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# Preliminary Studies on the Impact of Smoke on Digital Equipment*


**Tina J. Tanaka**
**Sandia National Laboratories**
**Albuquerque, NM 87185-0747**

**Kofi Korsah**
**Oak Ridge National Laboratory**
**Oak Ridge, TN 37831-6010**

**Christina Antonescu**
**United States Nuclear Regulatory Commission**
**Office of Research**



## Abstract

Last year the USNRC initiated a program at Sandia National Laboratories to determine the potential impact of smoke on advanced safety-related digitial instrumentation. In recognition of the fact that the reliability of safety-related equipment during or shortly after a fire in a nuclear power plant is more risk significant than long-term effects, we are concentrating on short-term failures. We exposed a multiplexer module board to three different types of smoke to determine whether the smoke would affect its operation. The operation of the multiplexer board was halted by one out of the three smoke exposures. In coordination with Oak Ridge National Laboratory, an experimental digital safety system was also smoke tested. The series of tests showed that smoke can cause potentially serious failures of a safety system. Most of these failures were intermittent and showed that smoke can temporarily interrupt communication between digital systems.



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# Introduction

In recent years nuclear power plants have been experimenting with new digital equipment for use in safety systems.[1] Replacement of the older analog equipment with newer systems has raised questions because of the compact nature of the digital systems, the possibility that many functions will be multiplexed in the same equipment, and the potential that new common-mode failure mechanisms might be introduced. The Advisory Committee for Reactor Safeguards (ACRS) has been concerned about these changes and how the replacement of these safety systems will be regulated. In particular, the reaction of digital equipment to smoke has been questioned. These concerns about smoke are raised partly in reaction to the experience of the telecommunications industry which includes one case in which a fire in a central switching center caused extensive smoke damage to electronic equipment.[2] As a result of this fire, the industry has changed their requirements on cable insulation so that the insulation, which supplies a large fraction of the fuel in an accidental fire, is less corrosive if burnt.

While smoke is a known hazard for electronic equipment, very few tests have been performed to determine the reliability of electronic equipment in a smoke atmosphere. In 1994 the U. S. Nuclear Regulatory Commission (USNRC) began a program at Sandia National Laboratories (SNL) to assess the vulnerability of digital equipment to smoke and other synergistic fire conditions. As a preliminary test in this program, SNL exposed operating multiplexer modules to smoke in December 1994. Oak Ridge National Laboratory (ORNL) is investigating the effect of various environmental conditions on digital equipment, and hence, this first test was conducted on equipment suggested by ORNL and with software written by ORNL. One module failed intermittently during the tests, but could be restarted after the completion of the smoke exposure.

In May and June 1995, a series of smoke exposure tests were conducted on an experimental digital safety system designed and built by ORNL. This system was developed to identify short-term environmental stress-related vulnerabilities of technologies that are likely to be used in safety-critical applications in nuclear power plants. The stresses tested by ORNL were elevated temperature, humidity, electromagnetic and radio frequency interference (EMI/RFI), and smoke. The smoke exposures were modeled after likely fire scenarios in nuclear power plants based on past fire events and fire testing. These exposures also showed some failures, however, assuming good engineering design, no failures likely to prevent a safety system from performing its function were identified.

SNL is now performing a series of smoke exposure tests on digital components and printed circuit boards. One of the primary objectives is to measure the impact of smoke on the insulation resistance between contacts in typical components. The smoke environment will be varied to simulate different scenarios such as a high burning temperature versus a smoldering fire and high or low ambient humidity levels. This series of experiments will also compare different methods of component protection, such as conformal coatings and mounting the components in a box.

Studies on the reliability of digital equipment in a fire are rare, at least in part because smoke environments are not easy to quantify and reproduce. Standardized tests have been developed by professional groups such as the American Society for Testing and Materials (ASTM) and the National Institute of Standards and Technology.

At this time, the standardized tests of the behavior of smoke and electronics are limited to measuring the corrosive effects of smoke from various fuels on metals. These tests measure the relative amount of metal lost or the acidity of the smoke. Smoke-induced corrosion, however, typically damages electronic equipment over weeks, while our preliminary exposures show that smoke can damage components in other ways within minutes of a fire.

Recently, a group of researchers in the telecommunications field (in a collaboration among DuPont, Underwriters Laboratory, and AT&T)[3] have become concerned about another potential mode of failure for electronic systems: soot on electronics can bridge conductors. Instead of measuring metal loss or smoke acidity, these researchers are measuring the loss of insulation resistance. This loss and the resulting short circuit can cause immediate failure of a digital system.

This failure mechanism coincides with the concerns relevant to nuclear power plants. That is, for safety reasons, nuclear power plant operators are concerned about the failures that take place during or shortly after a fire—those that happen within minutes or hours rather than weeks.

Although the failure mechanism that DuPont/UL/AT&T are studying is more useful for nuclear power plants than corrosion studies, this group is not investigating the reactions of the digital equipment itself. Instead, it is investigating the surface insulation resistance of a printed circuit board exposed to smoke from a variety of materials. The USNRC is interested in the effect of smoke on the digital equipment itself and how any problems that may result may be mitigated. Because of the lack of a standard test method, SNL has adopted an approach to testing that includes features from standardized smoke corrosivity tests being developed by the ASTM. This report describes three test series on (1) multiplexer modules, (2) an experimental digital system, and, (3) circuit bridging of typical digital components.

## Equipment Tested

### Analog-to-Digital Modules and Multiplexer

The first smoke tests on components at SNL evaluated the effect of smoke deposited on the analog-to-digital (A-to-D) modules, multiplexer, and backplanes from Analog Devices®. These components were selected by ORNL for testing because they incorporate technologies that are likely to be used in safety systems of nuclear power plants.

