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Screening Tests of Representative Nuclear Power Plant Components Exposed to Secondary Environments Created by Fires

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SCREENING TESTS OF REPRESENTATIVE NUCLEAR POWER PLANT COMPONENTS EXPOSED TO SECONDARY ENVIRONMENTS CREATED BY FIRES

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Abstract

This report presents results of screening tests to determine component survivability in secondary environments created by fires, specifically increased temperatures, increased humidity, and the presence of particulates and corrosive vapors. Additionally, chloride concentrations were measured in the exhaust from several of the tests used to provide fire environments. Results show actual failure or some indication of failure for strip chart recorders, electronic counters, an oscilloscope amplifier, and switches and relays. The chart recorder failures resulted from accumulation of particulates on the pen slider mechanisms. The electronic counter experienced leakage current failures on circuit boards after the fire exposure and exposure to high humidity. The oscilloscope amplifier experienced thermal-related drift as high as 20% before thermal protective circuitry shut the unit down. In some cases, switches and relays experienced high contact resistances with the low voltages levels used for the measurements. Finally, relays tested to thermal failure experienced various failures, all at temperatures ranging from 150^{o}C to above 350^{o}C. The chloride measurements show that most of the hydrogen chloride generated in the test fires is combined with particulate by the time it reaches the exhaust duct, indicating that hydrogen chloride condensation may be less likely than small scale data implies.

Table of Contents

Page

Table of Contents (continued)

List of Figures

List of Figures (continued)

List of Tables

Executive Summary

During a nuclear power plant fire, numerous safety-related components may be exposed to secondary environments created by the fire. These environments include increased temperature levels, increased humidity levels, and the presence of particulates and corrosive vapors. Past accounts of fires have reported extensive damage by secondary environments created by fire, but none state whether any electrical equipment was damaged sufficiently to prevent it from performing satisfactorily. Consequently, this study was undertaken to screen the components considered to be most vulnerable to secondary environments created by fire. Also, temperature measurements were made at numerous locations, and chloride concentrations of the room exhaust were monitored in several of the tests to help characterize the fire environments.

Twenty-four switches, thirteen meters, five relays, two strip chart recorders, two electronic counters, one power supply, one power amplifier, and one oscilloscope amplifier were tested in actual fire environments created by burning cabinets in a room. The component locations and orientations were varied and some components were installed with protective covers removed. In addition, three relays were tests to thermal failure in an environmental chamber. The relays were exposed to step increases in temperature level until failures were observed.

Results show actual failure or some indication of failure for the strip chart recorders, the electronic counters, the oscilloscope amplifier, and the switches and relays. The first chart recorder tested had the covers removed to increase the severity of the environment and it failed to operate after the test. The failure resulted from the accumulation of particulates on the pen slider mechanisms and functionality could not be easily restored by cleaning the sliders. A second chart recorder was tested in a panel-mounted configuration with all covers intact. It experienced significantly less particulate accumulation on the pen sliders. However, one of the three pens did not work properly after the test, although functionality was easily restored by exciting the malfunctioning channel with a rapidly changing voltage which was sufficient to clean off the light particulate accumulation.

The first electronic counter tested had the covers removed and experienced heavy particulate deposition, but continued to function normally after the fire. Subsequently, the counter was exposed to a high humidity environment to simulate high humidity that may be encountered during or after a fire. The electronic counter experienced leakage current failures on two different circuit boards after the humidity exposure.

The oscilloscope amplifier tested experienced thermal-related drift as high as 20% before thermal protective circuitry shut the unit down. Switches and relays experienced high contact resistances in some cases with the low voltage levels used for the measurements.

Finally, the relays tested to thermal failure experienced various failure modes, all at temperatures ranging from 150°C to above 350°C. Two Agastat GPI relays tested both had failures associated with the relay sockets warping severely. Both short circuits and open circuits were observed in the sockets. One additional failure of the Agastat relays was a melted contact support on the contact carrying a load current. One General Electric model HMA relay had its coil lead wires shorted above 350°C, resulting in a fire in the test chamber.

The results show that most components survived the environments created by the cabinet fires. Failure modes for many of the components considered to be most likely to malfunction during a fire were tested either directly or indirectly. The one notable exception identified is high voltage breakdown which could occur on motor control centers and switchgear.

Several additional secondary environments created by fire remain to be addressed. These include the following: 1) direct spray from suppression activities, either manual or automatic, 2) response of cool components to steam exposure resulting from from suppression activities (although high humidities were addressed by the humidity exposures, relatively cool components were never exposed to rapidly changing humidity which would likely cause condensation), and 3) hydrogen chloride/humidity interactions (condensation) which might occur in certain circumstances.

1.0 OBJECTIVES

Accounts of several past fires [1-9] have reported significant levels of damage caused by secondary environments created by fire, primarily as a result of hydrogen chloride generated by burning polyvinyl chloride (PVC). Little mention of thermal damage is included in these reports with none indicating whether any electrical equipment exposed to the secondary environments created by fire actually failed electrically. Clearly, much electrical equipment has required cleaning or replacement because of fire damage with the great New York telephone fire [4] a significant example; millions of switches and relays were cleaned and much equipment was replaced. The main objective of this work was therefore to assess the functionality of representative nuclear power plant components when subjected to secondary environments created by fire. The fire environments were established by other test programs, specifically a cabinet fire test program run by Sandia National Laboratories [10,11], conducted in part at Sandia and in part at Factory Mutual Test Center.

An additional objective of this work was to establish the secondary environments created by fire that power plant components could be exposed to as a result of the cabinet fires. To accomplish this additional objective, temperatures were measured throughout the fire test rooms and a system was developed to measure the amount of chlorides (expected to be mainly hydrogen chloride) leaving the room in the ventilation duct.

This report documents the tests conducted and the data obtained for component functionality before, during, and after the tests and the data obtained for the chloride measurements.

2.0 TEST PHILOSOPHY AND APPROACH

The basic premise for the tests run was that some components may be easily damaged by exposure to secondary environments created by fire. Secondary environments include increased temperature levels, increased humidity/ moisture levels, and exposure to particulates and corrosive vapors generated by the fire. A report prepared by NUS Corporation [12] as a subcontract to Sandia National Laboratories judged components for their potential for damage by secondary environments created by fire. Each category of component was ranked from 0.00 to 1.00 based on criteria for equipment functionality and equipment damageability. The top-ranked components were thus considered most likely to fail when exposed to secondary environments created by fire. The top fourteen ranked components and their ranking are included here for completeness and are, in order:

Equipment Type	Relative Score
Recorders	0.79
Logic Equipment	0.77
Controllers	0.71
Power Supplies	0.67
Meters	0.61
Solid State Relays	0.60
Electromechanical Relays	0.59
Transmitters (Pressure, Level, Flow)	0.50
Hand Switches/Pushbuttons	0.50
Battery Chargers/Inverters	0.49
Motor Control Centers	0.49
Switchgear	0.49
Batteries	0.44
Temperature Switches	0.41

Components were selected for testing based on this ranking and the additional criteria of component usage in nuclear power plant safety systems (based primarily on one selected nuclear power plant) and what components were on hand or readily available. Components were tested in different configurations (covers removed or intact, different orientations, different locations, etc.) with some powered and some not powered. Different components had different expected failure modes and in some cases attempts were made to make the expected failure modes more likely (for conservatism or to represent other components). For example, the covers on some components were removed to allow more penetration of the environment into the component.

3.0 EXPERIMENTAL

3.1 Environment Creation and Planned Environmental Profiles

The components were tested in environments created by a burning cabinet in a room with the exception of three relays which were tested to their thermal failure limits in an environmental chamber. Some of the components tested in the actual fire environments were subsequently subjected to humidity environments in another environmental chamber. The reason for exposing the components in the humidity chamber was to try to account for the potential effects of high humidity during or after a fire. High humidity can be created by any combination of the following: high humidity in purge air used to remove smoke from the burning room, generation of moisture as a combustion product, and humidity created by water suppression equipment used on the fire. In the cabinet fire tests, the only real contributor to increased humidity was the combustion process since the ambient humidity was relatively low during all of the tests and no water suppression was ever used.

A description of the facilities where the fire tests were conducted, as well as comprehensive data for the room environment (temperatures, gas species concentrations, heat flux measurements, smoke density measurements, etc.) may be found elsewhere [10,11]. General arrangement drawings are shown in Fig. 1 for the tests run at Sandia and in Fig. 2 for the tests run at Factory Mutual.

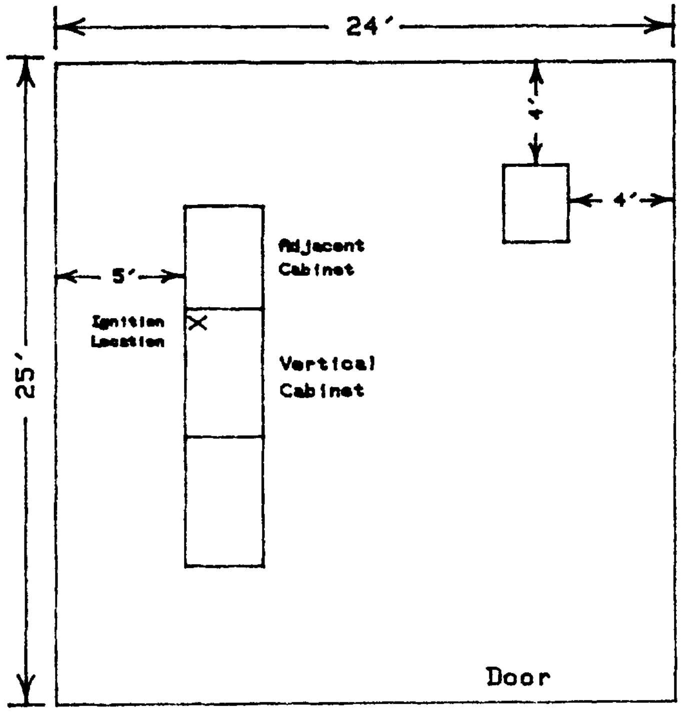
The environmental chamber used for the three relays tested to thermal failure was a chamber equipped to control temperature to levels significantly higher than expected failure levels for the relays. The purpose of the environmental chamber testing was to test components to thermal limits. Failure temperatures can then be compared with actual temperatures from fires to aid in establishing thermal margins. The humidity chamber used to test some components was equipped to control both temperature and humidity.

No specific profiles could be planned for the components put in the cabinet fire tests. Rather, the components were exposed to whatever environment was created by each fire.

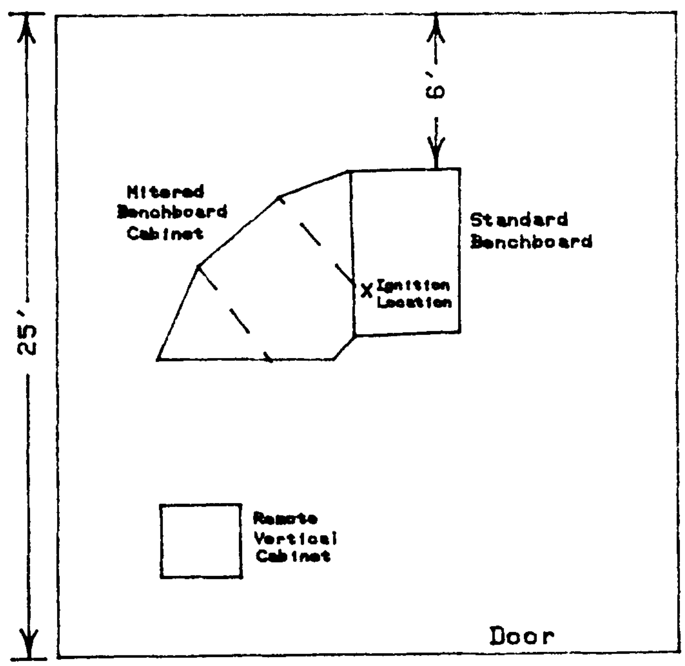
The environmental profile planned for testing the three relays to establish their thermal failure limits was to begin by ramping the test chamber up to 50°C and then stepping the temperature up by 10°C every 10 minutes.

3.2 Component Procurement

The switches, meters, and chart recorders tested were obtained as excess inventory of components which had been initially intended to go into actual service in nuclear power plants. The relays tested were obtained directly from the suppliers and are effectively identical to Class 1E qualified relays sold to nuclear power plants, although the relays were not specifically procured to 1E specifications. The major difference for class 1E relays is the amount of paperwork provided and in some cases more controls on the materials used for construction and/or a



(a)



(b)

Fig. 1 General Arrangement Drawings for Tests Run at Sandia
(a) Tests 1 and 2 (b) Test 3

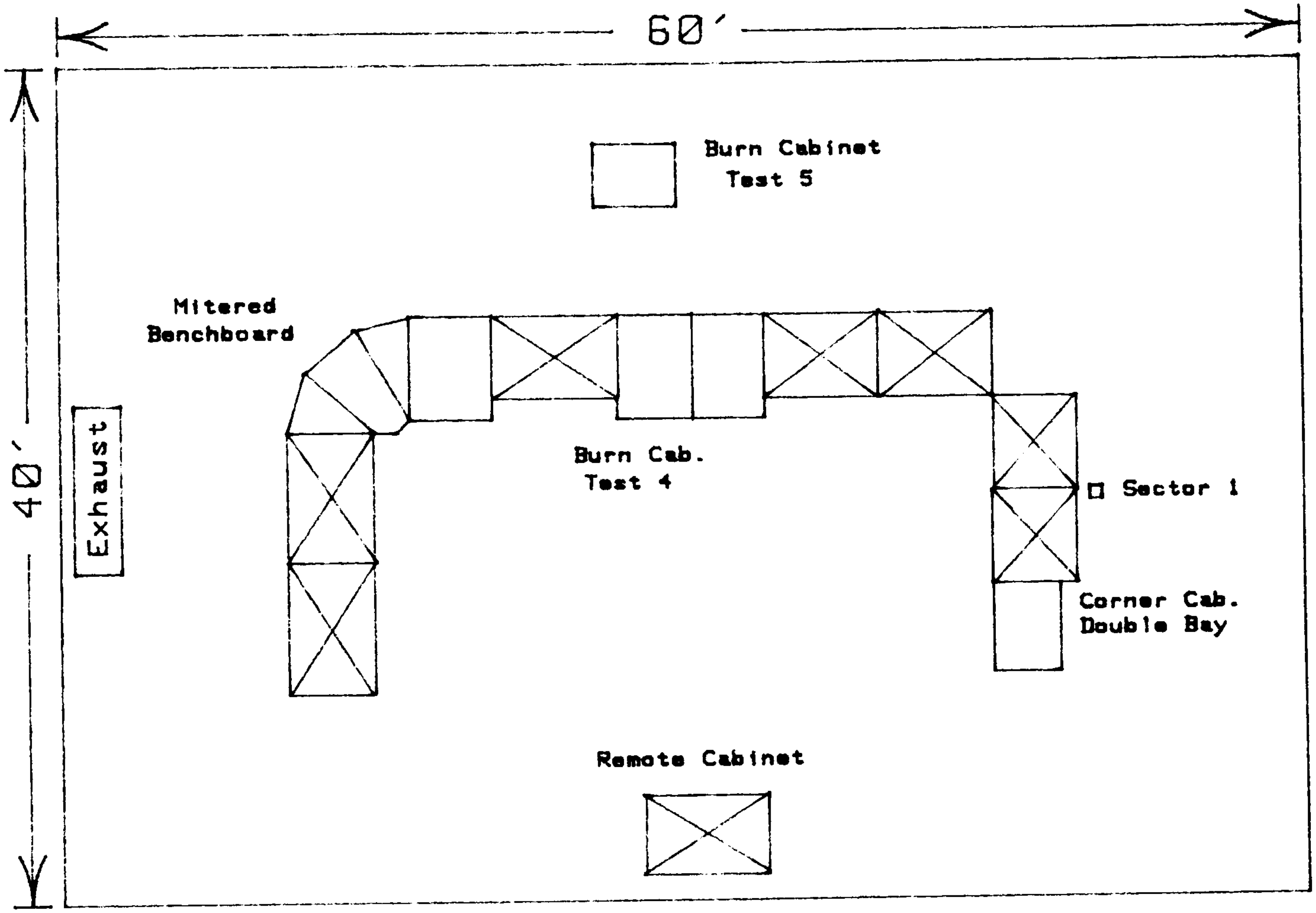


Fig. 2 General Arrangement Drawing for Tests 4 and 5
Run at Factory Mutual

separate production lot to insure traceability. The remaining components were selected from available equipment at Sandia and were chosen in an effort to establish whether generic types of equipment might be vulnerable to fire environments. The particular equipment chosen has no direct relationship with equipment used in power plants but does have similar kinds of subcomponents. For example, although amplifiers do not appear on the component ranking list, they were chosen to test because they have subcomponents similar to some components on the list. Since the purpose of the component tests was to screen component vulnerability to secondary environments created by fire and not to test or qualify particular components, the decision to use available generic components was justified. No evidence was found before or after testing to indicate that the observed survival or failure of components would be any different for pedigreed equipment. In fact, the equipment tested represents components normally installed in benign power plant control areas with very little special qualification required (primarily seismic and some aging considerations).

3.3 Chloride Ion Measurement System

The system used to measure chloride ions in the room exhaust is described in Appendix A.

3.4 Quantity and Location of Components in Cabinet Tests

A test matrix for components tested in cabinet tests is given in Table 1 with a description of each test in Table 2. Components were positioned at different locations throughout the room. The individual component locations and model numbers may be found in the results section 4.0.

