. As a result, some level of redundancy will need to be maintained in the digital design. For example, it would clearly be inappropriate to multiplex all of the redundant train signals for any given critical instrument reading onto a single transmission/communications link. Rather, some redundancy will be needed to ensure that loss of a single communications link would not compromise critical instrument readings. This will likely require component level redundancy and spatial separation of those redundant components. At least two sets of communications cables will be needed, and these cables would need to be protected from failure in a single fire. Similarly, at least two processing/transmission systems that are adequately separated may also be needed. The power sources for these systems will also need to maintain redundancy and separation. Finally, for areas like the control room where adequate separation cannot be maintained, provisions for alternate shutdown will also be needed.

3.2.3 Choice of Suppression Agents

The choice of suppression agents could strongly influence the magnitude of smoke damage. In particular, the SNL tests and practical experience have shown that higher moisture levels contribute to significant increases in the level of smoke damage. Based on SNL tests, this appears to include both short-term and long-term damage. Hence, whenever possible the use of nonwater-based fire suppressants, such as carbon dioxide, would be preferred in areas containing digital components. Halon or a Halon replacement product may also be a possibility. However, the choice of such products should consider that Halon and some of the replacement products would produce corrosive decomposition products, especially including halogen acids such as HBr, in the presence of a heating source such as an open or smoldering fire.

Note that this concern is not the same concern that digital components might be directly sprayed with water during a fire. While this may also be a concern, in the context of the smoke damage issue, the simple airborne moisture level (relative humidity) is a significant factor. The mere presence of high humidity levels (on the order of 60% RH or more) is sufficient to sharply increase the damage potential. The lower the humidity levels, the lower the damage potential. Hence, avoiding the introduction of excessive moisture is a desirable strategy to minimize smoke damage.

In many situations, it may not be possible to make significant changes to the existing fire suppression capabilities. In others, a switch to a gaseous fire suppression agent may be impractical or inappropriate for a particular fire area or fire threat. It must also be anticipated that firefighters may eventually fall back on water hose streams as the ultimate suppression agent in almost any area of the plant. Putting out the fire will remain the number one concern.

However, to the extent possible, the digital design should consider what suppression agents would be used in the fire area housing the digital components. For example, replacing water-based hand-held fire extinguishers with gaseous extinguishers in the area may be appropriate and desirable. Alternatively, if the designer is faced with a choice of which area a digital component is to be located in, an area protected by a gaseous suppression system might prove more favorable than one protected by a sprinkler or deluge system.

3.2.4 Avoidance of Known Hazards and Vulnerabilities

In implementing digital system upgrades, it is likely that the designer will have some latitude in determining where a specific component is to be placed within the plant. While this latitude may be limited by other design and equipment placement constraints, smoke damage should be considered. The likelihood and potential severity of the fire threats in the area should be considered. It may well be possible to locate components to minimize the potential that fire will occur and threaten the equipment, and to increase the likelihood that those fires that do occur will be less severe.

For example, putting digital components in a diesel generator bay or electrical switchgear room may be undesirable owing to the comparably high incidence of fire in such areas. Similarly, locating such components on upper-level decks overlooking a turbine hall may be poor practice because of the numerous potential fire sources in the area and the relatively high frequency of fires in such a large space. Such large open areas hold the potential for widespread and unchecked smoke dispersal under comparatively severe fire conditions.

In making the placement decision, the designer must also balance the considerations of the external fire threats to the new components against the internal fire threat represented by the new components themselves. There is a limited database on fire incidents, and while the data are sparse, experience suggests that printed circuit boards can represent a significant fire threat in terms of both the initiation and the spread of fires. Thus, it is also appropriate for the designer to include the consideration of how these new components might alter the fire risk perspective in critical plant areas. For example, placing such components in a cable spreading room might be a highly desirable option from the standpoint of accessibility and convenience, but may introduce a potential fire threat into this fire area that was not previously considered. The designer should be careful to ensure that a critical set of cables or equipment is not subjected to a new fire threat as a result of the digital upgrade process. Clearly, the use of low-flammability materials, including the connecting cables, conformal coatings, and to the extent possible, the digital components, will also minimize the fire threat introduced by the digital system.

Another consideration is that the traditional approach to fire risk/hazards assessments based on subdividing fire areas into fire zones for analysis may not be appropriate when the smoke issue is considered. In fire protection terminology, a "fire area" is a strictly defined term and implies that the area in question is fully bounded by rated fire barriers ("rated" is used here to imply performance consistent with the ASTM E119 fire barrier test standard). In contrast, a "fire zone" is typically defined more loosely as a subsection of a fire area that is expected to largely contain a fire. Fire zones will often include nonrated boundary elements, and may even include open doorways, penetrations, and/or hatchways between zones. This approach is generally based on the potential for the spread of flames and/or quantities of heat sufficient to cause thermal damage. In terms of smoke damage, these considerations are not sufficient. While an open hatchway in the ceiling of a compartment may not represent a realistic conduit for the spread of flames (due, for example, to the lack of proximate combustibles), it certainly represents a ready conduit for the passage of smoke.

The digital system design must take a broader view of the fire threat than that traditionally taken in a fire risk/hazards assessment. This view should include the realistic consideration of potential smoke movement and the placement of components accordingly, especially placement for redundant safety trains. For example, the 10CFR50 Appendix R requirement for the physical separation of redundant trains by a minimum of 20 horizontal feet with no intervening combustibles is based on concerns about thermal damage and flame spread. This provision will not mitigate smoke damage in any meaningful way. The digital design should take a more complete view of the potential fire threat.

3.2.5 Fire Barriers

Fire barriers will represent the ultimate line of defense against smoke spread. Such barriers include the primary structural elements such as walls, floors, and ceilings, but also secondary elements such as penetration seals, doorways, hatchways, and ventilation dampers. To address smoke damage concerns, the designer will need to consider how fire barriers can be utilized to protect critical components. Many aspects of this topic have already been discussed in Section 3.2.4 in relation to placement decisions. However, there are additional aspects of fire barrier elements that should be specifically recognized.

While the primary barrier elements (e.g., structural walls) will generally contain smoke effectively, the secondary elements (e.g., doors, seals, and dampers) may allow the passage of significant quantities of smoke from area to area. Consider, for example, that fire barriers are not generally designed as smoke barriers, but rather are designed to limit the spread of flames and heat. This is especially true for U.S. fire barrier testing standards compared with internationally accepted testing standards. Specifically, U.S. testing standards impose no pressure differential across a barrier element during testing, whereas international standards do. This means that certain types of rated barrier elements will allow the passage of significant quantities of smoke under realistic fire conditions in which pressure will build up modestly in the fire compartment due to the generation of hot combustion products.