Analog Devices sells a series of plastic-encased modules that can perform different functions: measure voltage, measure thermocouple or resistive temperature device (RTD) output, and then output current or voltage. All of these modules plug into a printed circuit-type board called a backplane that is powered with a 5-V dc power supply. The backplane has ports for both RS232 and RS485 connections that allow the backplane to send and receive information from a computer over a serial port.

The commercial computer program that is provided with the modules was used to configure an output module to produce a 0 to 20 mA current to serve as a reference source. The output current was passed through a precision resistor so that the voltage could be measured. An input module was configured to convert the analog voltage to a digital output for the computer. The input module, acting as the test specimen, resistor, and backplane were placed in the smoke exposure chamber while the output module remained outside, along with the interrogating computer (see Figure 1). During the smoke exposure, the input module measurements were compared with the output module readings. Ideally, the measurements should match exactly.

The software for assessing the performance of the test modules was developed ORNL as a "Turbo Basic" program. For the test, the computer directed the output module to feed a known current to the input module. The computer read the actual output module current and the input module voltage measurements. Each voltage measurement was repeated 6 times at 1-second intervals. The computer then changed the output current and repeated the readings. To scan the range of possible output currents, the current started at 0 and was incremented by +0.1 mA steps up to 20 mA. After the output current reached 20 mA, the data from the entire scan were recorded in a data file. The process was then repeated.

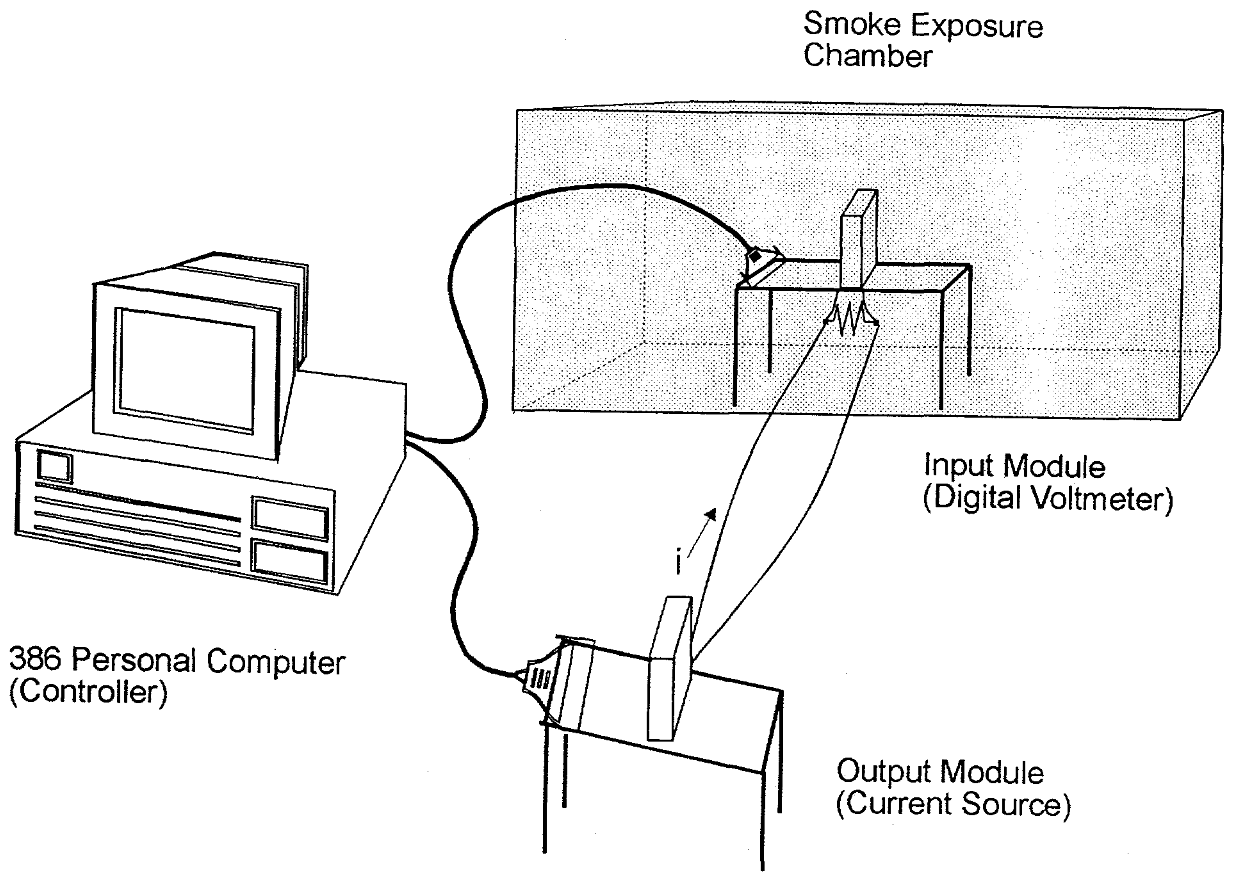


*Figure 1. Multiplexer Test Setup.*

## Experimental Digital Safety System

A reactor trip system typically consists of four divisions of process channels that are eventually interconnected at some points, typically in 2 out of 4 voting logic configurations, for final safety system actuation. For the purposes of the tests described in this document, only one division of a typical system was fully implemented. The functions typically performed by the three other divisions were implemented by a single computer or host processor. This approach was necessary to meet budgetary constraints but did not compromise the objectives of the task since the safety channel implemented incorporated a full complement of the various technologies of interest, namely multiplexers, computers, fiber optic line drivers, a fiber distributed data interchange (FDDI) network, and optical/electrical interfaces.