3.5 Physical Configuration of Relays Tested to Thermal Failure

The relays tested in the environmental chamber were positioned vertically on a flat metal base in the chamber. The base was isolated from direct contact with the heated wall by ceramic standoffs. A typical installation is shown in Fig. 3.

Table 1 Test Matrix for Components in Cabinet Tests

Test Number *	#1	#2	#3	#4	#5
Switches	2	3	0	10	9
Meters	4	4	0	3	2
Relays	0	0	0	3	2
Chart Recorder	0	0	1	1	0
Electronic Counter	0	0	1	1	0
Power Supply **	0	1 ***	0	1 ***	1 ***
Power Amplifier	0	1	0	0	0
Oscilloscope Amplifier	0	1	0	0	0

* See Table 2 for a description of the tests.
** Some components also include power supplies.
*** The same power supply was tested each time.

Table 2 Cabinet Test Descriptions

Test Number	Test Number in Refs. 10 and 11	Description of Test
1	PCT 1	Unqualified cable in vertical cabinet with closed doors. Peak HRR * 185 kW. Duration 40 minutes. Max. temp. in room 60°C.
2	PCT 2	Unqualified cable in vertical cabinet with open doors. Peak HRR 995 kW. Duration 15 minutes. Max. temp. in room 160°C.
3	PCT 5	Unqualified cable in benchboard cabinet with open doors. Peak HRR 791 kW. Duration 20 minutes. Max. temp. in room 210°C.
4	FM 4	Unqualified cable in benchboard cabinet with open doors. Peak HRR 860 kW. Duration 20 minutes. Max. temp. in room 125°C.
5	FM 5	Unqualified cable in vertical cabinet with no doors. Peak HRR 620 kW. Duration 20 minutes. Max. temp. in room 66°C.

* HRR=Heat Release Rate

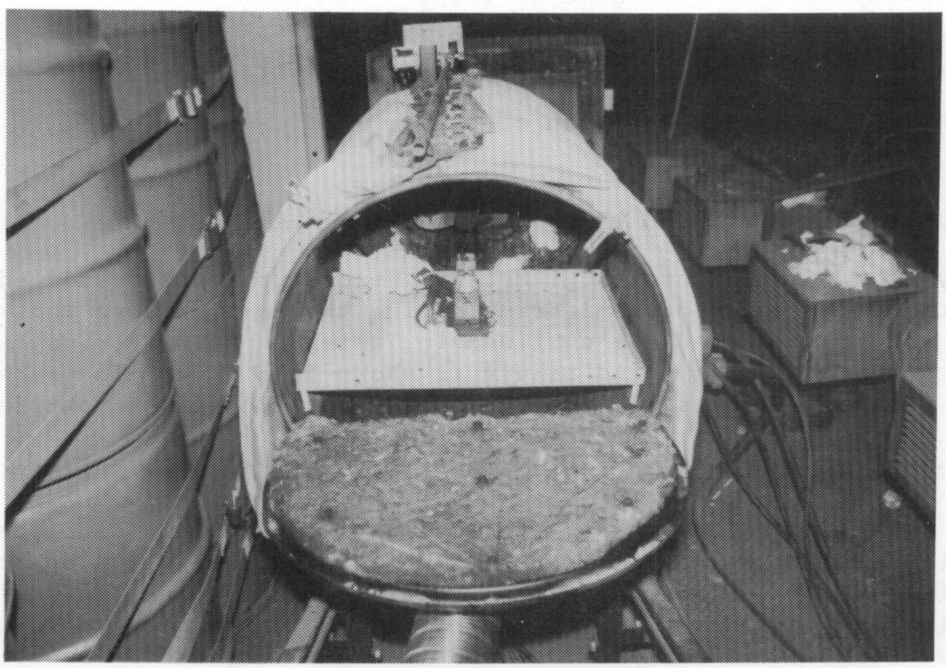


Fig. 3 Typical Configuration of Relay in Environmental Chamber

Table 3 Powered Components in Cabinet Tests

Test Number	Component	Description of Powering	Description of Monitoring
2 *	Power Supply	115 Vac line for main power.	Output voltage for maintaining set value.
2	Power Amplifier	115 Vac line for main power; dc input voltage	Output voltage for maintaining correct multiple of dc input voltage.
2	4-channel amplifier	Same as power amp.	Same as power amp.
3	Counter	115 Vac line for main power.	None continuously; checked self test immediately after fire.
4	Switch	115 Vac, 3 A load on one set of contacts.	Load current for continuity; Adjacent contact for leakage current.
4	Counter	Same as counter in test #3.	
4	Relay #1	115 Vac, 3 A load on one set of contacts; 115 Vac to coil.	Coil current, load current, and adjacent contact leakage current.
4	Relay #2	115 Vac to coil.	Coil current.
4	Power Supply	Same as power supply in test #2.	
5	Switch	Same as switch in test #4.	
5	Relay #1	Same as relay #1 in test #4.	
5	Relay #2	Same as relay #2 in test #4.	
5	Power Supply	Same as power supply in test #2.	

* See Table 2 for description of tests.

3.6 Electrical Configuration of Components in Cabinet Tests

Many of the components (e.g. meters, recorders) were installed in the room without any power or monitoring during the test. Those that were powered and/or monitored are outlined in Table 3. An electrical schematic for the powered and monitored relays is shown in Fig. 4. The schematic for the powered switches was identical except the coil was not present.

3.7 Electrical Configuration of Relays Tested to Thermal Failure

The relays tested to thermal failure were powered, loaded, operated, and monitored during the tests. A 115 Vac line source was used to operate the coils and selected contacts were loaded with a 115 Vac load of nominally 3 amps or a 115 Vac motor starter. Different contacts were monitored for leakage currents, contact resistances, and relay operability verification. Two of the relays tested were four-pole, double-throw (4PDT) relays and one was double-pole, double-throw relays (DPDT). The circuit diagram for the 4PDT relays is shown in Fig. 5. The circuit diagram for the DPDT relay was very similar to Fig. 5, except with two less contacts.

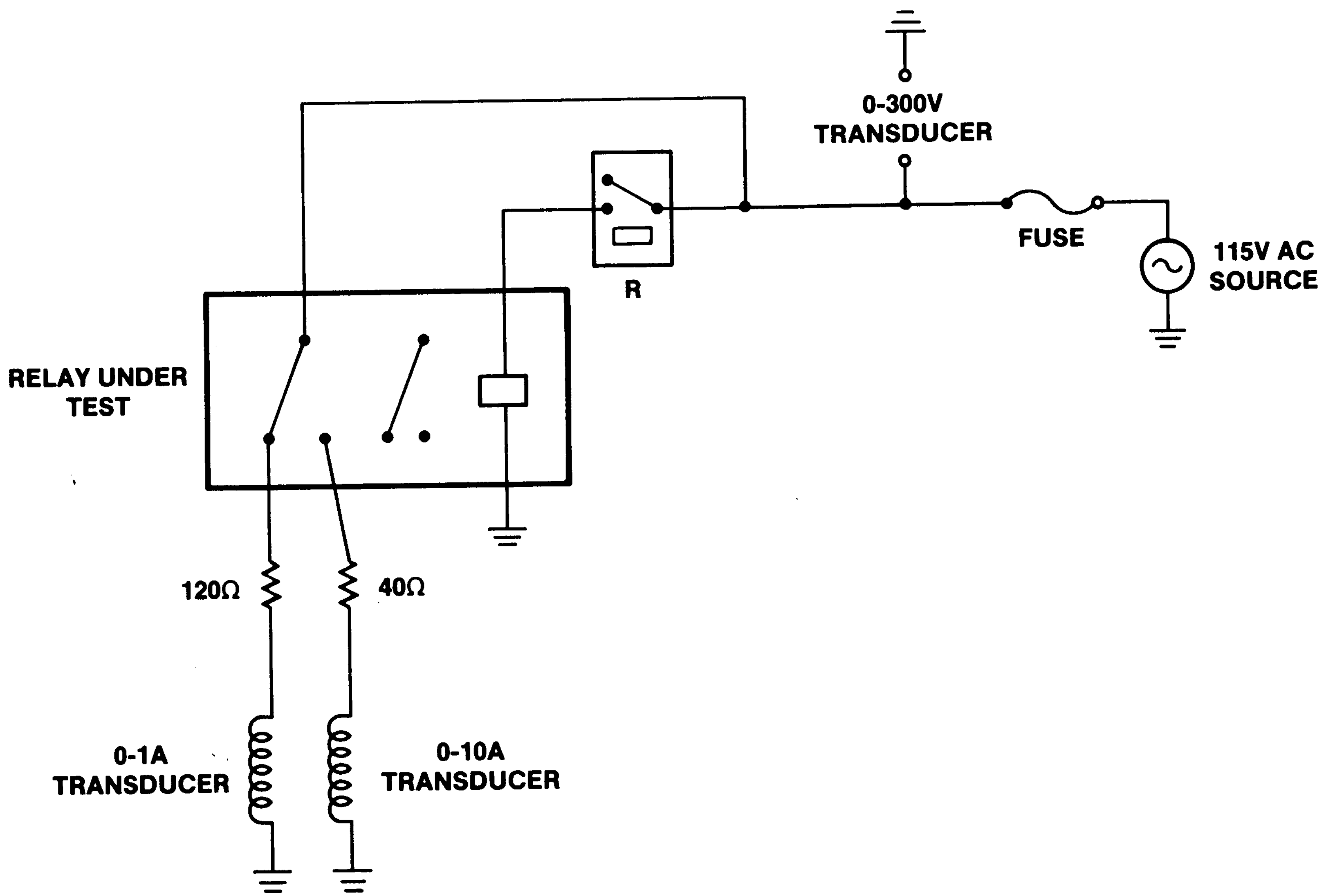


Fig. 4 Schematic for Relays in Cabinet Tests

4.0 RESULTS

The results presented in this section are organized by component. The generic components from the ranking described in section 2.0 which have similar expected failure modes to the tested component are also indicated. For example, leakage currents between the terminals of a terminal block and between the terminals of a switch or relay are expected to be governed by the same phenomenon. Consequently, although terminal block leakage currents were not directly tested, they were indirectly tested by the monitoring of leakage currents on relays and switches.

4.1 Components Tested

4.1.1 Switches

4.1.1.1 General

The switches were tested in various orientations with some panel mounted in a cabinet with an open back, some mounted on their sides to allow more particulate deposition in the contact area, and some put upright on horizontal surfaces. The amount of particulate deposition varied significantly with different tests, with ventilation rate and room size apparently the most important considerations with a given size fire. With higher ventilation rates and the larger room, much less particulate was deposited on the switches. In fact, the switches in test 5 were found to be virtually free of particulate. The particulate which did appear in test 5 was very light and could be removed with very little effort (light blowing or even just picking up the switch). In contrast, the lower ventilation rate of test 4 produced more particulate on the switches. The switch that was powered in test 4 was noted to have particulate polarized between adjacent powered and grounded terminals as shown in Fig. 6; similar behavior was not noted in test 5.

The switches experienced varying degrees of corrosion, with more severe corrosion after aging for days to weeks after the tests. One switch that was exposed in the humidity chamber for 12 days at 70% humidity appeared quite corroded with the appearance of rusting in the contact areas. In no case did the corrosion cause any noted malfunctions except for some high contact resistances as discussed in Section 4.1.1.4.

4.1.1.2 Unpowered Switches

The unpowered switches tested are summarized in Table 4. None of the switches were damaged sufficiently by the fire to prevent normal operation except that a few contacts required ac voltage stresses of up to 15 volts to allow them to start conducting (15 V was required on only one set of contacts). An application in a power plant using a switch (may be extended to a relay) in a low voltage instrumentation circuit such as an RTD circuit (typically 4 Vdc) or a thermocouple circuit (typically mV level signals) could potentially fail under these circumstances. No effort has been made to find out if any power plants have switching devices in any of these circuits, but it is considered unlikely. Further, the switches which were found with the high contact resistances were of larger varieties (more than 5 A contact ratings typical); smaller rated switches which were tested were effectively enclosed and did not exhibit any of the high contact resistances.

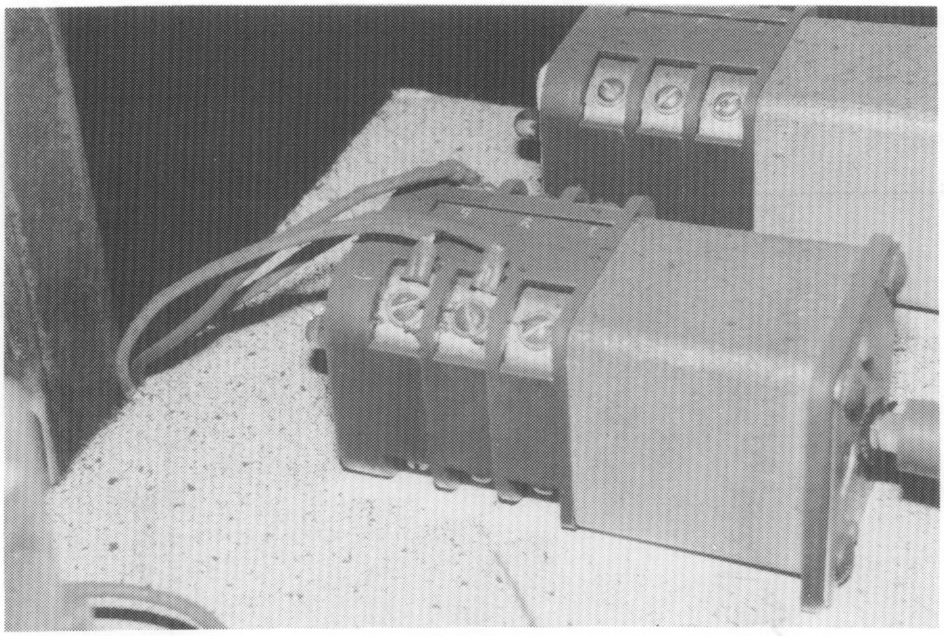


Fig. 6 Polarized Particulate Between Adjacent Terminals of Switch

4.1.1.3 Powered Switches

One switch was powered and monitored during each of tests 4 and 5. Both were located about four feet from the floor at sector 1 (see Fig. 2). The ac supply voltage remained between 108 and 116 Vac in both tests. The load current to the switch in test 4 is shown in Fig. 7 and to the switch in test 5 is shown in Fig. 8. Both show no evidence of the switch failing to carry its load. Leakage current for the switches never reached the level detectable by the ac current sensors used in the tests (0.25 mA) and therefore the data is not presented. Contact resistances and insulation resistances showed no evidence of problems except one of the contacts of the switch in test 4 took about 15 Vac stress to get a normal value in the milliohm range (original value was about 100 kohms).

4.1.1.4 Humidity Exposure of Switches

One switch from test 4 and one from test 1 were put in a humidity chamber at about 27°C (80°F) and 70% relative humidity for about 12 days to see if humidity exposure at moderate levels for prolonged periods following exposure to fire environments would cause any equipment operability problems. Neither of the switches exhibited any adverse effects except one set of contacts had a high contact resistance which was quickly corrected by the application of a low dc voltage stress across the contacts.

4.1.1.5 Applicability of Switch Data to Other Components

This section describes the expected failure modes of switches and what other components would be expected to experience similar failure modes.