Even given these observations, taking advantage of fire barriers in the digital design can substantially minimize the smoke damage potential. For example, while smoke leakage through secondary barrier elements may be observed even when the barrier performs as intended, the real likelihood that this leakage might lead to significant smoke buildup in adjacent areas is small for many situations. Provided that the movement is limited to general leakage, the adjacent area would need to be relatively small in volume for significant buildup to occur.

Another consideration in this process is the potential for smoke movement through a barrier due to a failure of the barrier element or delayed activation of an active barrier. For example, a normally closed fire door may be blocked open or may be opened by the plant personnel in an effort to access the fire area. Similarly, a normally open fire door may fail to close. These conditions would allow a significant and prolonged passage of smoke through the barrier. Another case to consider is that significant passage of smoke may occur before a fire barrier closure mechanism is activated. This might involve doors or ventilation dampers in particular. Note, for example, that a "fusible link" is a common actuation device for fire protection features. This device is heat activated and may cause a significant delay between the onset of smoke spread and the actuation of the protective feature.

All of these factors should be incorporated into the digital design strategy. However, even given the observation that significant smoke spread through a fire barrier is possible, it can be highly beneficial to take full advantage of fire barriers in the design of digital equipment. Even lesser barriers and obstructions may provide some protection against the spread of smoke, albeit perhaps only for limited time periods. This would include ceiling-level obstructions such as beams and the soffit over open passageways between compartments. These features might provide some additional benefit because a longer time for detection, suppression, and manual intervention would be available and hence the probability of such intervention would be greatly increased.

3.2.6 Localized Encapsulation

The potential for smoke exposure may be minimized through localized encapsulation of the digital device. This is not in reference to conformal coatings (discussed elsewhere in this report), but rather to the placement of digital components in localized protective enclosures. For example, critical digital components could be placed in higher rated National Electrical Manufacturers Association enclosures for protection, or in enclosures with separate environmental controls (see related discussion on localized ventilation features in Section 3.2.8). Such measures may provide significant additional levels of smoke protection.

There are numerous complicating features of such an approach that may limit its applicability. For example, allowances must be made for:

- maintenance access
- electrical access
- heat removal
- cost
- physical size constraints
- separation of redundant trains

However, for at least some applications, localized encapsulation may represent a viable alternative. The overriding factor in this approach would be to ensure that the component is not directly exposed to the smoke. This will require a level of environmental isolation well beyond that employed in general practice for electronic equipment. For example, the SNL tests found that simply housing the digital components in a computer chassis provided little or no protection. This is because the ventilation fan that is inevitably provided to remove heat from such a chassis circulates the smoke and compromises the potential protection (see related discussion on local ventilation features in Section 3.2.8).

3.2.7 General Ventilation Features

The tests at SNL have demonstrated important aspects of the smoke exposure problem that will be directly influenced by the ventilation systems servicing a given area. Hence, it may be possible to optimize the ventilation system's physical configuration and operating strategy so as to minimize the smoke damage potential. These options include, in particular, the prompt and effective removal of smoke from the fire area, the management of smoke transport, and the control of humidity levels.

The SNL tests demonstrated that there are two modes through which a damaging smoke exposure can occur. The first is direct deposition of smoke onto the surfaces of a component. This is the classically considered smoke exposure problem. The SNL tests indicate that this is certainly a concern, especially in the context of long-term damage and degradation by corrosion. However, the SNL tests also show that short-term damage may occur as a result of the mere presence of airborne ionized smoke particulates. Both of these damage modes can be effectively mitigated by prompt and efficient removal of smoke from the fire area, or by preventing smoke from spreading from adjacent areas into the area housing the digital equipment.

Unfortunately, testing has demonstrated that common design practices for ventilation systems will not provide efficient smoke management or smoke removal from general plant areas[28]. The most effective systems for smoke removal will have high flow rates in comparison with the room volume (one room air change per hour would be typical, with on the order of 10 air changes per hour a rough upper bound on typical ventilation rates). However, for efficient smoke removal, it is also important that the system be designed so that exhaust is taken from near the room ceiling and fresh incoming air is introduced near the floor of the space (to minimize mixing of the hot upper-layer gases and to take advantage of the natural buoyancy of hot fire products).

It is not expected that the digital design process will typically provide significant opportunities to enhance the general ventilation system, especially in retrofitting existing sites. These systems tend to be deeply integrated into the structure of the plant and hence are often not amenable to significant change. However, the designer may have the opportunity to select the area in which the components will be housed or may have the opportunity to make minor modifications to the ventilation system to enhance smoke removal. For example, given typical industrial ventilation configurations (inlet and outlet ports located high in the room), a simple extension of the inlet ports to floor level in the room might provide a significant smoke control benefit. It may also be possible to add extra-capacity smoke purge fans in the exhaust stream. A review of the configuration and capacity of the ventilation system would be appropriate and might provide an additional criterion upon which to base the placement decision.

There is a clear advantage in housing digital components in humidity-controlled environments. If the humidity level in the area is low at the outset of the fire, then the potential for short-term damage will be reduced. After the fire, the availability of a ventilation system with the capability to reduce humidity back down to levels below which significant corrosion will occur will also help significantly in the post-fire recovery process. Hence, normal ventilation systems can be included in the digital design process to help minimize the smoke damage concerns. Placing components in areas with well-designed and higher capacity ventilation systems will help to minimize both the deposition of smoke and the exposure of the equipment to airborne smoke.

Another aspect of the general ventilation system design to be considered is the fire response strategy for the system. There are at least four different strategies that can be implemented in response to a fire.[29] One strategy is to completely shut down the ventilation system, both inlet and outlet flow. This is the typical approach taken in practice today, and it is often implemented through ventilation duct dampers installed at area boundaries and fan power control circuits tied, for example, to in-duct smoke detectors. This strategy will tend to deprive the fire of needed oxygen and minimize the potential for fire products to spread through the ventilation system, but it also allows fire products (heat and smoke) to accumulate unchecked. A second strategy is to raise both inlet and outlet flow rates to maximum levels. This would be a typical response to a fire in a critical manned area such as the main control room. This approach will tend to minimize increases in room temperature and reduce the density of the smoke. However, it will also cause enhanced mixing of the smoke layer given typical ventilation configurations, and may actually result in faster descent rates for smoke layers (this is the rate at which the smoke layer develops from the ceiling downward).

The third strategy is to shut down the inlet flow into the fire area and to maximize the outlet flow from the fire area. At the same time, the inlet flow rates into the adjacent areas are pushed to maximum levels, and exhaust flow from those adjacent areas is restricted or shut down. In this configuration, fresh air flows into the adjacent areas and moves toward the fire area. Fire products are preferentially vented from the fire area. The potential for smoke to spread out of the area in which the fire occurs is minimized, and the potential for removal of smoke from the affected fire area is maximized.