In order to test these systems at SNL for different exposure conditions, the equipment was cleaned and reused in multiple tests. The process multiplexing unit (PRS/MUX) was exposed four times to smoke while the digital trip computer (DTC) was exposed three times to smoke and once to $CO_2$. The fiber optic modules (FOMs) were exposed to a smoke environment as well as high temperature tests since it was determined that they are very sensitive to heat.

A block diagram of the experimental digital safety channel (EDSC) is shown in Figure 2. A description of the various subsystems follows:

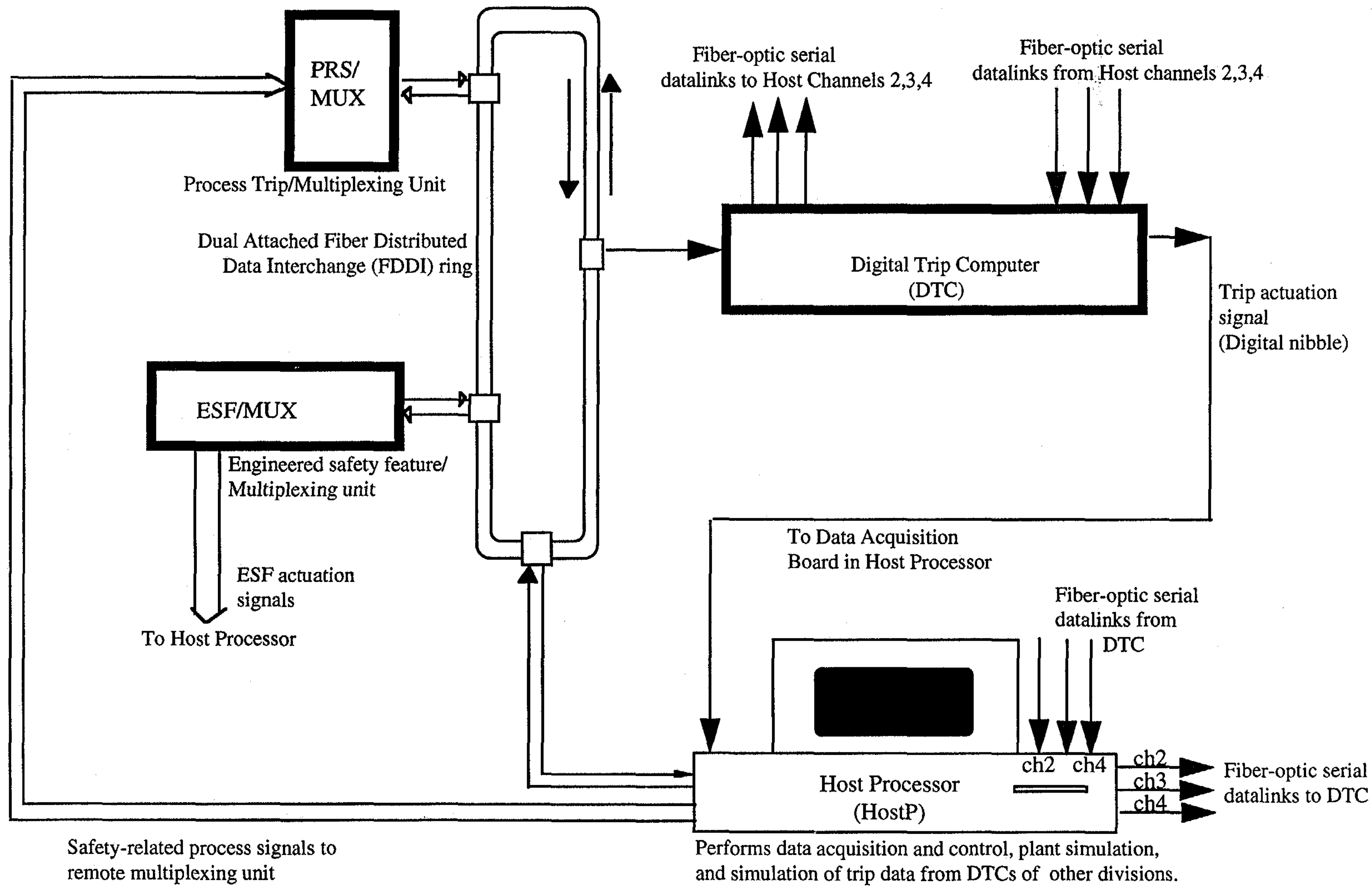


*Figure 2. Block diagram of the experimental digital safety channel.*

*Process Multiplexing Unit (PRS/MUX)*

The function of the PRS/MUX is to acquire analog data from the host processor (HOSTP), digitize these data, and format them into frames suitable for transmission over an FDDI network. In an actual plant, these process signals would come from field instrumentation such as transmitters. In this implementation, however, the signals are generated by a 16-channel digital-to-analog (D/A) plug-in card inside the HOSTP.

*Digital Trip Computer (DTC)*

The DTC polls the network to acquire the digital values of the process signals from the PRS/MUX. It then compares individual process values with trip setpoint values and sends a trip/no trip indication for each variable over three independent fiber optic serial datalinks to the host processor. (Note that in an actual protection system, these fiber optic datalinks would go to three other digital trip computers belonging to the three other divisions, the functions of which are being simulated by the host processor in the EDSC.) At the same time, the host processor sends trip/no trip information for each variable to the DTC via three independent serial datalinks. The DTC performs 2 out of 4 voting (local coincidence) on each set of process trip/no trip information received (note that for each process parameter, there are four trip/no trip data to vote on—one calculated from the process data received via the fiber distributed data interchange (FDDI) network, and three received from the host via the serial datalinks).