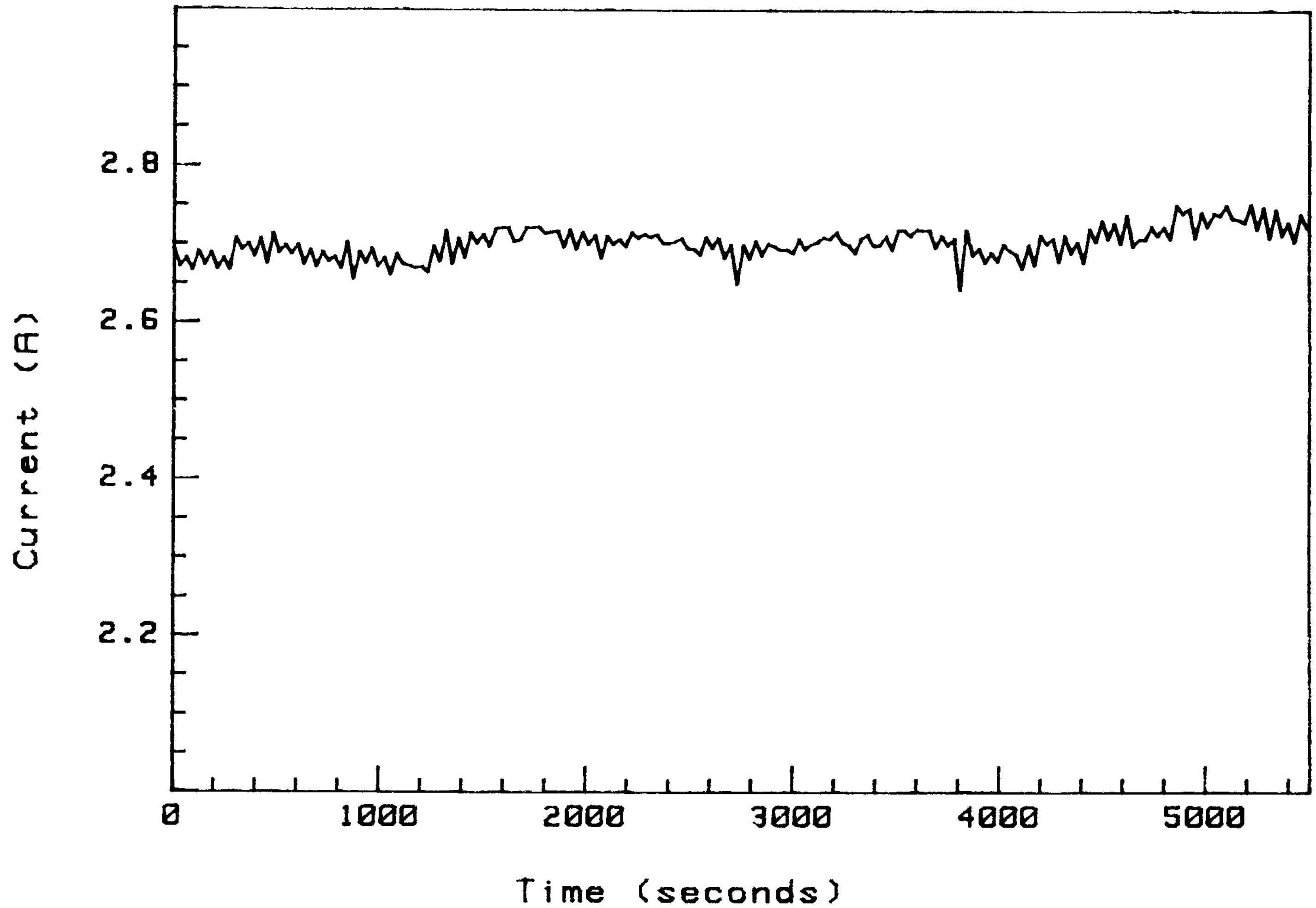


Fig. 7 Load Current to Switch in Test 4

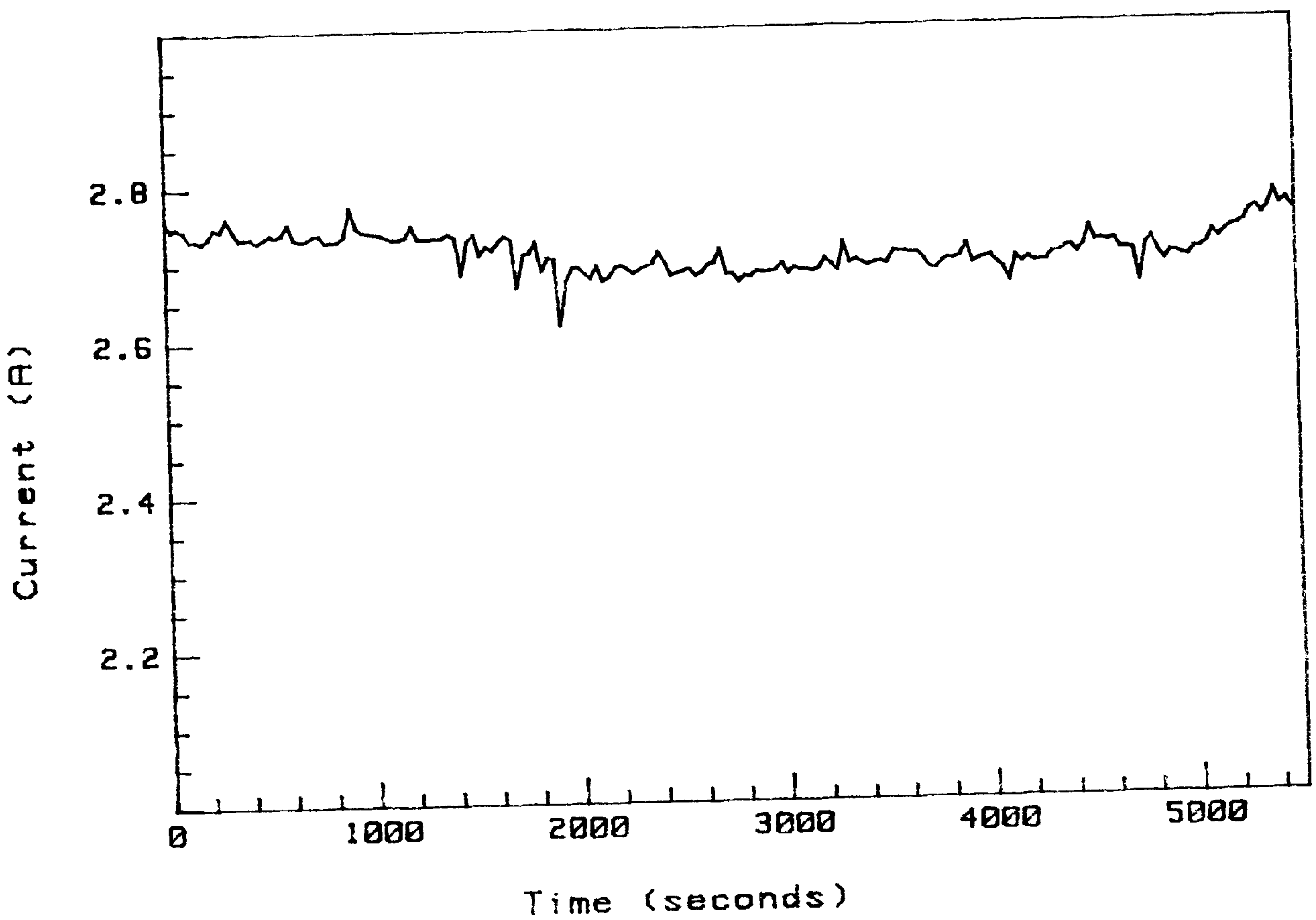


Fig. 8 Load Current to Switch in Test 5

Where the switches did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

The general failure modes expected for switches are failure to carry a load or leakage currents/shorts between terminals or to ground. The monitored switches gave continuous data for load current and leakage current. The unpowered switches give data for before and after contact resistances and insulation resistances. Based on calculations of condensation temperatures for a hydrogen chloride, water, and air system, together with an indication of the amount of hydrogen chloride generated by burning PVC [13], the potential for hydrogen chloride condensation on cool components appeared significant. Consequently, many of the switches were left unpowered because hydrogen chloride condensing on the switches could lead to rapid corrosion or high leakage currents when the switch was later powered up. The switches that were powered were intended primarily to monitor leakage currents on the premise that particulates and hydrogen chloride might cause conductive media on the switches, leading to immediate leakage currents.

Components not tested which might experience similar failure modes include motor control centers (MCCs), switchgear (SG), terminal blocks, and temperature, pressure, and limit switches. All of these components have contacts and connections which are generically similar to those found on switches. The switch data should effectively cover all terminal block failure possibilities under the same conditions. However, the remaining equipment may have additional failure modes not addressed by switch data alone. For example, failure modes of a motor controller failing to engage could be unrelated to any switch failure modes.

4.1.2 Relays

4.1.2.1 General

In general, the relays appeared similar to the switches described in section 4.1.1.1. All of the relays tested were originally protected by some type of cover, but some of these covers were removed to allow more environmental penetration and simulate other relays which are of open construction. The powered and monitored relay in test 4 exhibited the same type of particulate polarization that was experienced by the switch in test 4. The relays in test 5 showed very little evidence of particulate deposition, similar to the switches in test 5.

4.1.2.2 Unpowered Relays

Only one relay was left completely unpowered in the tests (test 4). This relay was located in the corner cabinet toward the bottom (about one foot from the floor) and the cover of the relay was left off to expose the inside of the relay as much as possible. The only evidence of any degradation resulting from the fire was light corrosion on the metal parts of the relay. The corrosion was insufficient to cause any malfunctioning of the relay.

It was noted that the Agastat relays tested can be vulnerable to high contact resistance at low test voltage levels, both before and after exposure to the fire environments.

4.1.2.3 Powered Relays

In each of tests 4 and 5 one relay was powered, loaded, operated, and monitored and another relay was operated and only the coil current was monitored. In both cases, the powered and monitored relay was an Agastat GPI relay located about 4 feet off the floor at sector 1 (see Fig. 2). In test 4, the cover was left on the relay and in test 5, the cover was removed. In test 4, the second relay which was operated was a General Electric model 12HFA151A9F. In test 5, the second relay which was operated was an Agastat model GPI relay. Both of these relays were located in the bottom of the corner cabinet about 1 foot from the floor (see Fig. 2). The relays in test 5 appeared almost as new after the test as did the General Electric relay in test 4. The Agastat relay in test 4 had no evidence of damage other than the polarized particulate described above. The particulate was insufficient to affect relay operation or create measurable leakage currents.

Plots of the temperature environment outside the relay and inside the relay near the contacts from test 4 are shown in Fig. 9. These plots give an idea of the amount of thermal lag caused by the cover being on the relay. The current flowing to the load on the relay contacts is shown in Fig. 10. The relay was operated in both directions every minute, accounting for the drop to zero load current every minute. The two sections of lost load current shown on the plot were the result of a sticking relay on the datalogging system and are not failures of the test relay. (The datalogger relay was found with severely pitted contacts and was verified to be sticking after the test.) A similar plot for the relay in test 5 is shown in Fig. 11. The relay in test 5 was operated every 5 minutes. Neither plot showed any indication of failure of the relay to pick up and carry its load. In neither test did the leakage currents measured to the normally-closed contact (open when the relay was energized) ever exceeded the detection threshold of the ac current sensors used (0.25 mA). The coil currents showed expected behaviors and are not shown. The values of coil current when energized were nominally 50 mA for the Agastat GPI relays and 210 mA for the General Electric HFA series relay.

4.1.2.4 Humidity Exposure of One Relay

The relay which was powered and monitored during test 4 was put into the humidity chamber (at 27^{o}C and 70% relative humidity) with its cover intact along with the switches described in Section 4.1.1.4. No adverse effects were noted on the relay after the 12-day exposure.

4.1.2.5 Relays Tested to Thermal Failure

4.1.2.5.1 Agastat GPI Relays

Two Agastat relays were tested to thermal failure in an environmental test chamber. The two relays use an external socket for termination. Two different socket configurations are available and one relay was tested with each type of socket.