A similar but subtly different approach is to manage the airflow, not necessarily for the fire area, but rather for the protection of certain critical areas. In this case, the exhaust from a critical plant area is restricted or completely shut down in the event of a fire anywhere in the general vicinity of that area. At the same time, the inlet flow ventilation rate to the critical area is pushed to maximum levels. In this way, the potential for smoke to spread from adjacent areas into the critical area is minimized. Testing at the Heiss Dampf reactor (HDR) facility in Germany has illustrated that this method can be quite effective in controlling smoke migration into protected areas.[30]

While the last two strategies have a clear potential to contribute to an overall smoke management strategy, their implementation in existing plants will be problematic. These two strategies require the ability to realign ventilation systems in response to a fire that goes beyond the capabilities currently provided in typical power plant installations. This is likely to be more of a consideration in the design of new reactors (or other critical structures) than it will be in the retrofitting of existing reactors. Nonetheless, in some cases there may be an opportunity to optimize the ventilation design strategy, and it should be taken advantage of.

As a final note to this discussion of general ventilation systems and the smoke control issue, the design of digital equipment should recognize that ventilation systems are not in general designed with smoke management or mitigation in mind. In fact, ventilation systems may actually contribute to the spread of smoke to areas remote from a fire. For example, in at least one instance a ventilation system introduced carbon dioxide from a fire suppression system actuated in a ventilation fan area into the main control room during an emergency event. [31] A similar potential exists for smoke movement as well. Another aspect of this issue is that general ventilation filtration systems will quickly become clogged with smoke and will likely force a system shutdown in the event of fire (owing to excess pressure across the filter elements). This was observed repeatedly in the German HDR tests despite efforts to plan for and manage this behavior. Hence, while some benefit may be gained through optimization of the ventilation system, the robustness and longer-term performance of such measures may be suspect. The ventilation interactions can be both beneficial and detrimental to the smoke damage concerns. Careful assessment will be needed to properly balance these effects.

3.2.8 Local Ventilation Features

In addition to the design of general area ventilation systems, there is also the potential to implement localized ventilation features to enhance the protection of critical digital components from smoke damage. These strategies might be especially useful in combination with the encapsulation strategy discussed in Section 3.2.6.

One strategy that was discussed in the context of encapsulating the equipment was to place the critical components in an environmentally sealed panel. Electrical panels of this type can be readily obtained on the commercial market either with or without environmental controls (local air conditioning and/or air filtration). In effect, the digital components can be placed in an independent sealed environment. There are, however, a number of potential disadvantages to this approach. The most obvious is that because the waste heat from the digital components may need to be removed, a sealed panel installation might require an independent local refrigeration system. This introduces yet another system into the plant that would require maintenance. The design would also need to assess the performance of the digital system and its effect on plant safety if the local environmental system fails (buildup of waste heat within the panel might eventually cause failure of the digital system; the question would be how long this would take). It would almost certainly be judged impractical if the importance of these environmental control systems elevated them to the level of a safety-grade system. Another obvious disadvantage is the added cost of these systems in comparison with generic electrical panels. It may also be prudent to allow for some fire detection capability within the sealed environment. For critical applications, the additional expense may be warranted. For example, this might be one means of protecting one train of equipment from smoke damage in areas such as the main control room, where multiple equipment trains might converge, particularly if a 24- or even 72-hour survival time in the absence of the environmental control system could be demonstrated.

A second less invasive strategy would be to provide filtered air flows into and out of the electrical panels of critical interest. As noted above, some mechanism for removing waste heat from the digital components will likely be needed. This strategy would allow for this through communication with the general enclosure volume, but only through a filtered local air handling system. That is, airflow could be provided through filtered, fan-driven inlets and through filtered outlets.

An enhancement of this strategy might involve placing the inlets as low as possible in the panel to take advantage of the hot layer effect in an enclosure fire. This would, however, also make the filters more prone to collection of general dirt and dust from the ambient environment as well. While the technology required for this approach is not especially sophisticated, and should be readily available, it is likely to be unproven for smoke mitigation. As noted above, the German HDR tests illustrated quite clearly that high-efficiency ventilation filters were easily clogged by smoke. Some evaluation of the performance of such filtration systems would likely be needed. In order to prevent rapid clogging, a cascading set of progressively finer filter elements may also be needed to ensure that the finer filters are not immediately clogged by the coarse smoke particulates. As with the full isolation strategy discussed above, the impact of loss of airflow on system performance and plant safety would have to be assessed.

A final strategy would be to provide a direct connection between the electrical panels and the normal area ventilation system. This has already been implemented at some plants, in particular in the main control room. One such configuration involves the use of the electrical control panels, either individually or as a group, as a return air plenum for the ventilation system (see, for example, the ventilation configuration for the LaSalle main control room). That is, fresh air is introduced into the general area and exhaust air is taken from the electrical panels. Ventilation grills in the faces of the electrical panels allow air to flow from the general area into the panel. This allows the direct removal of waste heat from the panels using the normal ventilation system. This approach would ensure that the smoke from a developing panel fire was preferentially removed from the area, at least during the initial stages of the fire (the system would likely be overwhelmed within a short time if the fire continued to grow). However, in the event of a fire external to the panels, this approach would actually worsen the exposure problem by drawing the smoke directly into the electrical panels.

An alternative version of this strategy would be to provide a fresh air supply link from the normal ventilation system directly into the critical panels. In the event of fire, so long as the fresh air supply is maintained, the panel would be provided with some added protection from smoke intrusion. This would, however, tend to force smoke from a given panel fire more quickly into the general area. Individual panel dampers actuated by smoke or heat detectors could easily manage this. The results of the German HDR fire tests would provide useful design and optimization data in this regard (Kernforschungzentrum Karlsruhe developed a relationship for the pressure differential required to prevent smoke intrusion through an opening).

3.3 Fire Protection Analysis Tools

3.3.1 Fire Risk Assessment

The problem of smoke damage is largely neglected in current fire risk assessments. At most, one can argue that certain aspects of the initial screening phases inherently include the potential for smoke damage. That is, in screening it is quite common to assume that given a fire in an area, all of the equipment in that area will fail. For some analyses, similar screening assessments are also made for combinations of fire areas that assume the spread of fire or fire damage beyond the compartment of fire origin. Provided that adequate consideration is given to the potential extent of smoke spread, this would include the possibility that smoke was the cause of the equipment failures. Any scenario with a risk contribution above a certain threshold level given these conservative assumptions would be analyzed further.

However, in the detailed quantification of surviving scenarios, this assumption of widespread damage is almost certain to be significantly relaxed. In particular, given current methods, the detailed quantification process focuses only on the issue of thermal damage. The extent of the thermal damage will typically be estimated using a computer fire model to predict the rates of fire growth and spread and the timing of equipment damage. This is then weighed probabilistically against the possibility that the fire would be suppressed before critical damage occurred. No direct consideration of smoke damage is currently included in this process. This is due to both a lack of proven methods of analysis and the general lack of knowledge regarding the vulnerability of plant equipment to smoke damage.