*The Host Processor (HOSTP)*

The host processor performs the following functions:

1. Simulates process signals typical of either normal or accident conditions. These signals are hardwired to the PRS/MUX.
2. Sends a command via the network to the PRS/MUX requesting it to begin acquiring process data.
3. Acquires the analog process data sent over the network by the PRS/MUX. (Note that the data from the PRS/MUX are also acquired by the DTC.) In this way the HOSTP verifies that the process voltage values it sent to the PRS/MUX have not been corrupted.
4. Simulates the trip functions of three other divisions by generating process trip/no trip data for each of ten process signals and sends them via fiber serial links to the DTC.
5. Performs 2 out of 4 voting based on the internally generated trip/no trip information and the trip/no trip information sent from the DTC via the serial datalinks.
6. Provides specified pump, valve, and other ESF actuation signals to the ESF/MUX via the FDDI network.
7. Monitors the ESF/MUX outputs via a plug-in analog-to-digital (A/D) card inside the host.
8. Performs error logging functions.

*The Engineered Safety Feature Multiplexing Unit (ESF/MUX)*

The ESF/MUX demultiplexes the digital information sent by the host via the FDDI network into the appropriate analog signals.

## Circuit Bridging

There will be 28 circuit bridging tests to determine the amount of insulation resistance between contacts on different chip packages and on the surface of a printed circuit board when they are exposed to smoke and soot. As of the writing of this paper, three tests have been completed. The chip packages include both hermetically sealed ceramic packages and plastic packages and both surface mount and through-hole mount styles. The printed circuit board tests consist of a set of four interdigitated comb patterns on one board with different dc voltages across each comb (see Figure 3). This printed circuit board pattern is similar to the standard pattern that the DuPont/UL/AT&T team will use for developing a new corrosivity standard.

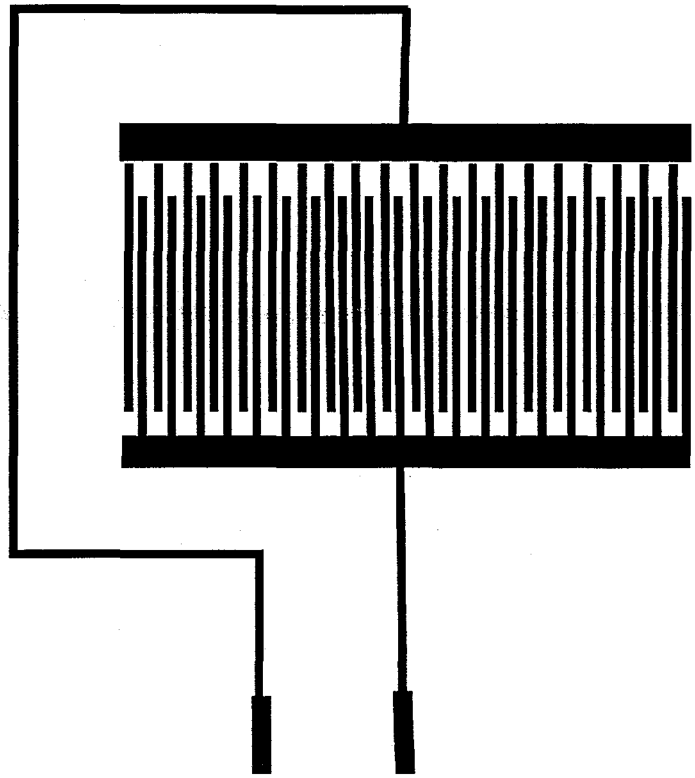

*Figure 3. Comb Pattern for Measuring Insulation Resistance of Printed Circuit Boards*

Other devices such as plastic-packaged optical isolators and memory chips are also being exposed to smoke and tested for functionality. The optical isolators are being tested during exposure to smoke while the memory chips are being tested before and after the exposure. The memory chips are powered up during the smoke exposure and are housed in one of two different packages, a plastic package and a hermetically sealed ceramic package.

## Description of tests

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

The procedure for exposing electronic equipment to smoke is as follows: The exposure chamber is a sealed Lexan box that contains the electronic equipment and into which all of the smoke is collected. The combustion cells, which are located underneath the exposure chamber, contain the fuel and are connected to the exposure chamber by a stainless steel chimney. Up to four such cells may be used depending on the total fuel load. Tungsten-quartz lamps located outside the combustion chamber provide radiant heat through the cell to the fuel inside. To aid in igniting the hot fuel, an electric sparker or a butane pilot flame is positioned above the fuel. The lamps are powered for 15 minutes each. For multiple cell burns, the lamps are powered sequentially. The equipment is exposed to the smoke for 1 hour after the smoke is first introduced. In the case of the multiplexer module, humidity was added to the exposure chamber after the 1-hour period from a portable steamer and in the case of the experimental digital system, by water heated with the radiant lamps. In the case of the circuit bridging components, humidity is added to the chamber by venting out the smoke and exposing the equipment to the environmentally controlled chamber that contains the testing equipment.