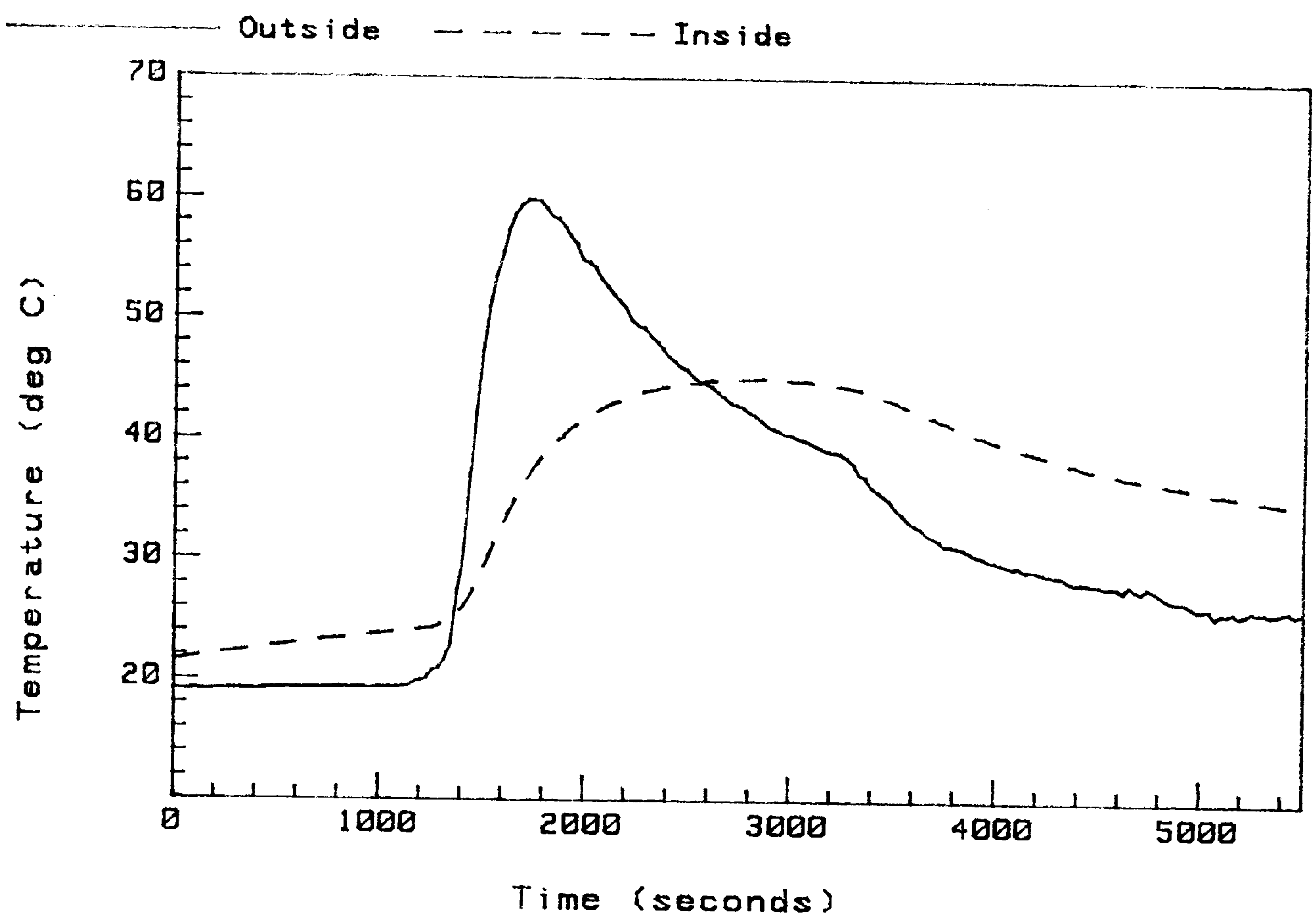


Fig. 9 Air Temperature Inside and Outside of Relay in Test 4

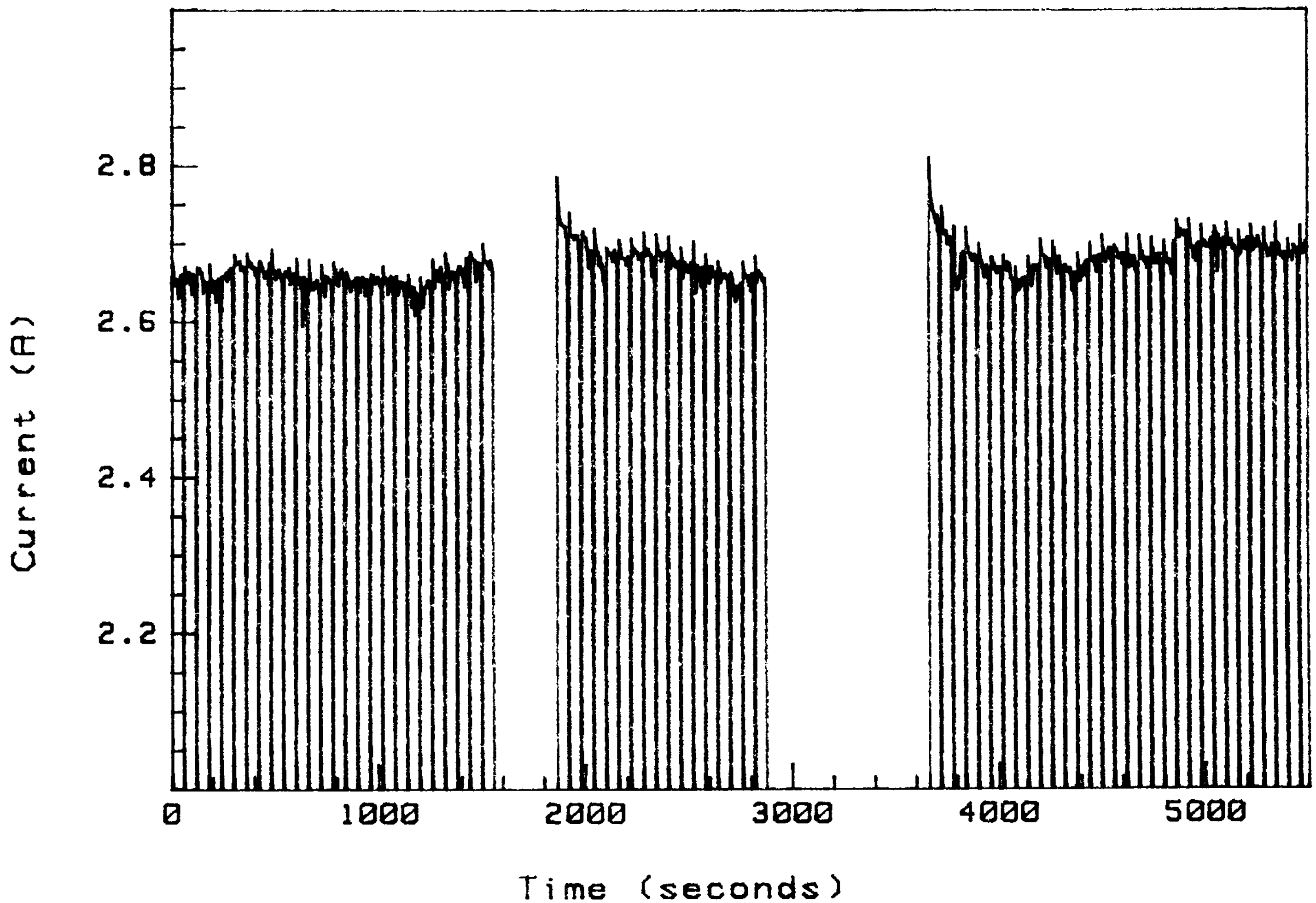


Fig. 10 Load Current to Relay in Test 4

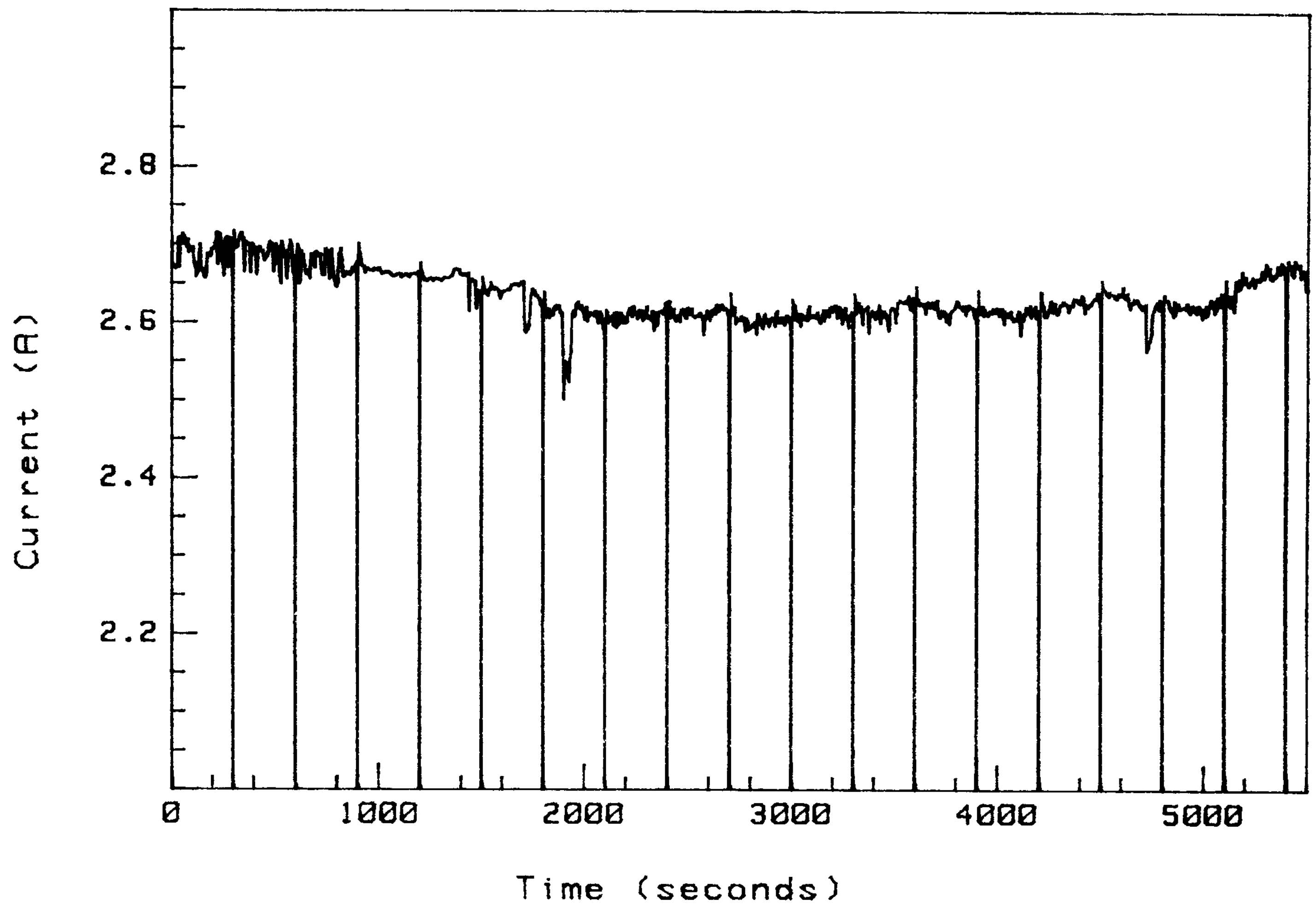


Fig. 11 Load Current to Relay in Test 5

A problem occurred in the computer program for the test chamber temperature control which caused two unplanned temperature excursions in the early part of the first test. The temperatures reached caused surface melting of the relay cover but no apparent internal damage occurred because of the short duration of the temperature excursions. The ultimate failure temperature of the relays was much higher than the temperature excursions, indicating that there was probably no significant damage from the temperature excursions. After the program was corrected, the test was successfully completed as described below.

The temperature profile for the first relay is shown in Fig. 12. The coil temperature is higher than the chamber temperature because of self-heating effects. Fig. 13 shows the leakage current for contact #2 as a function of time, Fig. 14 shows the coil current as a function of time, and Fig. 15 shows the motor starter current as a function of time. These plots (Figs. 13,14,15) show that at approximately 155 minutes into the test, the contact #2 leakage current went from 0 to 0.84 amps (maximum value limited by the 120 ohm resistor), the motor starter current went to 0, and the coil current jumped to about 0.94 amps from an initial value of about 0.03 amps. Operation of the motor starter became erratic and the test was terminated. It should be noted that the location of the sensor measuring motor starter current really measures the current supplied to the contact #2 common connection.

In addition to the above plots, data was taken for contact resistances, pickup voltages, and dropout voltages. With the exception of two points, contact resistances were all below 50 milliohms. The two extreme values were 150 and 250 milliohms. Pickup voltage ranged from 53 to 63 Vac with pickup voltage generally increasing with temperature. Dropout voltage ranged from about 21 to 24 Vac.

Post test analysis of the relay indicated several apparent failures. First, a short had occurred between one of the coil power leads and the normally closed terminal of contact #1. The two power leads to the coil were not specifically identified during the test since ac power was being used. Consequently, it is not known whether the short occurred to the hot side of the coil power or the neutral side. A slight decrease in the contact #1 current and a slight increase in the coil current which could not otherwise be explained were observed, indicating the short was probably to the hot side of the coil. However, the amount of the current changes indicates only a partial short (on the order of 100 ohms). The short found after the test was a more complete short which could have been caused by the fairly rapid cooldown after the test was over. The short was between two adjacent wires used for connections in the socket. A photograph of the failure area is shown in Fig. 16.

The second failure mode observed was apparently caused by the rapid cooldown after the test. An open circuit was indicated between the two coil terminals and between several of the terminals which should have been connected when the relay was in the deenergized position. Post test examination revealed severe socket warpage which apparently caused a loss of some connections between the socket and the relay.

The failures discussed thus far cannot account for the primary failure which resulted in the test being terminated. The cause of the primary