Hence, fire risk assessment methods as they currently exist are not conducive to a detailed assessment of smoke damage. At most, a risk assessment might provide some coarse bounding estimates of the smoke damage risk. This could be accomplished by supplementing current screening methods to include a refined widespread damage assumption. That is, rather than assuming that all equipment in an area is damaged, the assumption could be relaxed to include direct estimates of thermal damage (as per current practice) plus an assumed failure of all (or if justified, a subset) of the smoke-vulnerable digital components. This analysis would have to include consideration of smoke spread between fire areas or fire zones. This would allow for some conservative quantification of the fire risk associated with a given digital design and plant implementation. This type of analysis could be accomplished with relative ease given current methods.

3.3.2 Fire Modeling

In order to make a reasonable smoke damage prediction; several questions must be answered. These include:

- How much smoke is being generated in the fire as a function of time?
- Where does the smoke go once it is released from the fire (transport)?
- How much smoke accumulates in the immediate vicinity of the critical components?
- What is the threshold of damage for the components of interest due to airborne smoke particulates?
- At what rate is smoke deposited onto the surface of the component, and what is the deposition damage threshold?
- How will suppression of the fire and post-fire recovery actions affect the smoke exposure?
- What is the relative humidity of the environment around the digital component?

There are currently no known fire models that directly assess the potential for a fire to lead to smoke-induced equipment failures at any level of analysis. In particular, while some of the existing enclosure fire models do include predictions of smoke generation and spread, none of the current models includes any methods for assessing smoke damage to equipment.

The current approach to smoke modeling requires that the user effectively specify the rate of smoke production for the scenario under analysis. That is, the current state of fire modeling does not support a priori predictions of smoke generation. Only in the most advanced fire models are smoke generation and kinetics models being implemented. These models remain in the development stages. In more accessible models the user specification will typically take the form of a fractional parameter (between 0 and 1) that sets the percentage of the fuel mass burned that is liberated from the fire as smoke particulate. Enclosure models can then track the airborne concentration of smoke as a mass per unit volume parameter by tracking smoke generation rates and the rate of smoke removal from the enclosure due to either natural or forced ventilation flows. This is a common capability in current fire models. However, this does not provide all of the answers needed. The "missing links" in this process are (1) a submodel to assess the impact of airborne smoke on equipment, (2) submodels to predict the rates of smoke deposition onto component surfaces, and (3) data on the smoke damage thresholds for equipment.

Given current modeling capabilities and limitations, it would be possible to perform only relatively crude and bounding calculations to assess the likelihood of smoke damage in a given fire scenario. In particular, it would be necessary to make bounding assumptions regarding smoke generation and transport as well as equipment damage thresholds. This would leave a high level of uncertainty in the results obtained. Coupling such analyses with the statistical methods of fire risk assessment (see Section 3.3.1) would clearly be appropriate. That is, little reliance should be placed on any individual analysis scenario, but a statistical weighing of many scenarios coupled with treatment of the inherent uncertainties could provide relevant insights.

It is likely that advances in these capabilities will be forthcoming in the next decade through the development of a number of advanced fire physics models. These advanced models have not typically been used in nuclear plant risk assessments because of the high level of expertise required, the intensive level of model setup that is required for a given simulation, and the computing cost associated with these detailed simulations. However, the state of the art, the level of simplicity and user friendliness, and the cost of computing are all moving toward more acceptable levels.

4 POST-FIRE RECOVERY

4.1 Introduction

Fire causes permanent damage to electronics through excess heat and contamination from smoke. Since some smoke contains acidic compounds, it's important to reduce the corrosive action of these compounds as soon as possible. Many insurance companies have studied recovery from fires, and the long-term effects of smoke are well known. [32] Since losses for a business not only include equipment but also losses in productivity, it is often better to refurbish equipment rather than replace it. This is especially true for specialized equipment that has a long lead-time for delivery. Depending on the equipment and the amount and type of smoke deposition, equipment may be cleaned and reused without concern for long-term effects.[33] Besides the equipment itself, for computer systems it is often very important to recover data. Data have been recovered from hard disks that have been exposed to fire.[34] This type of work is best left to professional data recovery services.

The amount of chlorides or sulfates deposited on the surface of electronic equipment has been the standard for determining whether the equipment should be cleaned or if it must be replaced. Table 16 shows some guidelines that have been found in the literature on cleaning electronic equipment. Claims have been made that up to 80 to 85% of the cost of replacement equipment may be saved by swift response to a fire.

4.2 Steps to Reduce Smoke Damage

Common sense steps to reduce permanent damage to equipment are listed below:

1. Remove the power from the electronics if it can be done safely. Many times removing the power will be necessary to put out the fire. Power on the electronics accelerates corrosion in two ways: (1) potential fields tend to attract more soot because the soot particles are charged and (2) potential fields between traces on printed wiring boards encourage dendridic growth of the metal.

2. Vent out the smoke. Smoke contains ionized particles that can increase the chance of arcing. If the smoke is vented, it reduces the exposure of metal to acidic gases.

3. Lower the humidity. Acid gases tend to act faster in higher humidity environments. Humidity increases leakage currents of contaminated printed wiring boards.

4. Evaluate the equipment for smoke deposition. Evaluating the amount of chloride deposited generally does this. This will help determine what equipment should be cleaned

and what equipment should be scrapped. Do not waste time and effort on equipment that will not be usable after cleaning.

5. Clean salvageable parts. Several commercial companies specialize in disaster recovery and can provide help. Recovering equipment can reduce the monetary losses due to fire. A combination of detergent and water has been cited as the most effective cleaner rather than petroleum-based or halogenated solvents.

Table 16. Smoke Deposition Guidelines

	Deposition amount (µg Cl/cm^2)	
Reference	Should clean if greater than	Replace if greater than
Bellcore [25]	31	93
AREPA Benelux *	10–20	—
Elektronik Centralen *	10	100

4.3 Environments that Contribute to Smoke Damage

As shown in Section 2 of this report, high humidity and high voltage are both significant contributors to failure in smoke.

4.3.1 High Humidity

Humidity greatly increases the amount of damage that can result from smoke. When the humidity is high, water combines with the salts (such as $ZnCl_2$) formed from the interaction between acid gases in the smoke and the metals, such as lead and zinc that can be part of the mechanical structure or solder in the electronics. These salt solutions may be higher in conductivity than either the salt in a dry atmosphere or a higher humidity atmosphere without the smoke contamination.[35] Thus, smoke works synergistically with humidity to increase leakage currents.

The effects of smoke and dust contamination in a humid environment have been studied by Comizzoli, [36] Caudill,[16] and Chapin[17] on comb patterns. In general, for outdoor dust samples, the log of the leakage current varies linearly with the relative humidity. However, if the smoke sample contains a large fraction of graphitic carbon, as in the samples taken from the Kuwait oil fires, the leakage current is fairly constant, but higher, until the RH goes above 60%. Then the log of the leakage current increases linearly with RH.[35]

Caudill and Chapin have found a wide variation in behavior of the leakage currents from comb patterns exposed to smoke from a range of cable materials. Some of these comb patterns had high leakage currents throughout all humidity levels and some maintained a profile similar to outdoor dust samples. The materials that exhibited higher leakage currents, independent of humidity, were the cables with higher heat of combustion. We surmise that these cables burned more completely and a greater amount of smoke was deposited on the combs.