SNL has built two smoke exposure units, one following the dimensions of the ASTM draft standard (0.2 $m^3$ in volume), and a larger 1-$m^3$ unit required to test the experimental digital system built by ORNL. This is a static experiment in the sense that that all of the smoke produced is enclosed within the exposure chamber until the end of the exposure period. The 0.2-$m^3$ volume includes one combustion cell, while the 1-$m^3$ unit had four cells. The multiple combustion cells allow us to add smoke when desired and provided enough smoke to simulate a high fuel-load fire. The smoke production and exposure equipment is illustrated in Figure 4. The radiant heat lamps are adjusted so that a fixed heat flux level of either 50 kW/$m^2$ or 25 kW/$m^2$ is produced at the fuel surface to simulate full flaming and smoldering fires respectively. The heat flux is measured with a Schmidt-Boelter (thermopile) heat flux meter before each test to determine the amount of heat that would be incident on the fuel at the beginning of the test. Small variations in the positions of the lamps can affect the heat flux that is incident on the sample. As smoke is produced, the quartz chamber becomes coated with some soot and so the heat flux is reduced. No attempts were made to compensate for this effect..

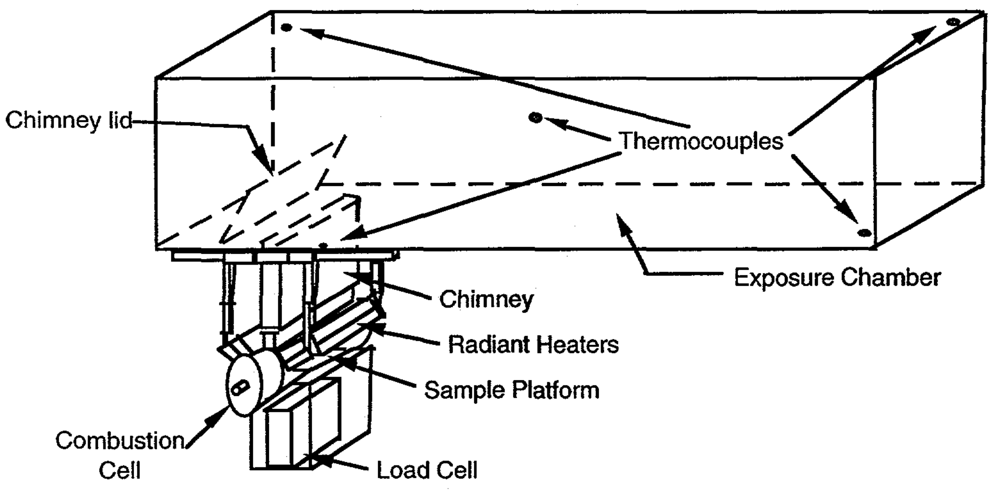


*Figure 4. Small Smoke Exposure Chamber*

Measurements of the condition of the smoke environment were also recorded. These included temperature, humidity before and after the exposure, smoke optical density, soot deposition on horizontal and vertical planes, chemical composition of gas, and soot. For the tests of the multiplexer modules, the copper lost from a standard corrosion probe was also measured. This measurement has been discontinued because of the cost and a lack of consistency.

Nowlen[4] reported on the types of fires that take place at nuclear power plants and their typical fuel load, where the fuel load is defined as the ratio of the weight of fuel consumed to volume of air. The highest fuel load occurs in small confined cabinet fires because of the limited volume of air in the cabinet. Of course, if the fire is very large, it will burn up all of the equipment in the cabinet, but for a small-to-moderate fire, the equipment may survive the heat and flames but not the smoke. For these preliminary smoke exposures, the fuel load was selected to simulate this high fuel load condition of 75 $g/m^3$. Fuel loads of 2.8 $g/m^3$, 20 $g/m^3$, and 160 $g/m^3$ were burned for the digital system tests. The lowest level of smoke represents the smoke density present in a location in the control room far away from a large cabinet fire located in the control room. The middle level represents the amount of smoke in the general areas around the plant (not the control room) given a fire in another cabinet nearby, and the highest level represents the amount of smoke present during a small fire if the equipment were located in the same cabinet as the fire. In the circuit bridging tests, some of the exposures correspond to low fuel loads, while others will correspond to high fuel loads.

Since the most abundant fuel in a nuclear power plant is cable insulation and jacketing material, cables were used to produce the smoke. The amount of cable material burned was determined by stripping the insulation material from a sample cable piece and weighing the fraction of the total cable weight that is made up of insulation. Typically, the insulation and jacketing materials comprised 50 to 75% of the total mass of the cable. Approximately 75 $g/m^3$ of fuel load was burned for each multiplexer test.

We expected that the type of fuel would determine how destructive the smoke would be. In a power plant there are several different types of cables used for instrumentation, power, and control. In addition, there are cables with insulation types that are no longer used, such as polyethylene and polyvinyl chloride (PVC), but which remain in place at the plants. For the multiplexer module tests, three types of cables were burned, one type in each test. Multiplexer test 1 used Brand Rex cable made with cross-linked polyethylene (XLPE) insulation with a chlorosulfonated polyethylene (CSPE) jacket. This cable is the third most frequently used cable in nuclear power containment.[5] Multiplexer test 2 used Anaconda Flameguard cable made with ethylene propylene rubber (EPR) insulation and a CSPE jacket. This is the most common combination of materials used for insulation in containments. Multiplexer test 3 used a Belden, non-nuclear qualified PVC jacketed and insulated cable. Although PVC cables are no longer widely used in nuclear power applications, they are still found in power plants and represent one of the most corrosive of cable insulation materials.

For the multiplexer tests, an electric sparker was run continuously to provide an ignition source for hot gases produced by the radiant heat lamps during the entire 15-minute period (consistent with the ASTM draft standard.) After 15 minutes the lamps were shut off, the chimney damper was closed, and a small fan mixed the smoke vapors. Since this was a static smoke exposure, the smoke was contained within the exposure chamber for the first hour of the test. The smoke chamber was sealed as well as possible to prevent smoke leaks. To allow for the expansion of air and smoke vapors caused by the initial heating and subsequent cooling of the contained air volume, an empty plastic bag was placed over one of the ports. One hour from the beginning of the test the smoke was vented.