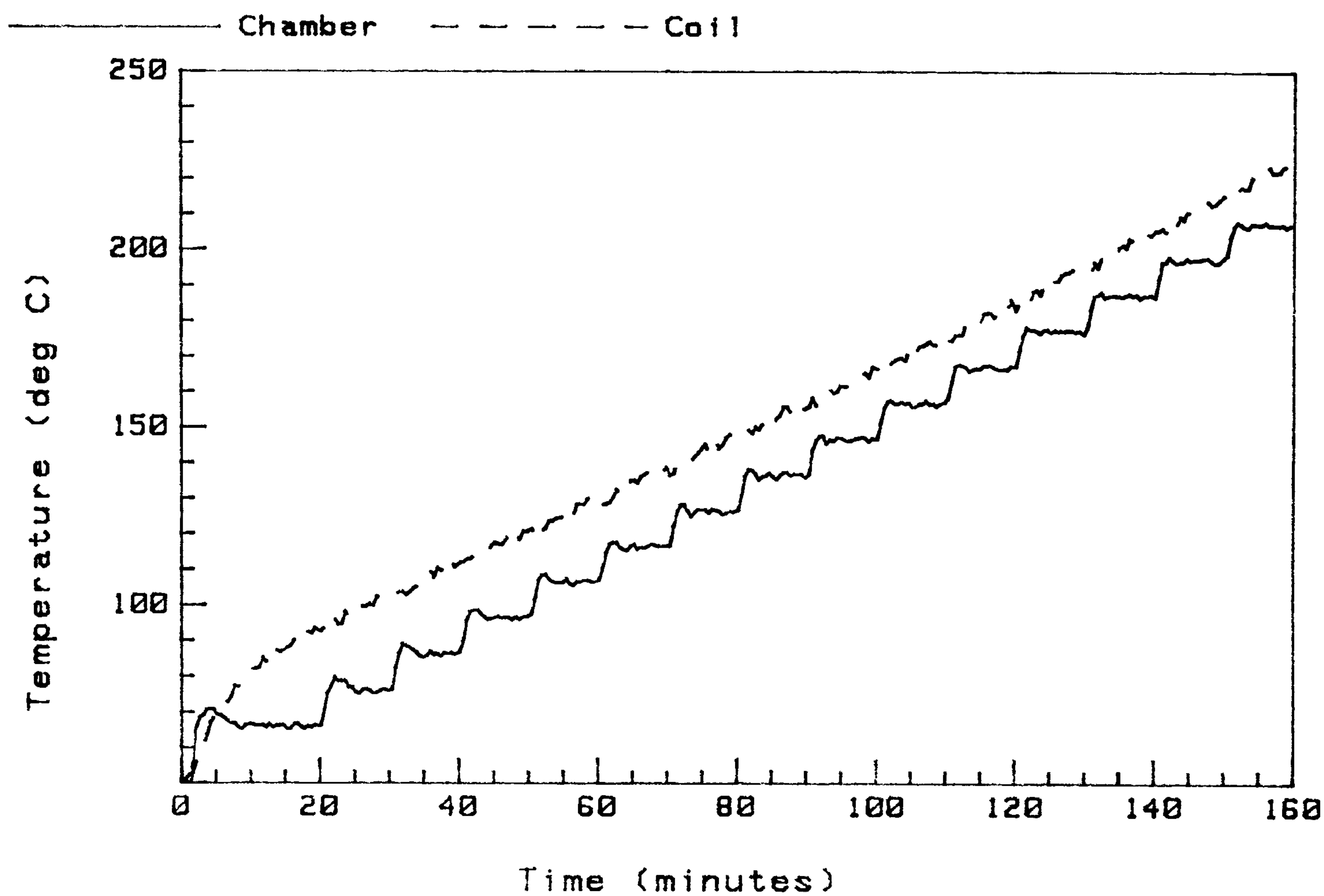


Fig. 12 Coil and Chamber Temperatures for First Thermal Failure Test

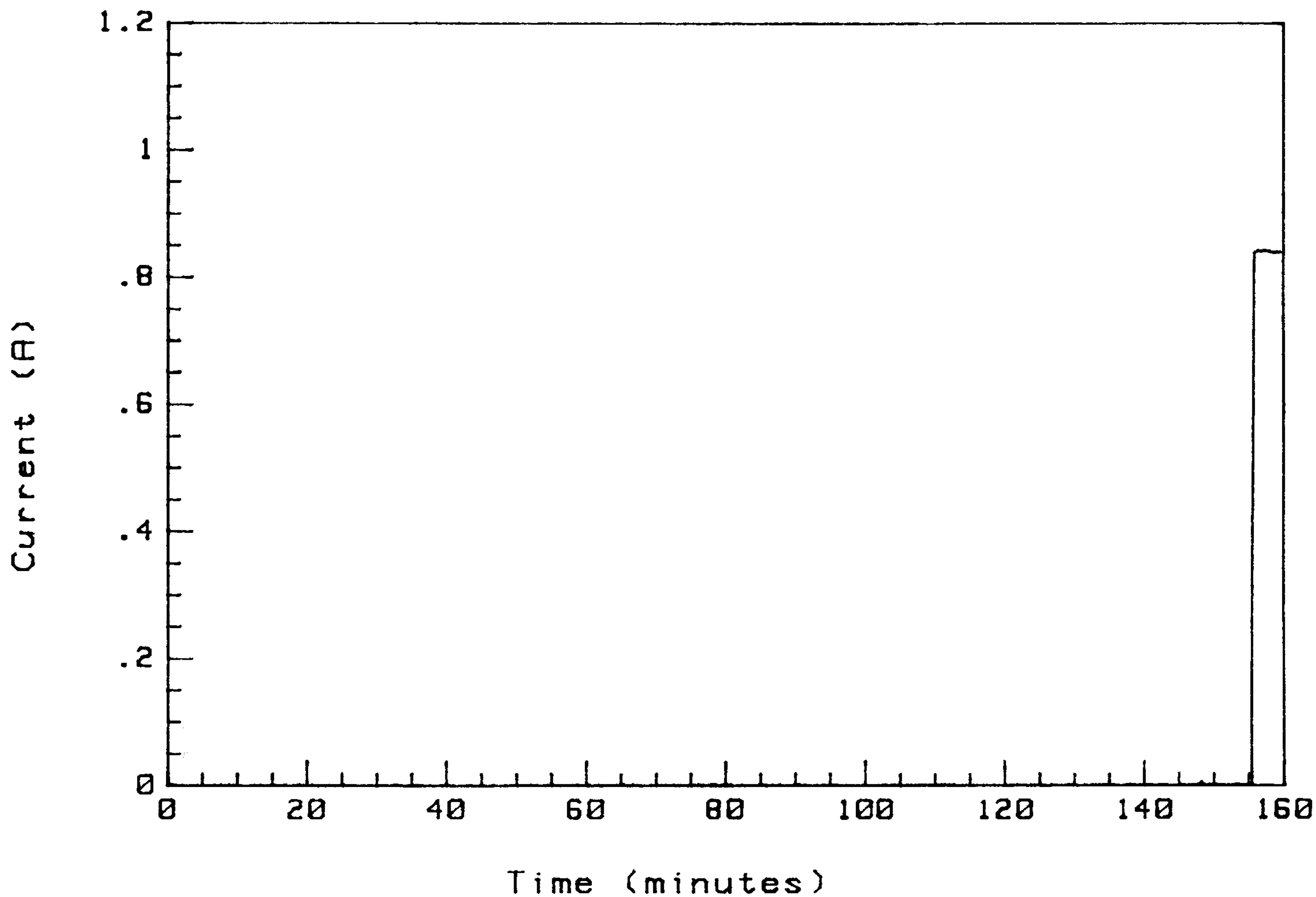


Fig. 13 Contact #2 Leakage Current for First Thermal Failure Test

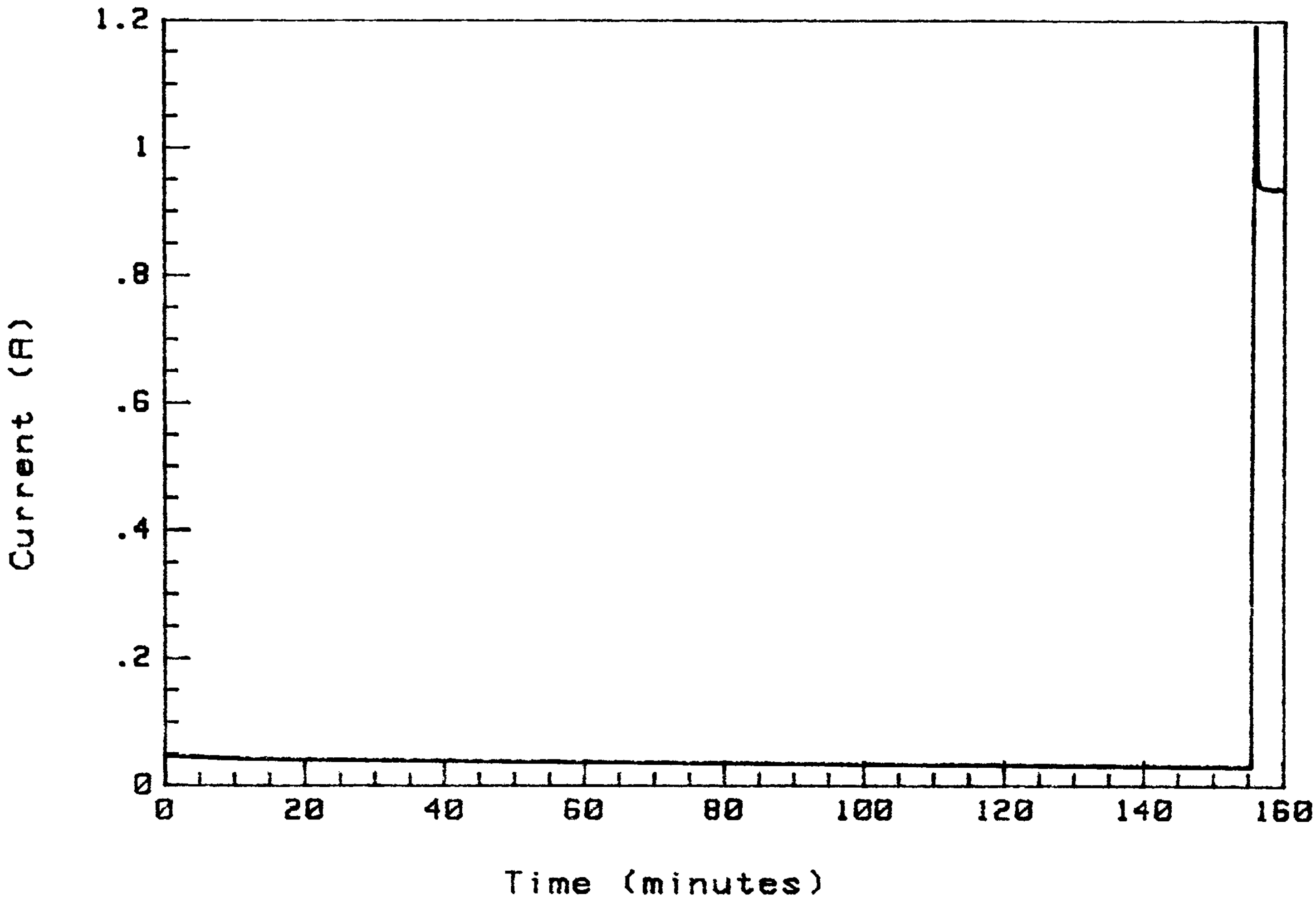


Fig. 14 Coil Current for First Thermal Failure Test

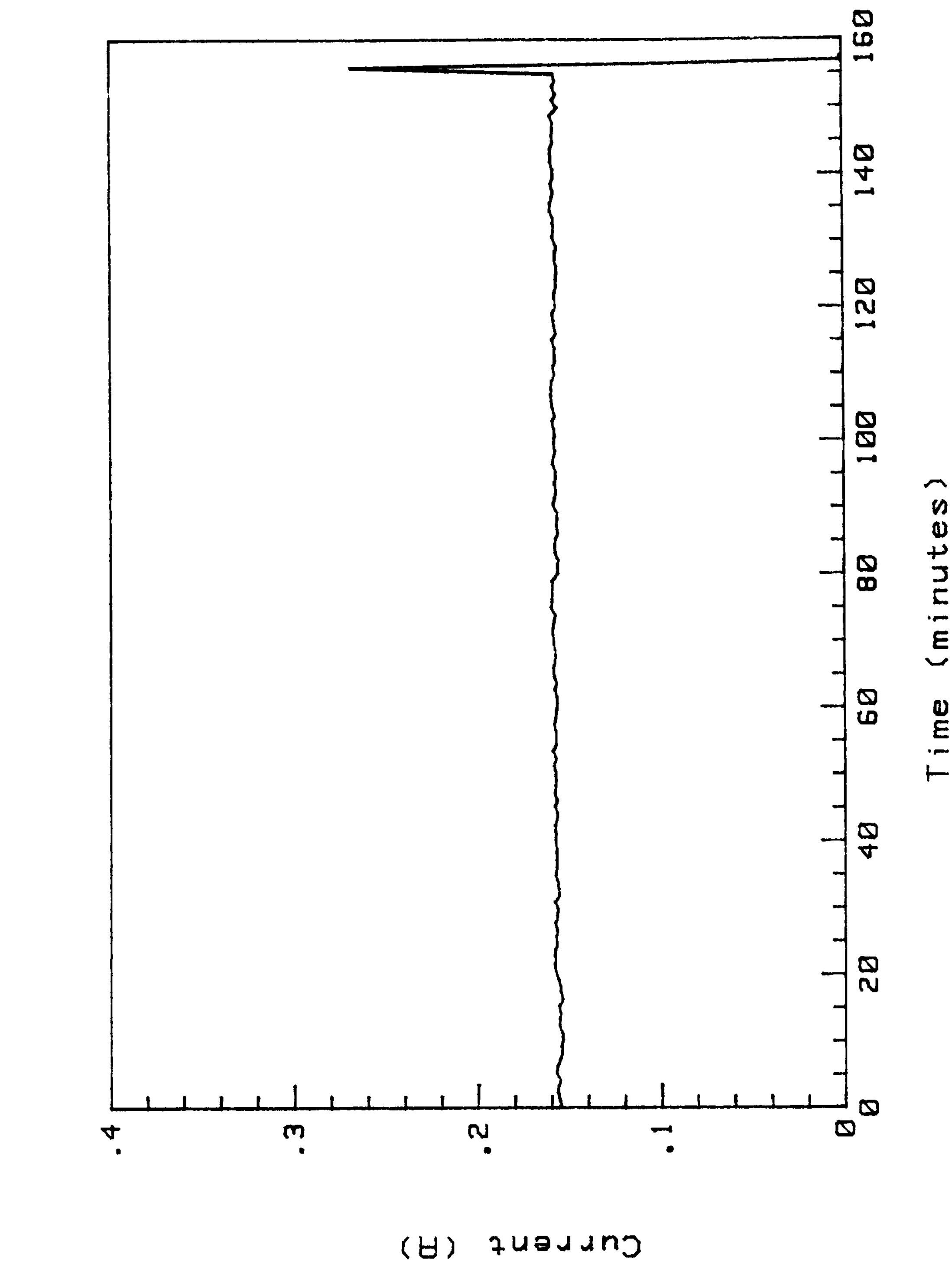


Fig. 15 Motor Starter Current for First Thermal Failure Test

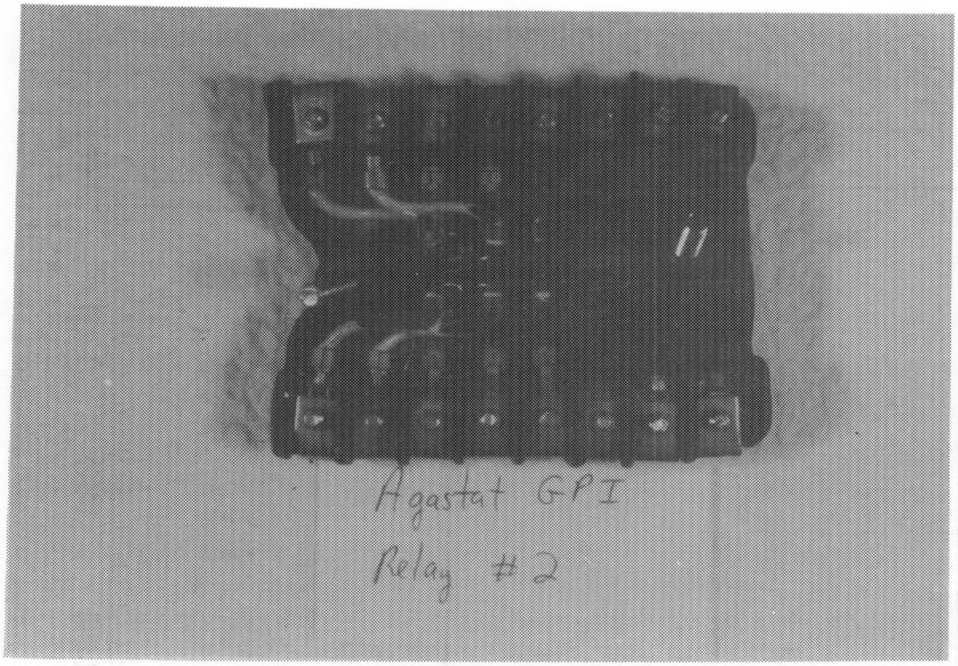


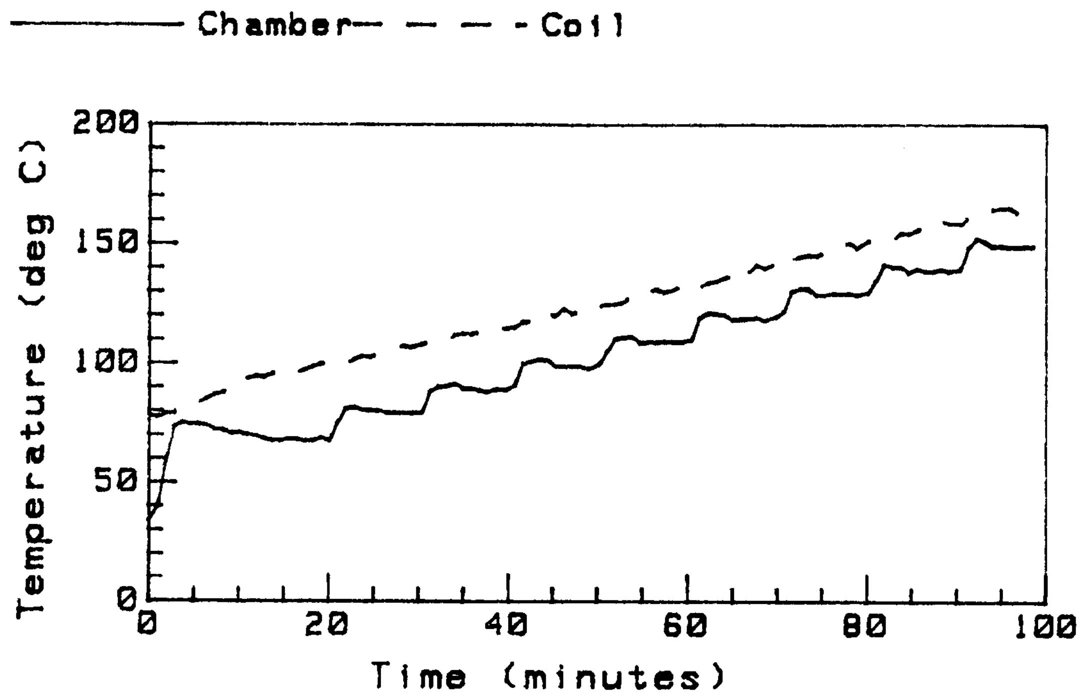
Fig. 16 Shorted Wires in the Socket from the First Thermal Failure Test

failure had to be a short between the hot side of the relay coil and the normally closed terminal of contact #2. No such failure could be found in examining the relay after the test. However, the base of the relay was so severely warped that apparently two or more of the terminal screws on the socket came into contact with the metal baseplate and shorted together. This was partially confirmed by checking continuity of different terminals when the socket was held onto a metal plate; several definite possibilities of shorting terminals were found.

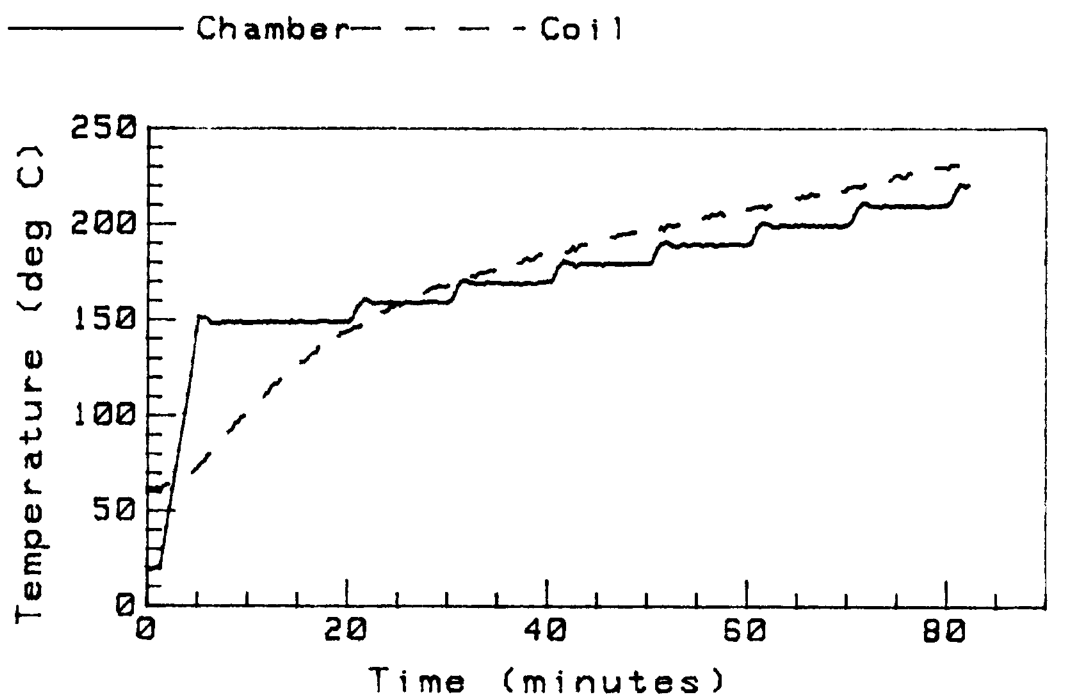
During the test of the second relay, a fuse blew at 99 minutes into the test. The cause of the blown fuse was traced to a relay in the datalogging system having fused contacts. The fuse and datalogger relay were replaced and since the test relay still seemed to be operating normally, the test was continued. The temperature profiles for the test and the coil temperature are shown in Fig. 17.

A plot of the motor starter current (actually current supplied to common terminal of contact #2) is shown in Fig. 18, the contact #1 load current is shown in Fig. 19, the coil current is shown in Fig. 20, and the contact #2 leakage current is shown in Fig. 21. About 30 minutes into the second part of the test, the current supply to contact #2 and the contact #2 leakage current both increased by approximately the same amount, indicating a dead short connecting the common and normally closed (open at the time) terminals of contact #2. The test was continued until between 75 and 80 minutes, the load current was lost twice and the the test was terminated.

Post test analysis of the relay indicated some failure modes similar to the first relay. Immediately after the test, several contacts which