4.3.2 High Voltage

High voltage also contributes to higher leakage currents because high potentials attract more charged smoke particles to the surfaces. The higher accumulation of particles increases the leakage currents. In addition, most high-voltage circuits have high input impedance. This makes these types of circuits more vulnerable to increased leakage currents because a small change in impedance will cause a relatively higher effect on the overall circuit.

4.4 Cleaning Methods

Some of the earliest smoke tests by SNL and ORNL included reusing smoke-exposed equipment to save money and time (see Section 2.3.1). Although equipment was cleaned after each smoke exposure, the network system never worked quite as well after the first smoke exposure. The baseline tests showed that the equipment was not cleaned well enough. The equipment was cleaned with a halogenated degreaser (like Freon) rather than a water-based detergent. Water-based detergents are better able to remove the salt deposits that are formed on metals exposed to acid gases than organic solvents. Salt dissolves in water better than in an organic degreaser such as Freon or benzene.

4.4.1 NRL Method of Cleaning Electronic Equipment Exposed to Smoke

Baker and Bolster (Naval Research Laboratory) detailed how to clean electronics that have been contaminated with seawater, oil, and smoke deposits.[37] This process was used on the *USS Constellation* after it caught fire and the fire was extinguished with seawater.[38] Although the process predates wide use of digital equipment, the chemicals used and the steps taken are well documented and the process should work on both analog and digital systems. The equipment described for this process is quite large and includes an ultrasonic tank that is 4 ×4 × 4 ft in size. The NRL steps for cleaning electronics after exposure to fire and smoke are:

1. Alkaline presoak—Soak 2–5 min at 120–160°F in a trisodium phosphate mixture of 2–3 oz of trisodium phosphate per gallon of water (1/2 cup of dishwashing machine detergent/ gallon of water)

2. NRL emulsion ultrasonic wash—Ultrasonic cleaning for 2–20 min, depending on the size of the parts in the NRL cleaning emulsion (94 vol.% dry cleaning solvent, Type II; 5 vol.% fuel oil, diesel marine, Type I; and 1 vol.% surfactant such as polyethylene glycol 400 Dioleate),

diluted in a 50–50 mixture with water or a general-purpose detergent (Mil-D-16791E, Type I) mixture with water (1 oz per gallon of water.)

3. Ultrasonic rinse—Rinse in plain water.
4. Compressed air blow—Blow water from equipment at 10–20 psi
5. Oven drying or spray-dry—dry in an oven at 120–160 °F or spray with water-displacing fluid such as 1-butanol (*n*-butyl alcohol)
6. Test equipment for function and cleanliness.

DOE rules on post-fire recovery refer to the NRL method of cleaning. This method is also specified in MIL-STD-2110.

4.4.2 Swedish Institute of Production Engineering Research Method of Cleaning Smoke-Contaminated Electronics

Cider compared three printed circuit board cleaning methods for boards exposed to smoke from a fire composed of a combination of wood, PVC cable, cellular plastic, and FR-4 boards.[33] The printed circuit boards contained both surface-mounted components and interdigitated comb patterns for surface insulation measurements. Dipping them into an acrylic conformal coating, Humiseal 1B31, the same coating SNL used in the coating tests conformally coated some of the boards. The three treatment methods Cider compared were:

1. A five-step process:
    a. Spray boards with cleaning agent (commercial alkaline cleaning agent, Euroclean F-42).
    b. Manually brush boards.
    c. Rinse with tapwater and deionized water.
    d. Dry with high-pressure air.
    e. Dry in vacuum at 40 °C.
2. A three-step process:
    a. High-pressure spray at 50 °C for 20 minutes with a mixture of 75% isopropanol and 25% water (in an automatic defluxing machine).
    b. Rinse with isopropanol.
    c. Dry with warm air.
3. A six-step process:
    a. Rinse with tapwater.
    b. Dip into Euroclean F-42 and brush manually.
    c. Leach in cleaning solution (Euroclean F-42) for 10 minutes.
    d. Ultrasonic agitation for 10 minutes in cleaning solution.
    e. Rinse with tap water and deionized water.
    f. Dry in pressurized nitrogen at 80 °C for 1 hour.

The methods were compared by leaching the test boards in water and analyzing the water by ion chromatography for Pb, Si, Cl^-, Br^-, SO_4^{2-}, and organic carbon. Out of these different methods, the best was the six-step process with ultrasonic agitation and the worst was the three-step process using a high-pressure spray. The conformal coating protected the electronics, but made them more difficult to clean.

4.4.3 Commercial Cleaning of Electronics

Data are typically recorded on magnetic media of some type, either tape or hard disks. Read/write heads hover very close to the surface of magnetic disks, and although the hard disk assembly is located in a filtered box, smoke particles may enter and cause the heads to stick to the disk or may clog the space between the head and disk.[34] If hard disks are exposed to smoke, it is important that the disk is not accessed until after it is cleaned because data can be lost. In general, many of the establishments who clean their electronic equipment after a fire feel that they may be able to recover very well and have a high level of confidence in their cleaned electronics if the cleaning is performed immediately and thoroughly. The decision to clean up the equipment may depend upon whether it is a commercial off-the-shelf item or a specialty item.

Companies who clean electronic equipment may be found in the yellow pages or on the World Wide Web. The companies are usually listed under "Disaster Recovery" or "Restoration," but the majority of these listings mostly deal with cleaning of buildings, carpets, and drapery after a fire.

5 CONCLUSIONS

This section summarizes the insights gained from this project, areas that have not been addressed but should be, and future work. Although not stated at the outset of the program, the overall goal of subjecting digital systems to smoke is to determine the amount of risk that smoke poses for equipment in a nuclear power plant and to identify methods by which that risk can be minimized or managed. Such a goal requires certain information, some of which may not be available. Risk assessments require knowledge about failure thresholds, failure modes (what the system will do when exposed to smoke), when failure takes place (immediately or after a few weeks), and failure probability. They also require knowledge on how often the equipment is likely to be subject to these failure thresholds, or in terms of smoke, fire frequency, amount of smoke generated, and smoke transport. In addition, during a fire, equipment is not subject to smoke only, but often to elevated temperatures and humidity. These stressors increase the vulnerability of digital systems because they interact synergistically.