In test 1, no humidity was added for the first 24 hours so that the equipment was exposed to a relative humidity (RH) below 20%. Since the draft standard recommends holding the RH at 75%, we attempted to do this after the preliminary 24 hours by setting a beaker of hot water in the exposure chamber. The test unit was left in the humid environment for 3 days. In test 2 we added humidity right after venting the smoke, using a portable hot steam humidifier. The humidity was adjusted by opening doors and running fans, but there was no control over the humidity overnight. In test 3 we added humidity right after venting the smoke. This humidity was added with a portable hot steam humidifier, but in a more controlled way than for tests 1 or 2.

For the experimental digital safety system, we burned a mixture of cables that would be found in power plants, as reported by Bustard and Holzman.[5] The amount of fuel was determined by the conditions we were trying to represent—control room for DTC and other more general areas for the PRS/MUX. Humidity was added by heating water with the radiant heat lamps. Carbon dioxide from a fire extinguisher was added to the tests of the DTC to represent one of the fire suppressants available in the control room. Table 1 shows the smoke conditions in which the experimental digital safety system was exposed. There were 3 levels of smoke for these tests; 3 g/m$^3$, 20 g/m$^3$ and greater than 65 g/m$^3$. In smoke exposure 3 on the FOMs, each of the three levels of smoke were tested, but the equipment was not cleaned between tests. Instead, after a 1 hour test period for a particular smoke level, an additional amount of smoke was added to bring the smoke to the new level. Six FOMs were exposed at a time. For the first two smoke levels, three of the FOMs were exposed without their plastic casings. Since these failed after the 20 g/m$^3$ smoke level, three additional FOMs were placed outside of the smoke exposure chamber and added to the circuit so that the testing program could continue.

*Table 1. Smoke Conditions for Experimental Digital Safety System*

| Test Name | Experiment Unit | Fuel burned (g/m$^3$) | Notes |
|---|---|---|---|
| 1 | PRS/MUX | 3.3 | No added humidity, electric sparkers |
| 2 | PRS/MUX | 2.8 | Added humidity, electric sparkers |
| 3 | DTC, no FOMs | 2.63 | No added humidity, electric sparkers |
| 4a | DTC, no FOMs | None | 2.64 lb. $CO_2$ added. |
| 4b | DTC, no FOMs | 2.8 | With sparkers–channel trip errors, restarted without sparkers, added 2.48 lb. $CO_2$ |
| 5 | DTC, no FOMs | 20.39 | No added humidity, butane lighter |
| 6 | PRS/MUX | 19.97 | Added humidity, butane lighter |
| 7 | PRS/MUX | 160.13 | No added humidity |
| 8a | FOMs | None | Temperature scan only |
| 8 | FOMs, some of these without case | 2.43 | No added humidity for next three tests |
| 8 | FOMs | 15.45 | Smoke added to previous amount |
| 8 | FOMs, replaced open FOM's that failed. | 46.42 | Smoke added to previous amounts |

The general procedure adopted for all the exposures was as follows:

1. The equipment under test (EUT) was placed in the exposure chamber and "baseline" data was obtained over a period of at least 3 h. This baseline test was performed on unexposed or cleaned equipment to assure the functionality of the equipment prior to the smoke exposure. (Note: The 1 m$^3$ exposure chamber is located inside of an environmental chamber). The environmental chamber was maintained at 75°F and 30% relative humidity (RH).

2. A predetermined mixture of different types of cables was burned to produce a desired smoke density in the exposure chamber. Most of these cables burned within 5 minutes.

3. In the case where the test called for smoke and humidity, a predetermined amount of water was heated inside the exposure chamber to provide the appropriate humidity.

4. The EUT was exposed to smoke for a total of 1 h. The smoke was then vented from the exposure chamber.

5. The EUT was left in the exposure chamber and monitoring continued for approximately 20 h. Chamber temperature was maintained at approximately 75°F and 30% RH.

6. The EUT was examined for damages/malfunctions and thoroughly cleaned. In general the cleanup involved removing the boards and blowing them with compressed air. The boards were then sprayed with Tech Spray no. 1677-125 Universal Cleaner Degreaser or Chemtronics Electronics Cleaner/Degreaser 2000.

The system tests were performed using spark ignition for the first three tests. During test 3, errors in the operation of the DTC started soon after the smoke was being produced. During the fourth exposure the same errors were found to be caused by the spark igniter. The DTC seemed to be more susceptible to errors caused by operating the sparker than the PRS/MUX. For tests on the DTC after test 4 a butane pilot lighter was used instead.

## Results of tests

### Preliminary Scoping Tests Using Multiplexer Board

Before each smoke exposure, the test units were assembled and tested to verify functionality. The test program was then run continuously throughout the smoke exposure and postexposure periods. The results of the multiplexer board exposures are listed in Table 2. The XLPE/CSPE cable (Brand Rex) and PVC cable (Belden) both ignited, while the EPR/CSPE cable (Anaconda Flameguard) only smoldered.

*Table 2. General Results of Smoke Exposure*

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

The smoke affected the equipment by stopping the host computer program rather than changing the reading for the current values as we had expected. The program stopped twice during Test 3. The first stoppage occurred at 0:08 (8 minutes) after the start of the test, while the radiant heat lamps were still on. The computer showed a timeout error, indicating that it was not receiving data from the input-output module. The program was restarted and the data were normal. The next malfunction occurred at about 1:00 (1 hour) when the chamber was beginning to be vented. The program did not stop; however, the numbers in the data file were unusual and the printout on the screen was shifted. At 1:20, steam was added to the environment so that the relative humidity of the chamber was 75% RH. The program stopped again at 1:29 and showed the same timeout error as before.