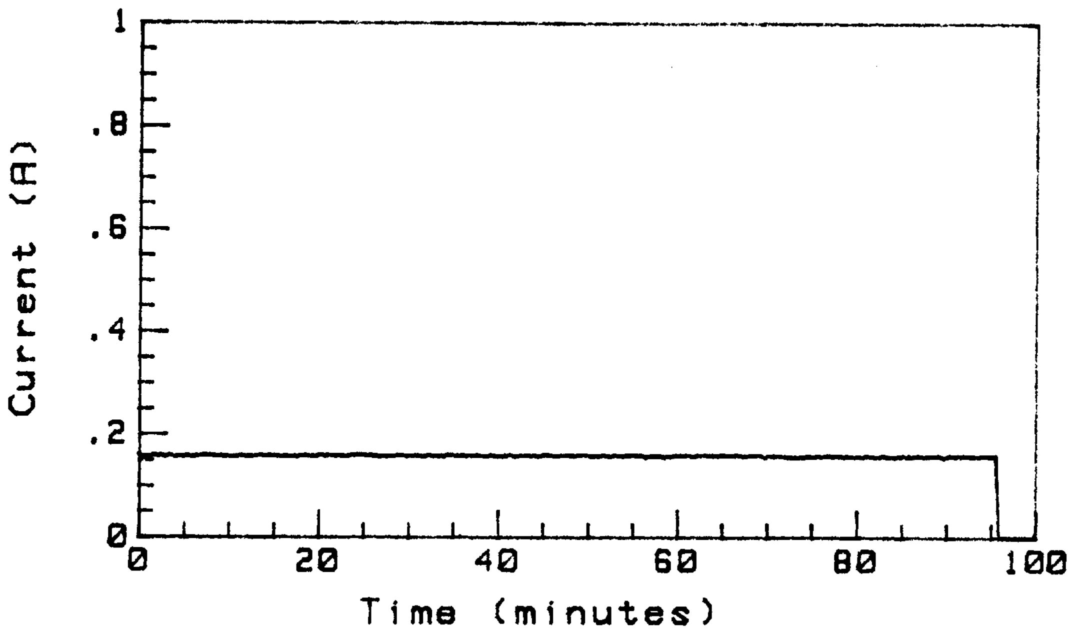


(a) Prior to Fuse Failure

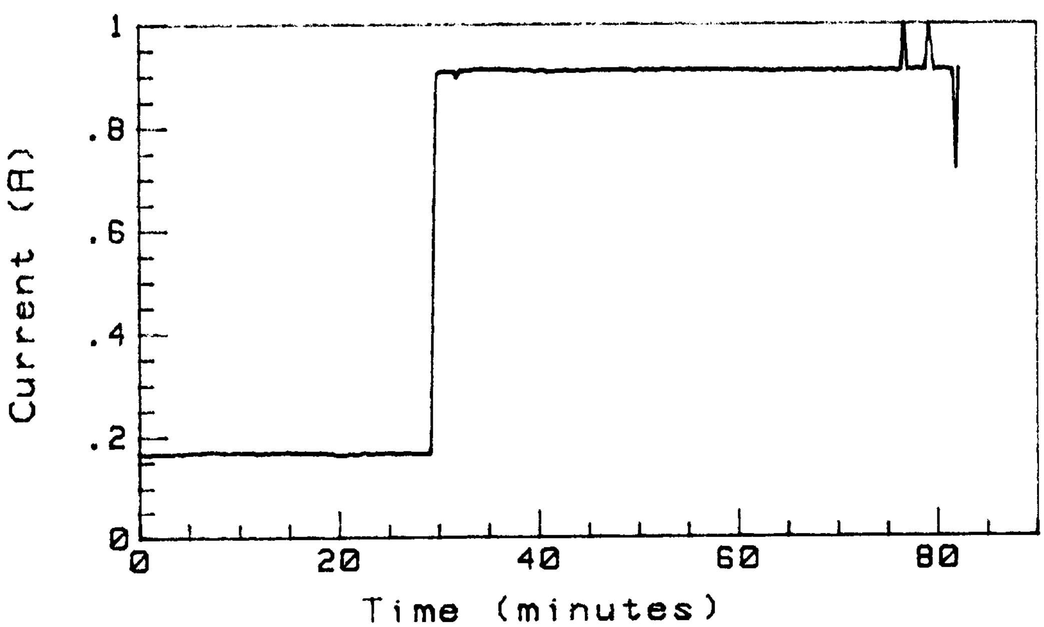


(b) After Fuse Replacement

Fig. 17 Coil and Chamber Temperature for Second Thermal Failure Test

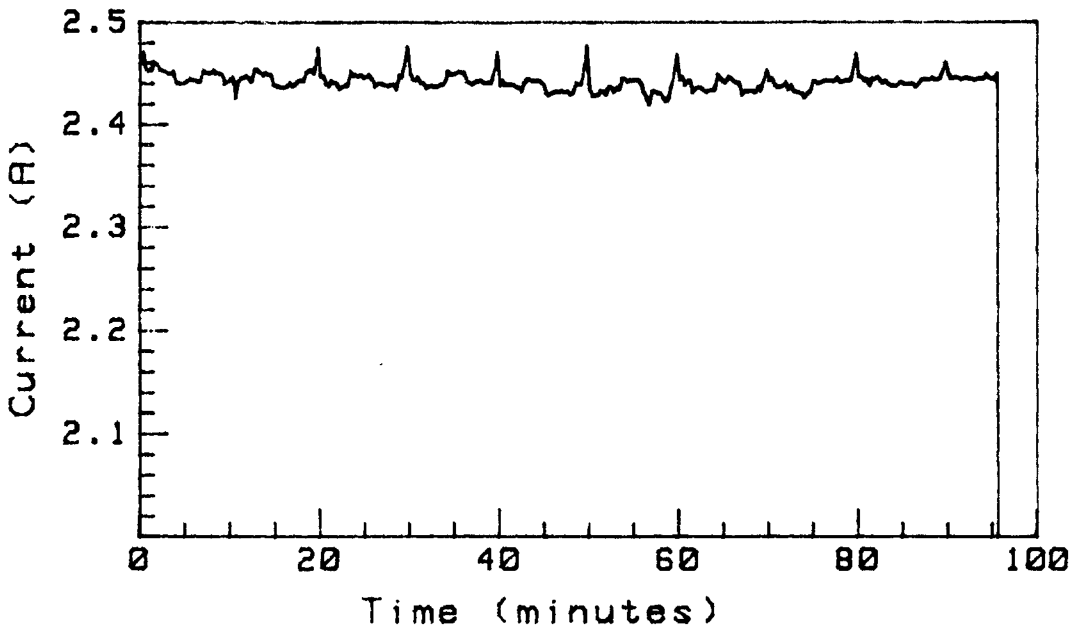


(a) Prior to Fuse Failure

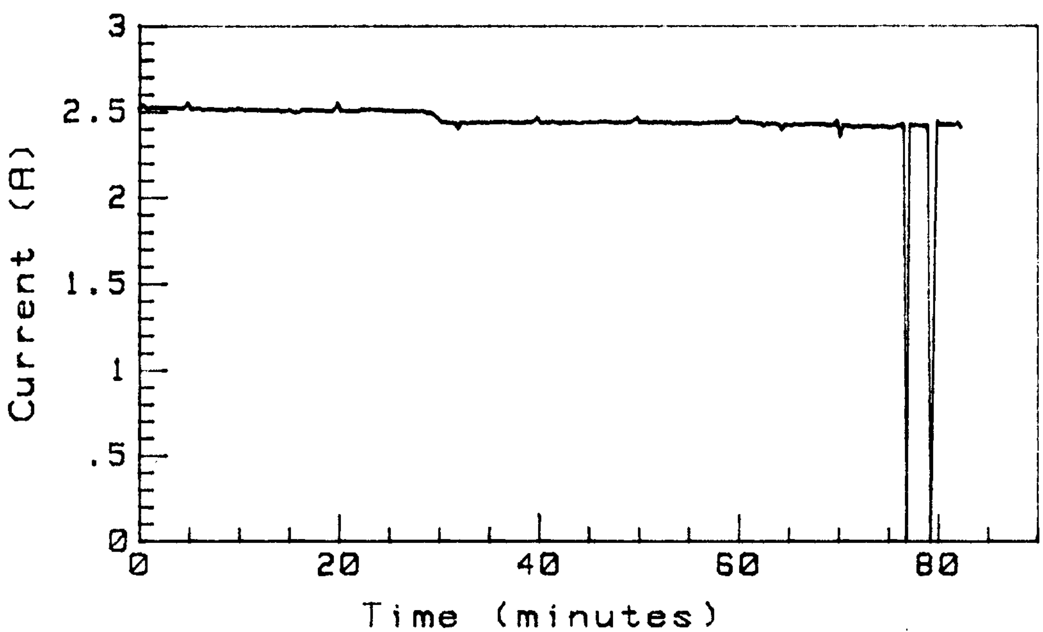


(b) After Fuse Replacement

Fig. 18 Motor Starter Current for Second Thermal Failure Test

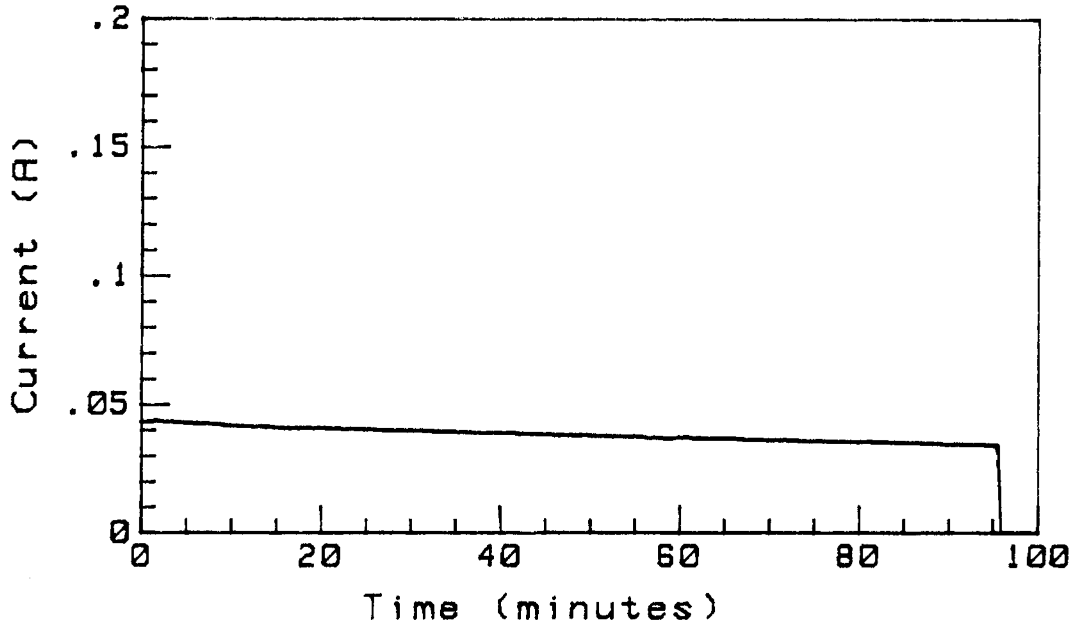


(a) Prior to Fuse Failure

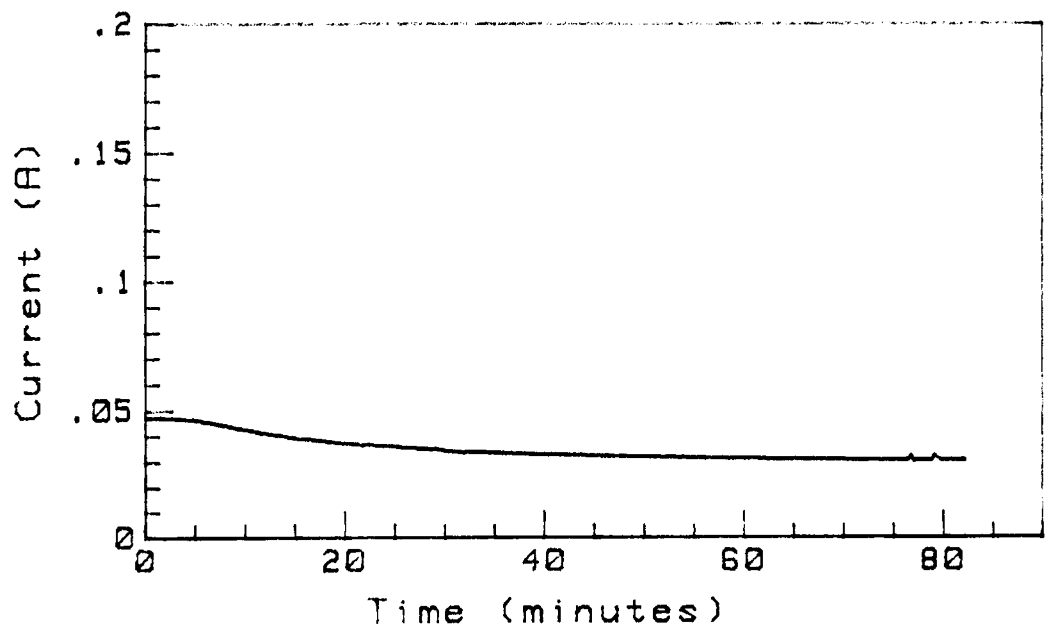


(b) After Fuse Replacement

Fig. 19 Contact #1 Load Current for Second Thermal Failure Test

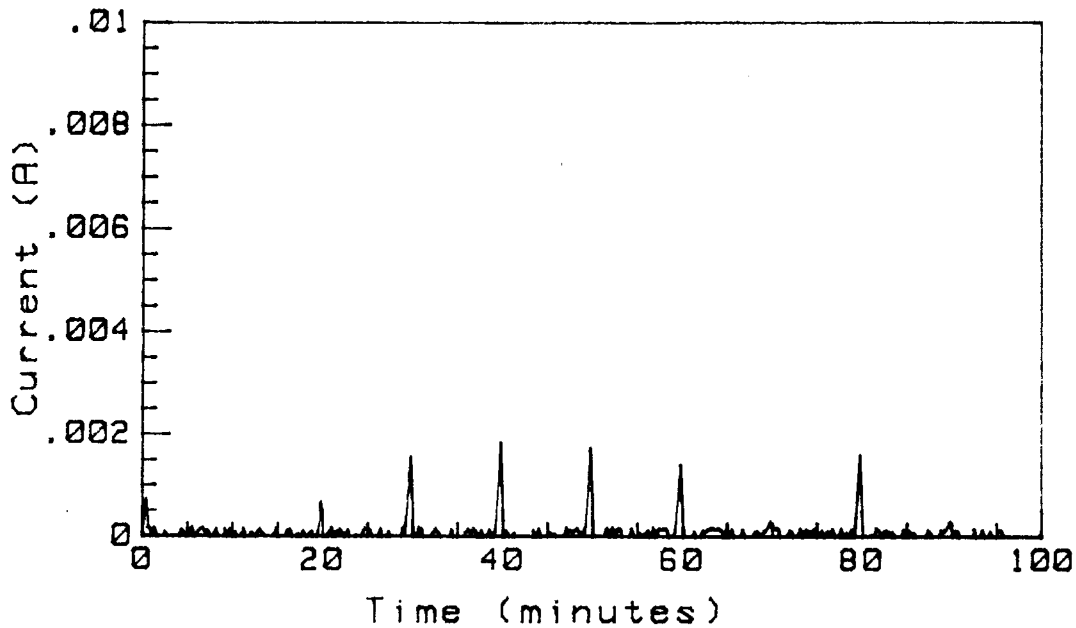


(a) Prior to Fuse Replacement

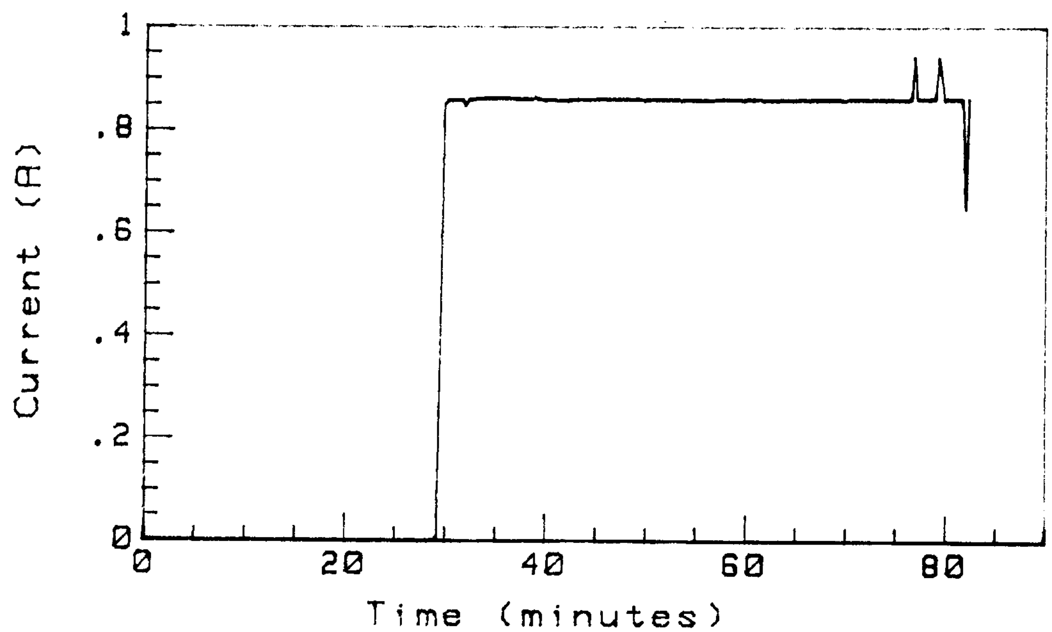


(b) After Fuse Replacement

Fig. 20 Coil Current for Second Thermal Failure Test



(a) Prior to Fuse Failure



(b) After Fuse Replacement

Fig. 21 Contact #2 Leakage Current for Second Thermal Failure Test should have been connected indicated open on an ohmmeter and all of the contact #3 terminals were effectively shorted together. This short was later found to be in the socket. Insulation resistance measurements on the socket produced what appeared to be breakdown at some dc voltage levels (different locations appeared shorted at all test voltages including the low voltage of a hand-held meter and all voltages of the insulation resistance tester: 50, 500, and 1000 Vdc). However, the apparent breakdown would come and go at different voltage levels and sometimes even at the same voltage level after applications of other voltages. Shorting of terminal screws to the baseplate was not observed in the second test because of the different socket design. However, a new failure mode was observed. The contact support of contact #1 (the contact carrying the nominal 3 A load current) had become hot enough to melt as shown in Fig. 22. The melted support was the cause of the loss of load current observed at 75 to 80 minutes into the second part of the test. Because of the melted support, the coil would no longer energize after the test although it did draw rated current at rated voltage.

At some times during the test, high contact resistances were noted with the voltage applied by the measurement circuits. In each case, the test was continued because the relay was carrying its load and no leakage currents were observed.

In addition to the data discussed above, insulation resistance measurements, contact force measurements, and pickup and dropout times were measured before and after the tests where possible. In all cases, except those noted above, no degradation was evident in the measured properties.

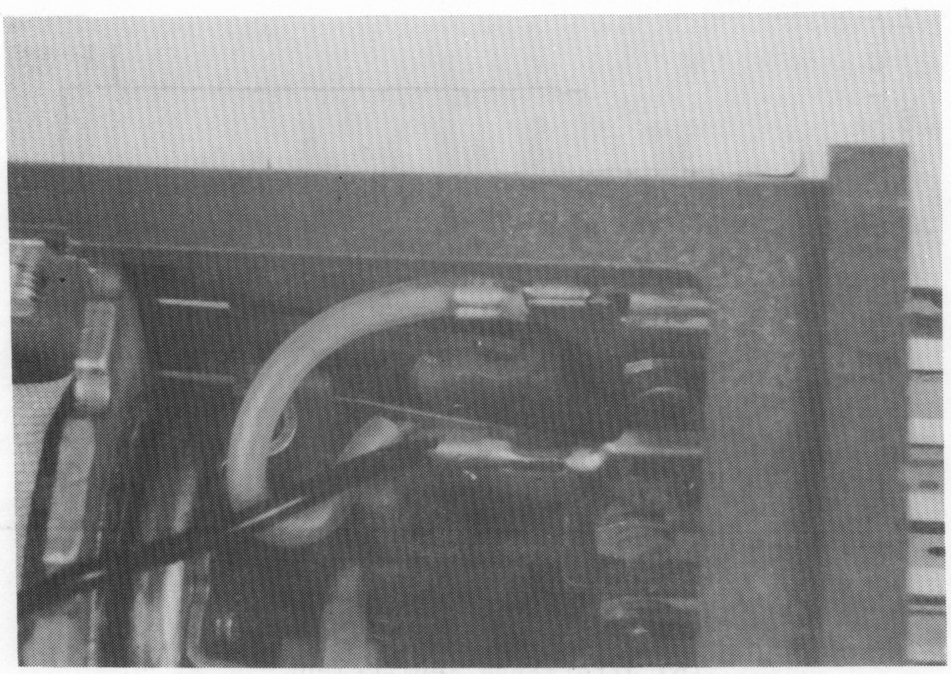


Fig. 22 Melted Contact Support from Second Thermal Failure Test

4.1.2.5.2 General Electric HMA Relay

One General Electric relay was tested in the environmental chamber. The relay was a model 12HMA111B9. Two profiles were run as shown in Fig. 23. The second profile was run because failure of the relay was not observed up to the first programmed maximum temperature of 270°C and the objective of the test was to continue until the relay failed. As can be seen from Fig. 23, the second profile was started when the chamber temperature was slightly above 200°C shortly after completion of the first profile. The coil current is shown in Fig. 24 and the load current is shown in Fig. 25. Leakage current is not shown since it never exceeded the ac current sensor detection limit of 0.25 mA. At about 92 minutes into the second test, the load current was lost and the coil current jumped significantly. The test was discontinued and when the chamber was opened, the lead wires to the relay were burning. After extinguishing with carbon dioxide and cooldown of the chamber, the relay was removed. The fire and extinguishment caused significant damage to the relay, as shown in Fig. 26. The fire was caused by the two coil lead wires shorting together and fusing as shown in Fig. 27. The fire apparently started at about 98 minutes, about 2 minutes after the load current was lost. The cause of the loss of load current could not be determined because of the fire damage.

Similar to the Agastat relays, the GE relay also had high contact resistance readings in some cases. The high readings occurred primarily when the relay was deenergized (and hence the contact forces were lower). As in other cases, the test was always continued since the relay continued to carry its load without measurable leakage currents. The relay was too severely damaged to make any post test measurements.