The main results found to date consist of preliminary information on how and when failures will occur, the basic underlying causes of failure, and methods of smoke protection. Insights from this project are important in determining how to proceed to an ultimate goal of determining or minimizing risk. Although research issues remain to be addressed before susceptibility to smoke can be fully characterized and a comprehensive consensus approach to mitigating the consequences of exposure can be established, several important conclusions can be drawn from project findings. Based on the investigation of smoke susceptibility and the resulting understanding of key failure mechanisms, it is clear that smoke has the potential to be a significant environmental stressor that can result in adverse consequences. However, there is no practical, repeatable testing methodology so it is not feasible to assess smoke susceptibility as part of environmental qualification. As a result, the most reasonable approach to minimizing smoke susceptibility is to employ design, implementation, and procedural practices that can reduce the possibility of smoke exposure and enhance smoke tolerance. In particular, current fire protection methods are an appropriate preventative approach, employing isolation and detection practices. Additionally, post-event recovery procedures can mitigate the extent of smoke damage. Finally, there are design choices and implementation practices that can reduce equipment susceptibility to smoke exposure, such as chip packaging and conformal coatings. In the absence of consensus methods and practices for smoke-tolerant design and implementation, the most effective approach is to rigorously adhere to the fire protection guidance given in Appendix R of the Code of Federal Regulations, Title 10, Part 50.

5.1 Summary of Insights

5.1.1 Environmental Stress Characteristics of Smoke

How and When Smoke Causes Digital Equipment Failure

When digital systems were tested (Section 2.3.1), the smoke caused errors during and within 24 hours of exposure. Most of the errors were diagnosed as errors in transmitting data from one computer or microprocessor to another. In general, the digital systems tested were designed to convert an analog to a digital signal and communicate the digital signal back to a main computer. There was no evidence of the smoke affecting the conversion from analog to digital; as long as the systems were communicating, these conversions were accurate.

The digital systems failed intermittently, except for the case of very high fuel loads on the fiber optic modules, and networked systems merely retransmitted correct data. This was not the case for the serial communications port because once data were corrupted, the program halted, but including error handlers for these transmission errors could have compensated this for. It would be better in most situations that a digital system fails to communicate instead of communicating erroneous information.

Causes of Failure

Smoke has been postulated to cause failure by many means: corrosion of metals, increased resistance of contact points, increased leakage currents, and impedance of small motion by smoke particles (i.e., motion of recording head on a disk drive). The results of the tests on the experimental digital safety system and the multiplexer imply that increased leakage currents or shorts are the most immediate problem. This is backed up by the tests on the functional circuit boards; current leakage is the most severe immediate reaction to smoke. Other effects have been noted during the functional board tests, but they were not significant. These include increases in resistance (open-circuit faults) from either component heating or breakdown of solder joints and connections.

The highest leakage currents occur when the smoke is suspended in the air because smoke particles are attracted to electrically charged surfaces and build conductive bridges. Air currents easily break these bridges, but while smoke is suspended, a supply of particles is available to rebuild the bridges. Leakage currents can continue to be high after the smoke has been removed from the air if the soot bridge is supported by a surface, for example, on a printed circuit board.

The amount of smoke necessary to cause failure depends upon the technology that is being used. Analog signals typically provide a current level (e.g., 4–20 mA) or a voltage level (e.g., 0–10 V) as a means to transmit a signal. Such a signal would be difficult to short by means of smoke since such circuits usually are of low impedance (50 Ω) and in general, the smoke has an impedance of 1000 ohms or higher. In the newer digital equipment, however, it may be easier to cause failures since a momentary short may disrupt communications.

Smoke deposition measurements have been a typical method of determining electronic equipment failure. There are several "rules of thumb" about how much deposition, particularly of chloride, will cause smoke damage. For example, the Bellcore Company uses 93 mg/cm^2 as a measure of how salvageable equipment is.[25] Of course, after a fire, smoke deposition is all that is available as a measure. There is no way to determine how much smoke was in the air.

5.1.2 Methods of Smoke Protection

There are four basic methods for protecting electronics from smoke: (1) prevent fires, (2) control the movement of smoke, (3) protect the electronics by physical methods, and (4) locate components to minimize exposure to fire and smoke. Methods 1 and 2 are addressed in fire regulations for nuclear power plants as discussed in Section 3. The third method can be difficult because all electronics use power and are a source of heat. If electronics are enclosed to protect them from smoke, they can overheat. Fans that are used to cool electronics under normal operations can distribute smoke and soot throughout the chassis. It would be best in terms of smoke if the use of fans were avoided if possible. The fourth method is most amenable to the digital design process, but implementation options may be limited.

Conformal coatings are a good way to protect electronics; however, connectors are generally not coated since they could not then provide an electrical connection. Use of coatings may also change flammability properties and may increase fire severity potential. Parylene is a very good coating, but it is expensive to apply, requiring vacuum deposition. Polyurethane and dipped acrylic coatings also performed very well in the SNL testing. Coatings should be selected carefully because they can cause problems if the underlying electronics are not cleaned before coating or if the coating starts to delaminate.[39] Then contamination and humidity may be trapped under the coating and cause leakage current problems.

Additional strategies for reducing the potential for smoke damage to digital systems include the following:

- Identify the components of the digital system that are most vulnerable to smoke damage. Protection of these components could improve the overall system smoke tolerance.

- Connectors are not amenable to protection by conformal coatings. Identify and utilize connector configurations or designs with greater smoke tolerance.
- Different chip technologies will have different smoke tolerances. Identify and utilize chip technologies with greater smoke tolerance.

5.1.3 Qualification Tests

At this time there are no standard tests for the effects of smoke on the operability of electronics. Current test standards that measure only metal loss are not adequate for this need. The development of such a test requires rigorous comparisons of test methods and results performed at different organizations. At present this process is in its infancy.

Standard tests, such as in IEEE 323-1983, are performed for electronics under controlled temperature and humidity conditions. These tests typically include standard measurements of the environment. For smoke, there is no standard measurement that would convey all of the variables that can be created in a smoke environment. For example, many different chemicals are added to the environment; the balance of O_2, CO, and CO_2 changes; and the particles in the air are charged and vary in size and mobility. Creating a repeatable smoke environment is also difficult. Tests using the same starting conditions had slightly different results.

At this time developing a standard test does not appear feasible. Such a test would require the participation of many organizations that could possibly use such a qualification test and many laboratories that could perform the test. Perhaps if there is enough interest in the subject, a standard could be developed in the future.

5.2 Unaddressed Questions

One question, which has not been explicitly addressed by the activities performed to date, is quantifying the fire risk contribution of smoke damage to electronics. In order to incorporate smoke damage into fire risk assessments additional information and tools will be needed. This includes the need to answer the following questions:

- How do the test results gathered to date compare to the behavior in full-scale fire conditions? All of the tests describe here were performed under controlled small-scale test conditions. Real fires may present unique behaviors that have not been captured in these tests. One example is smoke interaction with galvanized metals, which has been observed in real fires but was not well captured in the small-scale tests.
- What are the thresholds of damage due to smoke for the components that will be of interest to a fire risk

analysis? Can generic threshold values be established to cover broad classes of digital circuits and components? In order to estimate fire risk, one must be able to predict the fire conditions that will lead to the failure of specific components or classes of components.