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

To further explore failures that occurred during test 3, the equipment was periodically tested for 1 month after the exposure to smoke. The equipment continued to operate normally until humidity was added in the form of mist from a cool water mister. The mist condensed on the backplane and caused it to short. When the backplane began to short, the interrogation program stopped again and produced the same timeout error message as at 0:08 and 1:29 into the smoke exposure. This time, however, the equipment was permanently damaged and would not restart.

## Preliminary Results From System Tests

The smoke exposures to the experimental digital safety system caused a variety of system errors. The explanation of the types of system errors that occurred for each test is shown in Table 3. It is important to note that after the various units were exposed to smoke, the baseline tests were no longer error free. Communication errors were observed at all levels of smoke, ranging from network retransmissions at low smoke densities to serial link timeout errors at higher smoke densities. Although errors were observed, no functional failures occurred during the tests related to general area fires. Therefore there is evidence that digital equipment exposed to a small control room fire is likely to perform properly during a reasonably short period of exposure provided that the equipment is not located in the same cabinet as the fire source.

*Table 3. Failure Types from Smoke Exposures.*

| | B1 | S1 | B2 | S2 | B3 | S3 | B4 | S4A | S4B | B5 | S5 | B6 | S6 | B7 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Timeout from F.O. serial link to Host chn 2 | | | | | | | | | ● | | | | | | | ● |
| Timeout from F.O. serial link to Host chn 3 | | | | | | | | | ● | | | | | | | ● |
| Timeout from F.O. serial link to Host chn 4 | | | | | | | | | ● | | | | | | | ● |
| DTC had to retransmit data to Host | | ● | ● | ● | | | ● | ● | | | ● | ● | ● | ● | ● | |
| | (18h) | (1h) PRS/ MUX | (18h) | (1h) PRS/ MUX | (18h) | (1h) DTC w/o FOMs | (18h) | (2h) CO2 only | (1h) DTC w/o FOMs w/$CO_2$ | (18h) | (1h) DTC w/o FOMs | (18h) | (1h) TRP/ MUX w/HI RH | (18h) | (1h) TRP/ MUX | (4h) FOMs only |

B = Baseline test.
S = Actual smoke test (i.e., EUT was subjected to smoke during this time).
For the actual smoke tests (S1 through S8), the number in parentheses indicate the smoke exposure time, after which the test chamber was vented.
The failure modes indicated occurred within this window. For the baseline tests the numbers in parentheses indicate the test duration (the EUT was not subjected to smoke during this time).

It is important to note that an actual power plant safety system can, and typically is designed so that communication failures will not prevent the safety channel from performing its function. For example, the channel can easily be designed so that failure to receive data in a specified time will cause that channel to trip.

The computers under test exhibited no failures resulting from smoke particle deposition although soot was spread throughout each chassis by the computer's fan. It is believed that the conformal coating applied during fabrication of the main microprocessor boards served as an extra layer of protection against circuit bridging by conductive particles. This result suggests that packaging and integrated circuit fabrication techniques may provide some of the most important elements of a digital system's capability to withstand smoke exposure.

## Preliminary Results of Circuit Bridging Tests

The circuit bridging tests have begun at Sandia National Laboratories to determine how the insulation resistance of chip packages and printed circuit boards is affected by smoke. The devices being tested include through-hole devices such as a DIPs (dual-in-line packages) and transistor outline cans. Surface-mounted chips such as SOICs (small-outline integrated circuits), flat packs, and leaded and leadless chip carriers are also included. Interdigitated combs to measure the surface insulation resistance are being tested at dc voltages ranging from 5 V to 160 V. Figure 5 shows an example of the results for a 160-V-biased comb from the very first test. The comb was exposed to 2.8 $g/m^3$ of smoke from a mixture of cables burnt at a high radiant temperature in flaming mode. This fuel load corresponded to the exposure that a piece of equipment would be expected to experience if it were located across the room from a small fire. The combs were exposed to smoke for 1 hour and then to a 75 °F and 75% RH environment for 23 hours.

The relative resistance of four combs is plotted in Figure 5. These resistances are normalized to the value of resistance of each comb at the start of the smoke exposure. The uncoated comb was exposed directly to the smoke; the coated comb was sprayed with an acrylic conformal coating and then exposed to the smoke after drying overnight. The third uncoated comb was placed in a computer chassis whose fan was running, and the fourth uncoated comb was placed outside the smoke exposure chamber but inside an environment chamber which was controlled at 75 °F and 75% RH. The smoke exposure began after the first set of resistance values was measured. The insulation resistance of the uncoated board decreased a few minutes after the exposure began. Post-test examination of the uncoated board revealed a blackened spot on the comb, which is a likely area of low resistance. The conformal coating seems to be an effective way to prevent smoke from changing the insulation resistance of the printed circuit board. The comb in the chassis was affected by the smoke for a short time during the smoke production, but it seemed to recover later. This behavior may be related to the short-term failures observed in the tests of the multiplexer modules and experimental digital system.

## Conclusions

Smoke can affect the operation of digital equipment. It particularly impedes communication transfer from one instrument to another, as shown in the experimental digital safety system. These problems in communication transfer, however, were mostly temporary and with adequate software could be compensated by repeated attempts in transferring the data. The temporary nature of these problems was similar to that encountered with the multiplexer tests. In both cases, this indicates that smoke may be causing intermittent shorts between circuits. These shorts may be temporary because the material that caused the short may be burnt away by the current that passes through it.