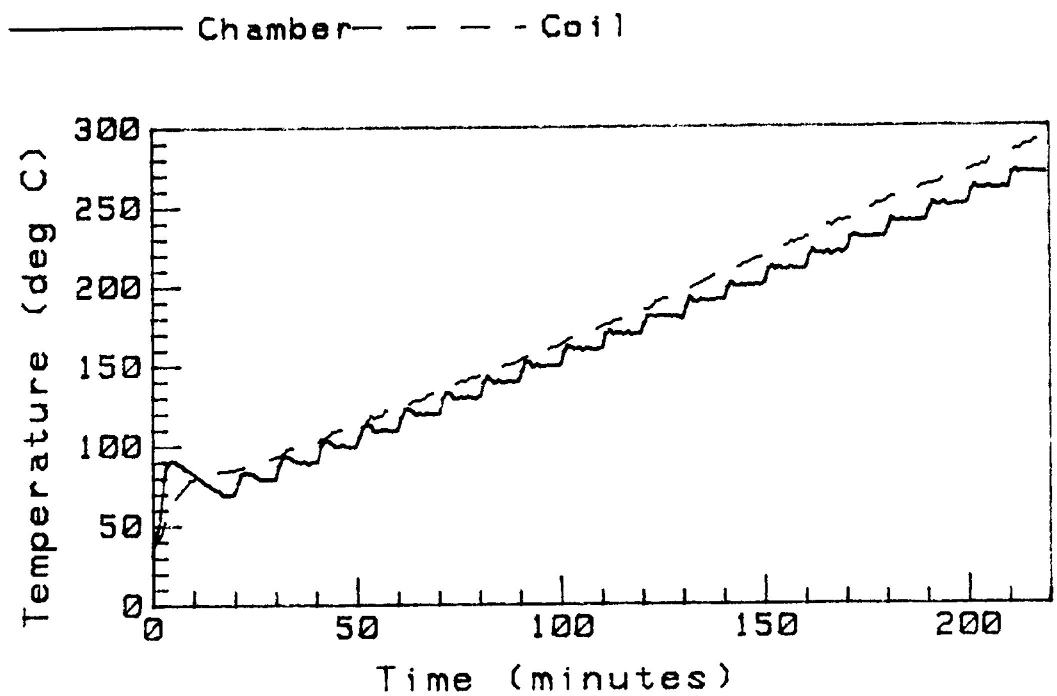
The coil operability indication was lost several times during the test, apparently resulting from high contact resistance on the relay at the voltage level used for the indication (12 Vdc). Again, the test was continued each time because the more important criteria of carrying the load and preventing significant leakage currents were normal.

4.1.2.6 Applicability of Relay Data to Other Components

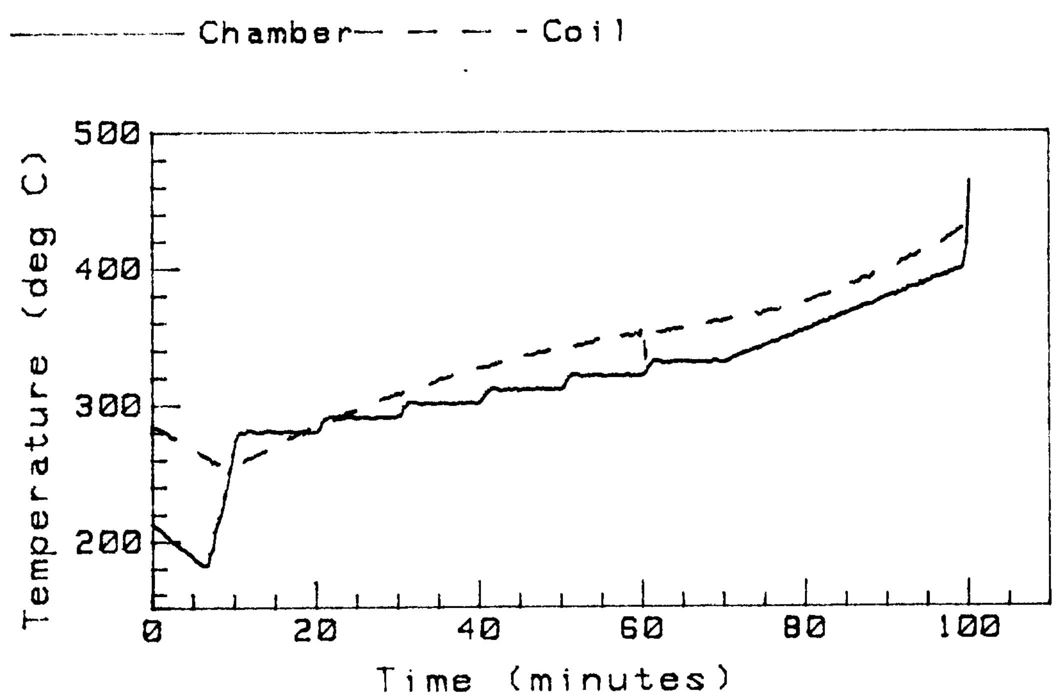
This section describes the expected failure modes of relays and what other components would be expected to experience similar failure modes. Where the relays did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

The general failure modes of relays are similar to those of switches and the data on relays and switches support each other. One additional general failure mode of relays is failures associated with the coil preventing the relay from operating. Normally, failure of the coil (as might be expected from high temperatures) would be expected to result in deenergizing the relay to what is normally the "safe" position, although other coil failure modes are possible.

Components not tested which might experience similar failure modes are the same as for switches. The relay data supports the switch data and adds to it by also considering the remote actuation function using a

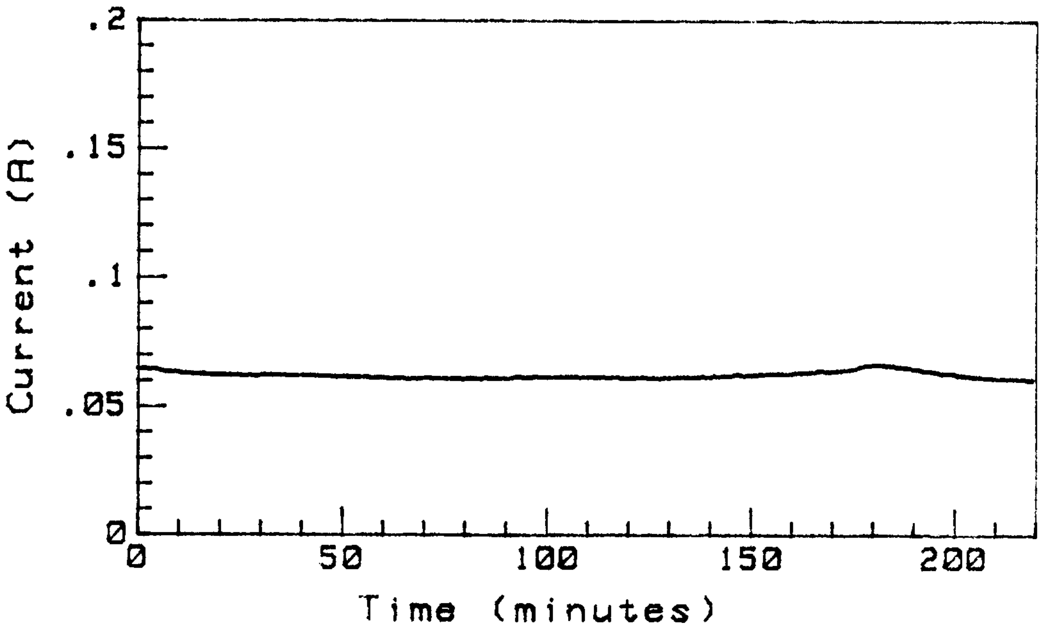


(a) First Profile

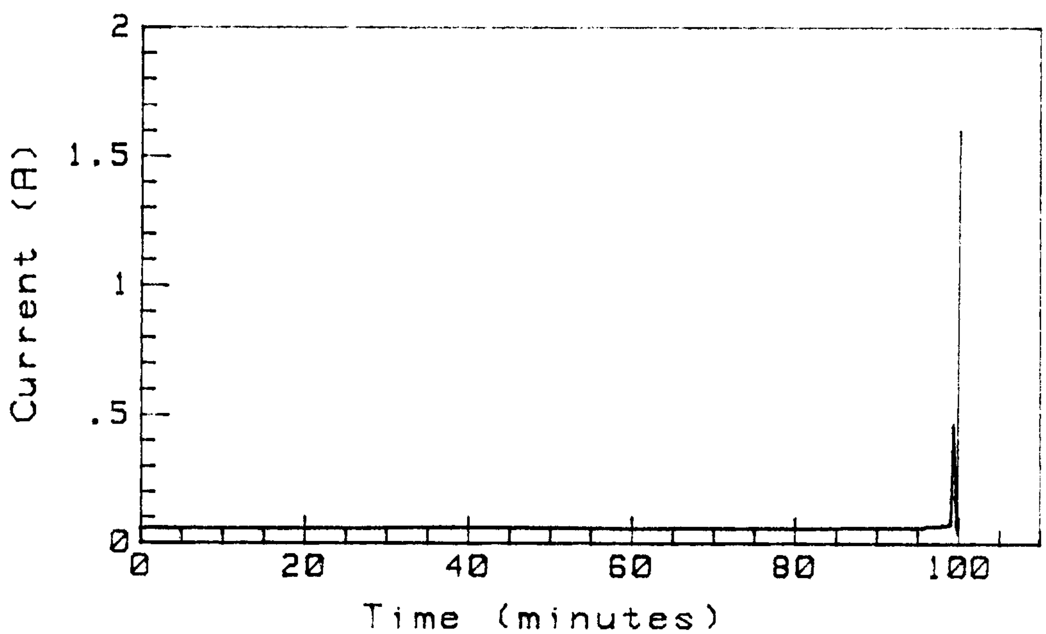


(b) Second Profile

Fig. 23 Coil and Chamber Temperatures for Third Thermal Failure Test

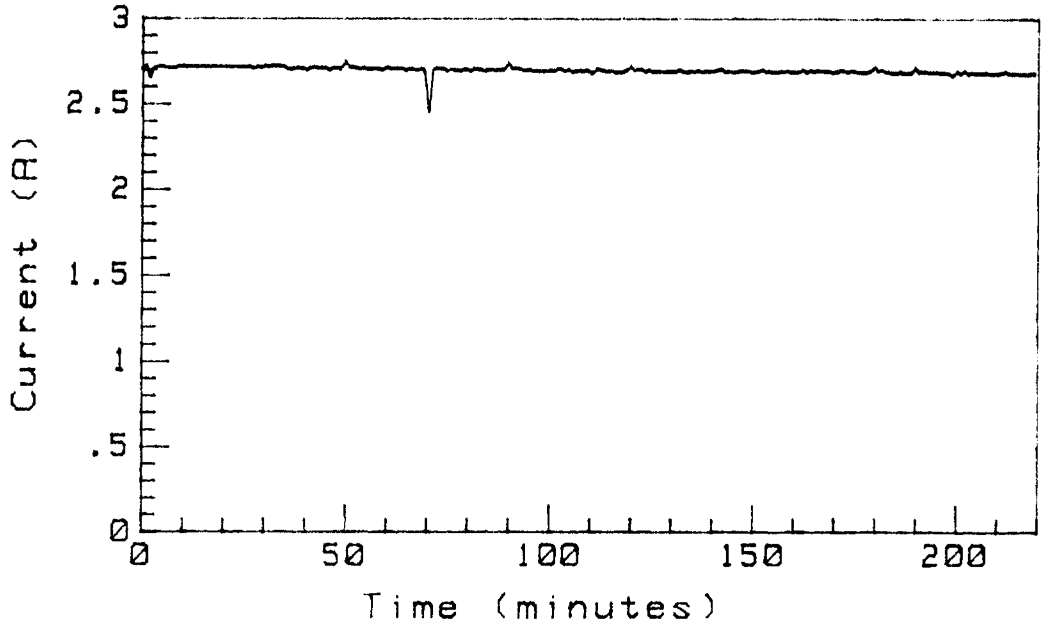


(a) First Profile

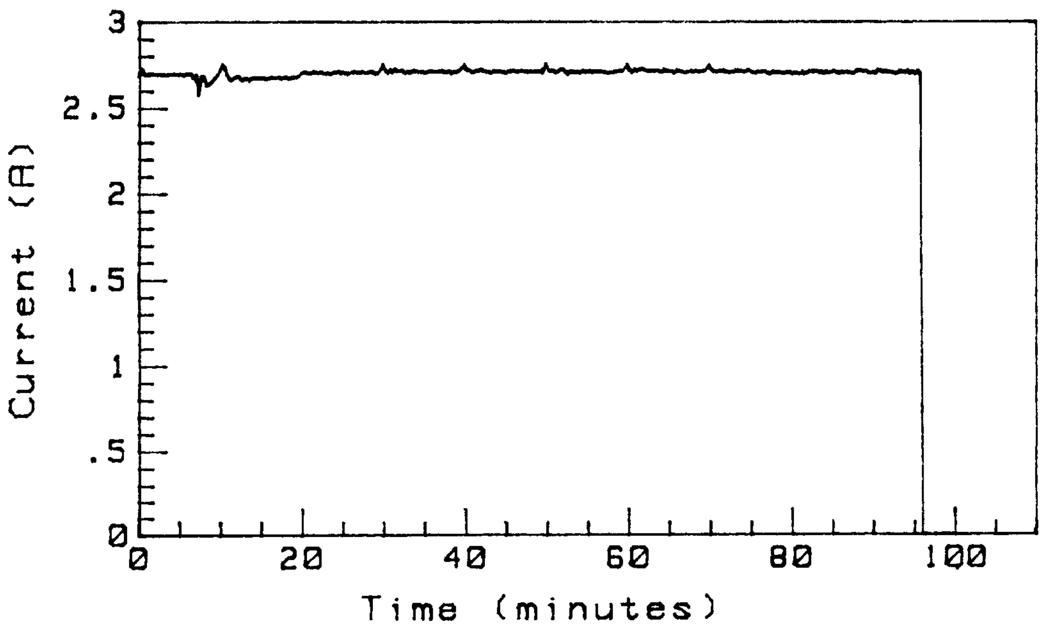


(b) Second Profile

Fig. 24 Coil Current for Third Thermal Failure Test



(a) First Profile



(b) Second Profile

Fig. 25 Load Current for Third Thermal Failure Test

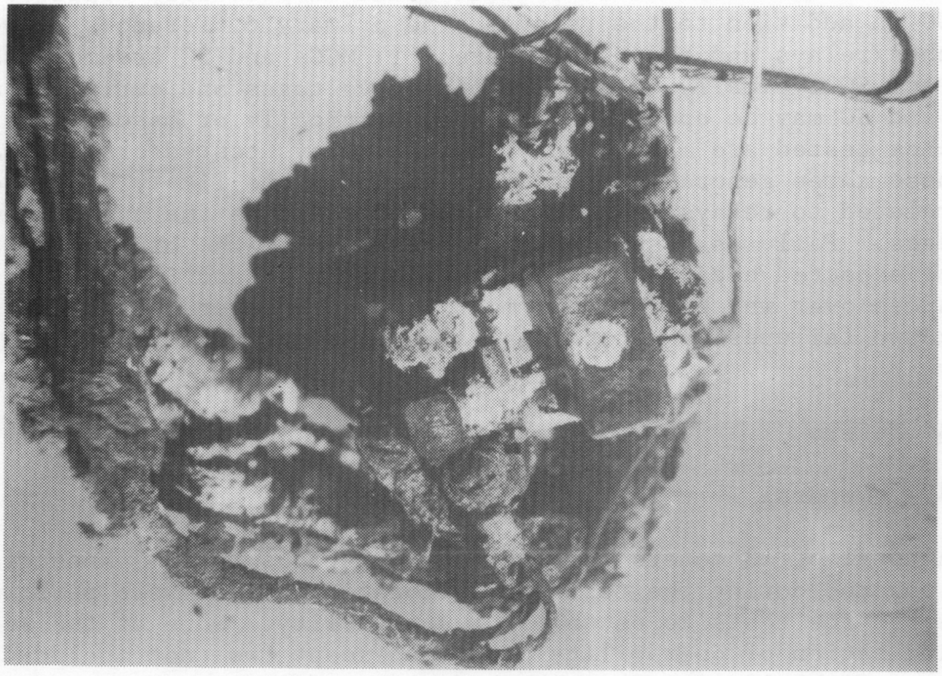


Fig. 26 Post-test Photograph of HMA Relay After Fire Occurred

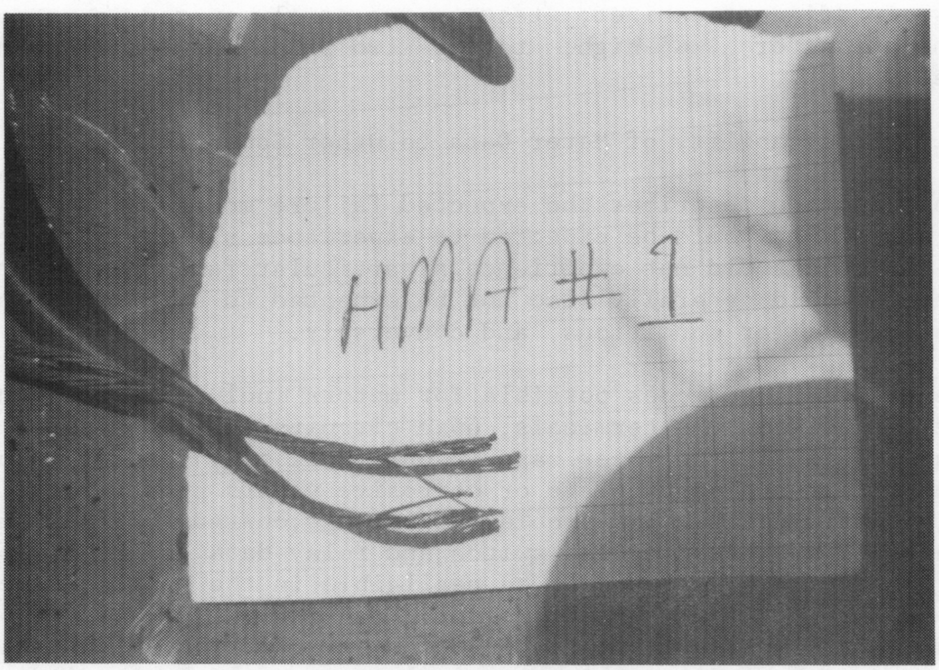


Fig. 27 Coil Wires Shorted Together to Cause Fire

coil. This additional failure mode would be primarily applicable to MCCs and SG in addition to the relays. The primary differences between the switches/relays and the MCCs/SG are: 1) MCCs and SG are much larger, 2) MCCs and SG typically operate at higher voltages and currents, and 3) many MCCs and SG may be operated either automatically or manually while the switches tested are manual only and the relays tested are automatic only. Of these three general differences, the only one likely to cause failures not related to relays or switches tested would be the higher operating voltages. Failures resulting from breakdown at the higher voltages might not be expected because the larger size of MCCs and SG increases the distances over which breakdown must occur. However, high voltage breakdown failures cannot be dismissed based only on the switch/relay data.