- Will smoke from a fire be transported to the site of the component of interest and in what quantities? A fire risk analysis must predict when environmental conditions will reach component damage thresholds. While some fire models do provide tools for the prediction of smoke generation and transport, their applicability to risk assessment has not been explored.
- How will smoke-induced failures impact the operation of plant systems and components? In the tests to date the primary mode of faulting was temporary communication errors, but it is not clear whether this is the only potential fault mode of interest to risk analysis. Fire risk analyses must assess how digital circuit failures will affect plant systems and components.

At present, fire risk assessments either assume that the electronic equipment malfunctions because the fire overheats cables leading to the equipment failure, or they assume that any equipment within the same zone as the fire will be damaged. In the case of the first assumption, the damage may be underestimated because the smoke may spread to a wider area than the heat of the fire. In the case of the second assumption, the damage may be overestimated. Both overestimates and underestimates are undesirable in risk assessment work.

5.3 Recommendations for Future Work

In light of the unanswered questions, much future work must be done to adequately quantify the risk of using advanced digital systems in a nuclear power plant in the presence of smoke. In this sections we outline some of the work that will be needed to be done to truly determine this risk and to assure that future safety systems will not suffer from vulnerability to smoke.

5.3.1 Validation and improvement of fire and smoke transport models

Fire models now include methods to calculate how much smoke will be produced, although they are better at calculating the smoke from liquid fuels than solids. Fire models can also be used to calculate transport of the smoke due to ventilation. However, this transport should also include the effect of electrical fields that will increase transport to areas of high electric field density. Validation of the existing models and/or development of improved models are needed to estimate how much smoke could be produced in the event of a fire.

The fire models need to compare full-scale fires with small-scale fires as used in these tests. In these tests we have assumed that the smoke density that is produced can be scaled by volume, but we know from the high voltage tests that smoke does not distribute itself evenly.

5.3.2 Develop models for different classes of electronic equipment

The reliability of electronic equipment that is exposed to smoke is highly dependent on the type of equipment. Electronic equipment (such as transducers) produces many different types of signals using different electronic circuits. For example, for some transducers, the frequency of oscillation is the important parameter, while for others it is the current or voltage level. With so many different electronic properties that are important, assessing the reliability of this equipment may be an enormous task.

Our data show that high impedance circuits are the most likely circuits to fail. If its highest impedance circuit can characterize equipment, then failures can be predicted based on whether smoke is likely to create alternative circuit paths with similar levels of impedance. The risk of smoke causing failure can then be predicted from the smoke transport and the likelihood that smoke would create circuit paths of comparable impedance. This would establish damage thresholds for level of conductance to cause failure.

5.3.3 Improve methods of smoke protection

Conformal coatings have been suggested, as a method to protect electronics from smoke, however, some industries, such as telecommunications, will not use this method because of flammability issues. New coatings should be developed that are non-flammable, but can insulate electronics from smoke and dust. Another improvement would be to cool electronics without use of fans and air movement. Fans increase the exposure of electronics to airborne smoke and dust, and hence, can shorten the life of electronics through shorts even if they lengthen the life through cooling. Perhaps cooling fins or the like can be used instead of the fans.

6 References

1. K. Korsah, R.L. Clark, and R.T. Wood, Functional issues and environmental qualification of digital protection systems of advanced light-water nuclear reactors. Technical Report NUREG/CR-5904, ORNL/TM-12164, Oak Ridge National Laboratory, Oak Ridge, TN, 1994.

2. S. W. Kercel, M.R. Moore, E.D. Blakeman, P.D. Ewing, and R.T. Wood, Survey of ambient electromagnetic and radio-frequency interference levels in nuclear power plants. NUREG/CR-6436, ORNL/TM-13171, Oak Ridge National Laboratory, Oak Ridge, TN, 1996.

3. K. Korsah, Tina J. Tanaka, T. L. Wilson, Jr., and R. T. Wood, Environmental testing of an experimental digital safety channel. NUREG/CR-6406, ORNL/TM-13122, Oak Ridge National Laboratory, Oak Ridge, TN, 1996.

4. M. Hassan and W.E. Vesely. Digital I&C systems in nuclear power plants; Risk screening of environmental stressors and a comparison of hardware unavailability with an existing analog system. NUREG/CR-6579, Brookhaven National Laboratory, Upton, NY, 1998. Draft.

5. Joint Report of the Office of the State Fire Marshal (Illinois) and the Illinois Commerce Commission Staff. Hinsdale central office fire final report, prepared by Forensic Technologies International corporation, Annapolis, Maryland, March 1989.

6. U.S. Department of Energy. DOE Handbook on Fire Protection, volume II. DOE-HDBK-1062-96, U.S. Department of Energy, Washington, DC, 1996.

7. T.J. Tanaka, S.P. Nowlen, and D.J. Anderson, Circuit bridging of components by smoke. NUREG/CR-6476, SAND96-2633, Sandia National Laboratories, Albuquerque, NM, 1996.

8. T. J. Tanaka, Effect of smoke on functional circuits. NUREG/CR-6543, SAND97-2544, Sandia National Laboratories, Albuquerque, NM, 1997.

9. K. Korsah, Mahbubul Hassan, T. J. Tanaka, and R.T. Wood, Technical basis for environmental qualification of microprocessor-based safety-related equipment in nuclear power plants. NUREG/CR-6479, ORNL/TM-13264, Oak Ridge National Laboratory, Oak Ridge, TN, 1998.

10. W. T. Wheelis, User's guide for a personal-computer-based nuclear power plant fire database. NUREG/CR-4586, SAND86-0300, Sandia National Laboratories, Albuquerque, NM, 1986.

11. S. L. Kessel, J. G. Bennett, Jr, C. E. Rogers, Corrosivity Test Methods for Polymeric Materials. Part 1—Radiant Furnace Test Method [1], Part 2—CNET TEST Method, Part 3—Modified DIN Test Method, Part 4—Cone Corrosimeter Method, and Part 5—A Comparison of Four Test Methods. *J. of Fire Sciences*, Vol. 12, No. 2. pp. 107–233.

12. J. D. Sinclair, Corrosion of electronics: The role of ionic substances. Journal of the Electrochemical Society, 135 (30) 89C-95C, 1988.

13. R.B. Comizzoli, R.P. Frankenthal, R.E. Lobnig, L.A. Psota-Kelty, G.A. Peins, D.J. Siconolfi, and J.D. Sinclair. Corrosion of electronic materials and devices by submicron atmospheric particles. Interface, fall, 26–36, 1993.

14. W. H. Abbott, Corrosion still plagues electronic packaging. Electronic Packaging & Production, pages 28–33, 1989.

15. D. Pauls, IPC cleaning and cleanliness test program phase 3: Water soluble fluxes. Part 1. Technical Report, Department of the Navy, Washington, DC, 1992.