Humidity may also be an important factor in creating temporary shorts. Water is one of the combustion by-products of most fires. Water from sprinklers and misters is also used to combat fires. As shown in the PVC multiplexer module test, the addition of humidity was a factor contributing to communication errors.

Another fire suppressant, $CO_2$, was applied to the experimental digital safety system. This test was conducted while all digital parts were encased in a chassis, so the equipment was somewhat protected from the drastic change in temperature that discharging this gas causes. The addition of $CO_2$ had very little effect on the equipment.

Exposure of the experimental digital safety system to smoke was important to show that smoke can indeed affect the operation of a trip channel; however, because the equipment was repeatedly exposed to smoke after cleaning, it is not known how much smoke would cause faulty operation if the equipment had not been previously exposed. Other unknowns that could affect equipment may become apparent as the tests progress.

The results from the circuit bridging tests are promising. The insulation resistance seems to confirm the behavior of the full digital systems by decreasing when smoke is applied and in some cases returning to the starting value after the smoke deposition stops. The advantage to these tests is that the effects on the components are simple to diagnose, each part that is tested has not been previously exposed, and many factors, such as smoke conditions and protection of the boards, may be varied.

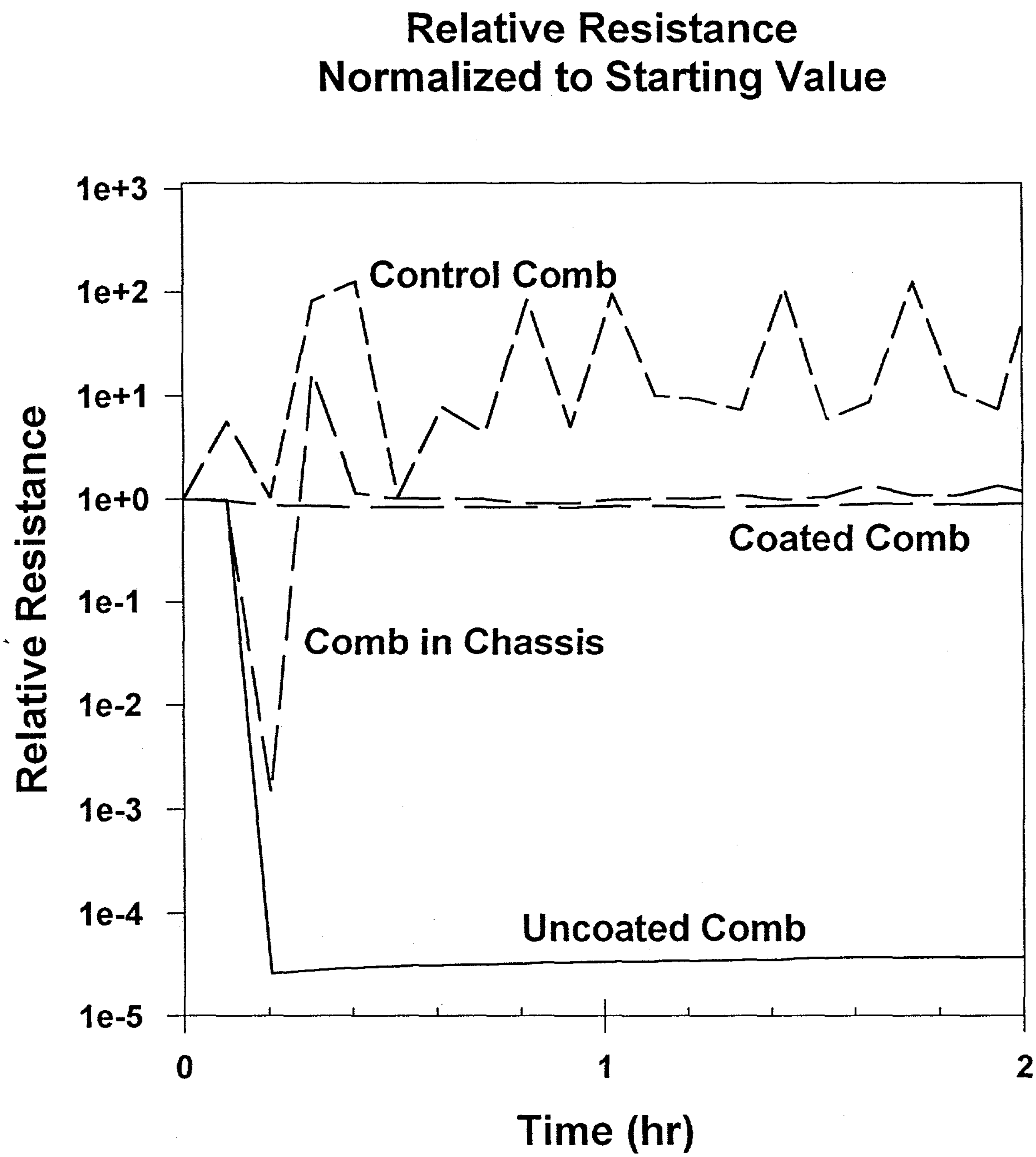


*Figure 5. Circuit Bridging Test on 160 V Comb pattern.*

## Summary

The program to assess the impact of smoke on digital equipment has discovered that the important failure mechanisms are not only long-term effects such as corrosion, but also short-term and perhaps intermittent effects of circuit bridging. Work in this program is continuing in an effort to determine what methods of protecting equipment are effective and what smoke conditions are most damaging. These results may improve the safety of our nuclear plants as they modernize and replace their analog with digital equipment.

## References

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