16. L.M. Caudill, J.T. Chapin, R.B. Comissoli, P. Ghandhi, G.A. Peins, and J.D. Sinclair, Current state of fire corrosivity testing: Preliminary electrical leakage current measurements. In International Wire and Cable Symposium Proceedings, pages 432–437, 1995.

17. J. T. Chapin, L.M. Caudill, P. Gandhi, and R. Backstrom. Leakage current smoke corrosivity testing comparison of cable and material data. in International Wire and Cable Symposium Proceedings, pages 184–192, 1996.

18. M.J. Jacobus. Screening tests of representative nuclear power plant components exposed to secondary environments created by fires. NUREG/CR-4596, SAND 86-0394, Sandia National Laboratories, Albuquerque, NM, 1986.

19. B.Bridger, D.W. Cooper, W.F. Powers, and L. B. McClung. Use of reduced emissions wire in switchgear equipments. In Proceedings of Industrial and Commercial Power Systems Conference, pages 127–137, 1994.

20. S.L. Kessel, J.G. Bennett, Jr., and C.E. Rogers. Corrosivity test methods for polymeric materials. Journal of Fire Science, 12(2): 107–133, 1994.

21. R.L. Iman et al. Evaluation of low-residue soldering for military and commercial applications: A report from the Low-residue Soldering Task Force. SAND95-1060, Sandia National Laboratories, Albuquerque, NM, 1995.

22. Adolf S. Jursa, Editor, Handbook of Geophysics and the Space Environment, Air Force Geophysics Laboratory, Air Force Systems Command, United States Air Force, 1985.

23. S. P. Nowlen, A Summary of the USNRC Fire Protection Research Program at Sandia National Laboratories; 1975-1987, NUREG/CR-5384, Sandia National Laboratories, Albuquerque, NM, 1989.

24. M. Arvidson and H. Persson. Koldioxides (CO2) Påverkan påelektronik—släckning med låga koncentrationer [carbon dioxide suppression systems—risk of damage to electrical equipment]. SP Report 1993:20, Swedish National Testing and Research Institute, Borås, Sweden, 1993.

25. B. T. Reagor. Smoke corrosivity: Generation, impact, detection, and propagation. Journal of Fire Sciences, 10:169–179, 1992.

26. H. P. Messmer, The Indispensable PC Hardware Book, Second Edition, Chapter 28, "Hard Disk Drives", Addison-Wesley Publishing Company, Workingham, England, 1995.

27. Doug Pauls, "IPC Cleaning and Cleanliness Test Program Phase 3 Water Soluble Fluxes Part 1," Paper presented at the IPC 1992 Fall Meeting, October 12-15, 1992, Minneapolis, MN, Institute for Interconnecting and Packaging Electronics Circuits, Lincolnwood, IL, IPC TP-1043.

28. S.P. Nowlen. Enclosure environment characterization testing for the base line validation of computer fire simulation codes. NUREG/CR-4681, SAND86-1296, Sandia National Laboratories, Albuquerque, NM, 1986.

29. J.A. Milloy. Nuclear power plant fire protection-ventilation (subsystems study task 1). NUREG/CR-0636, SAND79-0263, Sandia National Laboratories, Albuquerque, NM, 1979.

30. S.P. Nowlen. A summary of the fire testing program at the German HDR test facility. NUREG/CR-6173, SAND94-1795, Sandia National Laboratories, Albuquerque, NM, 1994.

31. E.L. Jordan. Feedwater line break. IE Information Notice, No. 86-106, Supplement 2. U.S. Nuclear Regulatory Commission, Office of Inspection and Enforcement, Washington, DC, March 1987.

32. E. Schutz. Coping when disaster hits your business. Friendly Exchange, page 23, 1997.

33. L. Cider. Cleaning and reliability of smoke-contaminated electronics. Fire Technology, 29:226–245, 1993.

34. J. Hildreth. Coping with information infernos. Fire Prevention, 274:32–34, 1994.

35. J.F. Maguire. Letter on effect of humidity on SIR. Personal communication, October 1996.

36. R.B. Comizzoli, J.P. Franey, T.E. Graedel, 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. Journal of the Electrochemical Society, 139(7): 2058–2066, 1992.

37. H.R. Baker and R.N. Boster. Guide to NRL cleaning and salvaging techniques for reclaiming equipment contaminated with seawater, oil, and smoke deposits. Technical Report NRL Report 7563, Naval Research Laboratory, Washington, DC,1973.

38. H.R. Baker, P.B. Leach, and C.R. Singleterry. Surface chemical methods of displacing water and/or oils and salvaging flooded equipment; Part 2—field experience in recovering equipment damaged by fire aboard USS Constellation and equipment subjected to salt-spray acceptance test. NRL Report 5680, Naval Research Laboratory, Washington, DC, 1961.

39. Carl J. Tautscher. Contamination Effects on Electronics Products: *A Basic Discussion of Common Contaminants, Their Origin, Effects, Removal, and Control, and Product Protection Against Contaminants from the Use Environment*, Chapter 3—Contamination Sources: Assembly, Soldering, Cleaning, Coating, and Testing, Marcel Dekker, New York, 1991.

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp.. Rev., and Addendum Numbers, if any)
NUREG/CR-6597

2. TITLE AND SUBTITLE

Results and Insights on the Impact of Smoke on Digital Instrumentation & Controls

3. DATE REPORT PUBLISHED

MONTH	YEAR
January	2001

4. FIN OR GRANT NUMBER
JCN W6051

5. AUTHOR(S)

Tina J. Tanaka
Steven P. Nowlen

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Sandia National Laboratories
P.O. Box 5800
Mail Stop 1129
Albuquerque, NM 87185

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Technology
Office of Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
C. Antonescu, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Smoke can cause interruptions and upsets in active electronics. Because nuclear power plants are replacing analog with digital instrumentation and control systems, qualification guidelines for new systems are being reviewed for severe environments such as smoke and electromagnetic interference. Active digital systems, individual components, and active circuits have been exposed to smoke in a program sponsored by the U.S. Nuclear Regulatory Commission. The circuits and systems were all monitored during the smoke exposure, indicating any immediate effects of the smoke. The major effect of smoke has been to increase leakage currents (through circuit bridging across contacts and leads) and to cause momentary upsets and failures in digital systems. This report summarizes two previous reports and presents new results from conformal coating, memory chip, and hard drive tests. The report describes practices for mitigation of smoke damage through digital system design, fire barriers, ventilation, fire suppressants, and post fire procedures.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Fire, Smoke, Corrosion, Electronics

13. AVAILABILITY STATEMENT
Unlimited

14. SECURITY CLASSIFICATION
(This Page)
unclassified
(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE

ISBN 0-16-050737-5

90000

9 780160 507373

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001