4.1.3 Meters

4.1.3.1 General

A total of 13 meters were tested in various tests. None of the meters were powered during the test but calibration checks were performed before and after the tests to establish functionality. None of the meters showed any indication of operability problems except two (not included below or as part of the 13 tested) which were put in or directly above the burning cabinet and were destroyed by heat. The meters were all General Electric Type 180, 185, or 195. The meter locations (see Fig. 1 for tests 1-2 and Fig. 2 for tests 4-5) were as follows: test 1--above burn cabinet (this one continued to work even though it was directly above the burning cabinet); 2′ out from burn cabinet, 5′ high ; in single bay cabinet about 8′ away; and 8′ from fire, 10′ high; test 2--one in single bay cabinet and two in adjacent cabinet; test 4--two panel mounted in corner cabinet and one at sector 1, 4′ high; test 5--two panel mounted in corner cabinet.

4.1.3.2 Applicability of Meter Data to Other Components

This section describes the expected failure modes of meters and what other components would be expected to experience similar failure modes. Where the meters did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

General failure modes possible for meters include leakage currents (shorting) between the terminals, open circuits (not considered likely), warping/melting of the meter case (usually plastic) leading to binding of the indicator, and particulate or corrosive vapors penetrating into the meter and jamming it. The problem of leakage current between the terminals is addressed by the switch and relay data given previously where leakage currents were found to be negligible in the tests conducted.

The only components not tested which may experience failure modes associated with binding or jamming indicators would be the indication portion of indicators/controllers and mechanical gauges. It should be noted that the types of meters tested are all reasonably well sealed from the outside environment. No evidence of particulate or corrosive vapor penetration into the meters was noted in any case except for the destroyed meters. Any type of meter or gauge which is not reasonably sealed could behave considerably different (see discussion of strip chart recorder failures). It should be emphasizes that failures from direct fire damage, such as meters becoming short circuits, were not addressed by this effort.

4.1.4 Chart Recorder

4.1.4.1 General

Two strip chart recorders, Bailey Controls Series 77, were tested. The first was tested in test 3 and was located about 8' from the burning cabinet near the burn room door and about 5' from the floor (see Fig. 1). The covers were removed from the recorder and it was not powered. The temperature profile that the recorder was exposed to is shown in Fig. 28. As a result of the fire environment, the strip chart recorder failed to function. The failure mode was particulate buildup on the pen sliders with the pens unable to move in either direction. After an attempt at cleaning with a solvent, the pens would still not move. The rest of the recorder, including the electronics and motor drives seemed to work properly. A photograph of the failed slider is shown in Fig. 29.

Because the intentional removal of the covers of the recorder may have allowed the failure, a second recorder was tested in test 4 and was panel mounted in an open-backed cabinet with all covers intact. After the test, light crud buildup was noted on the sliders, significantly less than in test 3. Two of the three pens worked correctly. The third pen would work correctly up to about 75% of its full scale. However, it would not deflect any farther. The recorder was checked using a slowly changing voltage as would be expected in a power plant application. After failing to deflect fully, the voltage was rapidly changed from a low value to a full scale value and the crud deposits were easily removed, allowing the recorder to work normally thereafter.

4.1.4.2 Applicability of Chart Recorder Data to Other Components

This section describes the expected failure modes of chart recorders and what other components would be expected to experience similar failure modes. Where the recorders did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

The general failure modes expected for strip chart recorders are corrosion or particulate buildup between moving parts (failure mode actually observed), thermal failure or degradation of electronic components, or low level leakage currents on the circuit boards leading to loss of correct recorder operation.

Components not tested which might experience similar failure modes include any type of meter, gauge, automatic switch (e. g. temperature), or small motor which is not sufficiently protected from the environment (mechanical binding problems) and many types of components which contain printed circuit boards and may be vulnerable to electronic component failure or degradation or leakage currents on the circuit board. Examples of the latter include logic equipment, controllers (some types), power supplies, solid state relays, and transmitters.

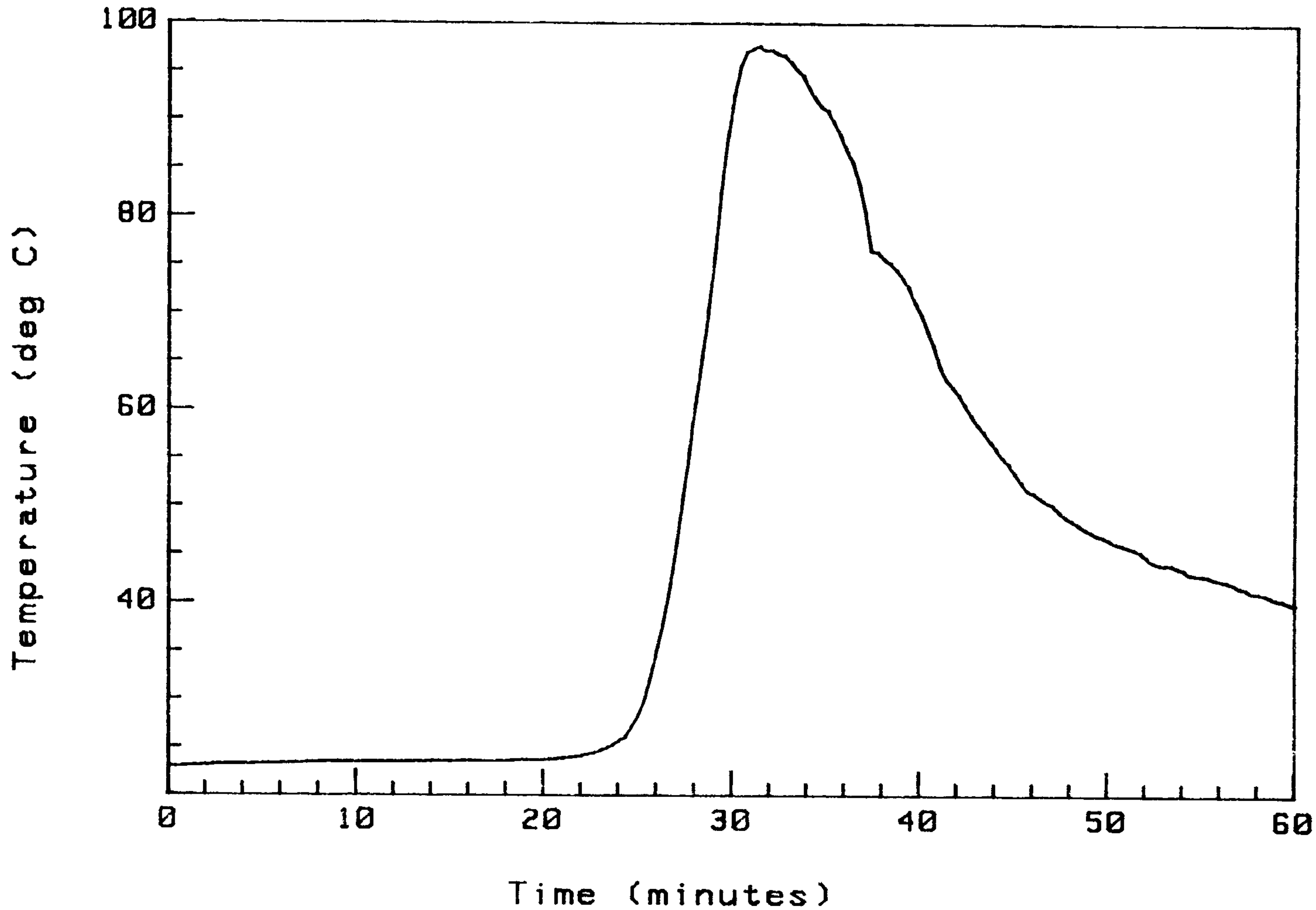


Fig. 28 Temperature Near Strip Chart Recorder in Test 3

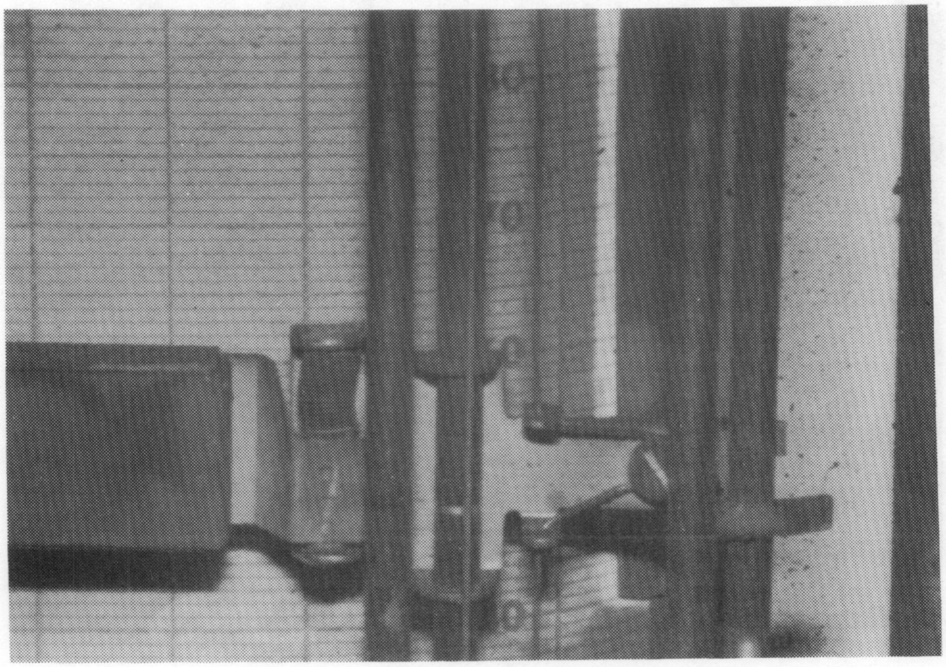


Fig. 29 Failed Slider Mechanism of Strip Chart Recorder

4.1.5 Electronic Counter

4.1.5.1 General

Two electronic counters were tested. Both were Hewlett Packard model 5300B measuring systems coupled to 5302A 50 MHz universal counters. The first was tested in test 3 and was located about 6′ from the burning cabinet and about 8′ from the floor. The covers were removed (to simulate the possibility of electronic circuit boards not being enclosed) and the counter was not powered. The temperature near the counter was recorded and was above 150°C for about five minutes and peaked at about 167°C. Significant deposits of particulate were found on the circuit boards after the test as shown in Fig. 30, but the counter still functioned perfectly. Because of the low humidity on the day of the test and because no water suppression was used in the room, the counter was subsequently put in a humidity chamber to evaluate the effects of high humidity. The first exposure was at 32°C (90°F) and 90% humidity for about 5.5 hours with the counter powered. No ill effects were noted and the humidity was raised to 95% with the counter still powered. After 17.5 hours at 95% humidity, front panel indication had been lost and the fuse was found blown. The exact time when the fuse blew was not known, only sometime during the 17.5 hours. Replacement of the fuse with a correctly rated fuse, even after drying of the counter, resulting in the fuse blowing. However, replacement with a high enough rated fuse would allow the counter to work for a short period before the readings would go erratic and the power supply rectifier diodes would get very hot. Before a positive diagnosis of the problem could be found, the counter began working

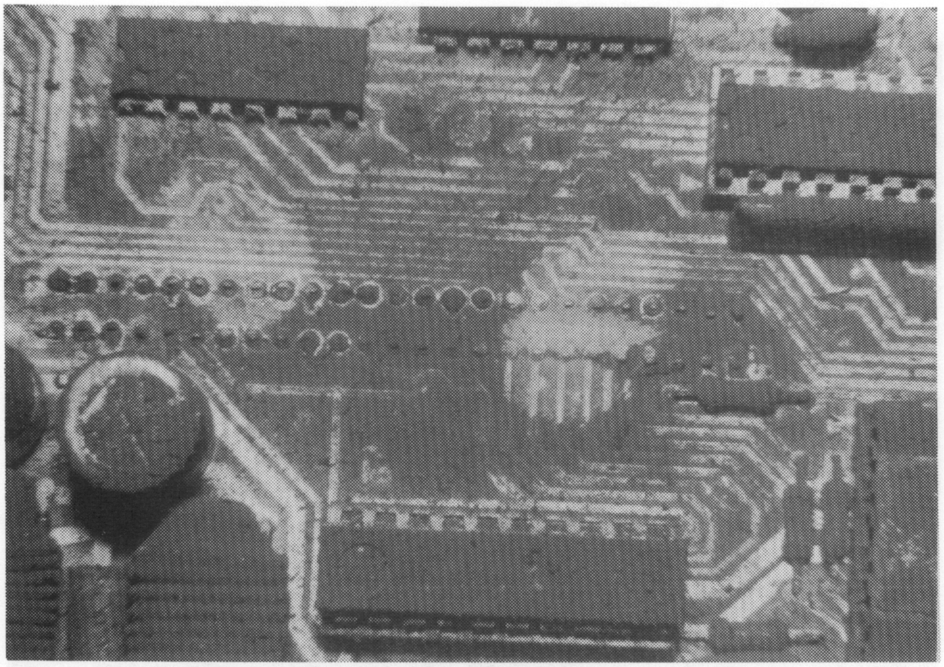


Fig. 30 One Location of Leakage Currents on Counter Circuit Boards

normally again. The counter was returned to the humidity chamber to see if the problem would return. The counter was powered and the conditions were 40°C (104°F), 95% relative humidity for 18 hours. The counter was found failed as before, again not knowing the exact time of failure. The problem was eventually traced to what appeared to be a transistor failure in the power supply. Based on examination of the counter schematics, failure of the transistor, manifested as high base-emitter leakage current, could cause the noted failure. Replacement of the transistor returned the power supply to normal, but curve traces of the original transistor did not show any problems. Subsequently, the original transistor was reinstalled and worked correctly. The only conclusion is therefore that a conductive media (probably corrosion related) had formed in the vicinity of the transistor and had allowed leakage currents. The transistor replacement must have removed enough of the conductive media to reduce the leakage current and allow the circuit to work properly.

Following the diagnosis above, the counter appeared to work perfectly. About an hour later, the counter was rechecked and found to be malfunctioning from a problem different than the power supply problem. The power supply outputs were verified by checking the various output waveforms. The problem was eventually traced to 4 parallel data lines which had improper values. Further, the values indicated were contaminated with a significant amount of noise. The 4 lines run adjacent to each other across the circuit board. Selective brushing of the circuit board first improved and then completely restored the output. The brushing was largely along the adjacent paths of the data lines. The incorrect output was probably caused by leakages among these data lines and possibly with other nearby lines resulting from the corrosive effects of the particulate in a high humidity environment. A photograph of the area of the data lines is shown in Fig. 30.

The second counter was tested in test 4 and the top cover was removed. The counter was located in the bottom of the corner cabinet and was exposed to the temperatures shown in Fig. 31. The result of the exposure was a limited amount of particulate deposited on the circuit board, almost none when compared to the counter in test 3. No loss of function occurred as a result of the test.

4.1.5.2 Applicability of Counter Data to Other Components

This section describes the expected failure modes of counters and what other components would be expected to experience similar failure modes. Where the counters did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

The general failure modes of the counters are similar to those for strip chart recorders with the exception of mechanical binding possibilities for the recorder. The reason for including the counters in the tests was to represent electronic circuits which are digital as opposed to the analog recorders and other analog equipment discussed later.

Components not tested which might experience similar failure modes include those with electronic circuits such as logic equipment, controllers (some types), power supplies, solid state relays, and transmitters.

4.1.6 Other Electronic Equipment

4.1.6.1 General

The remaining equipment was all tested in test 2. The equipment consisted of a Raytheon model QRD60-5 power supply, a Hewlett Packard model 467A power amplifier, and a Tektronix model 133 plug-in unit power supply with a type 1A4 4-channel amplifier plug in module. The power supply was located about 2′ above the burning cabinet, the power amplifier was located in the adjacent cabinet near the wall away from the fire about 6′ high, and the power supply/amplifier was located about 6′ directly out from the fire and about 4′ high. The burning cabinet had an open door, exposing the power supply/amplifier to the direct radiation effects of the fire. The Raytheon power supply was later tested in both tests 4 and 5 where it was located in the bottom of the corner cabinet about 1′ from the floor.

The power supply no load output voltage was monitored throughout all three tests and did not vary by more than 1.5% in test 2 and 0.05% in tests 4 and 5. The temperature profile from test 2 is shown in Fig. 32. The peak temperatures in tests 4 and 5 were about $40^{o}C$ and $25^{o}C$, respectively. Tests 4 and 5 were intended primarily to see if any corrosive vapors might condense on the power supply in the cooler regions low in the room. No evidence of any damage to the power supply was found during or after any of the tests.

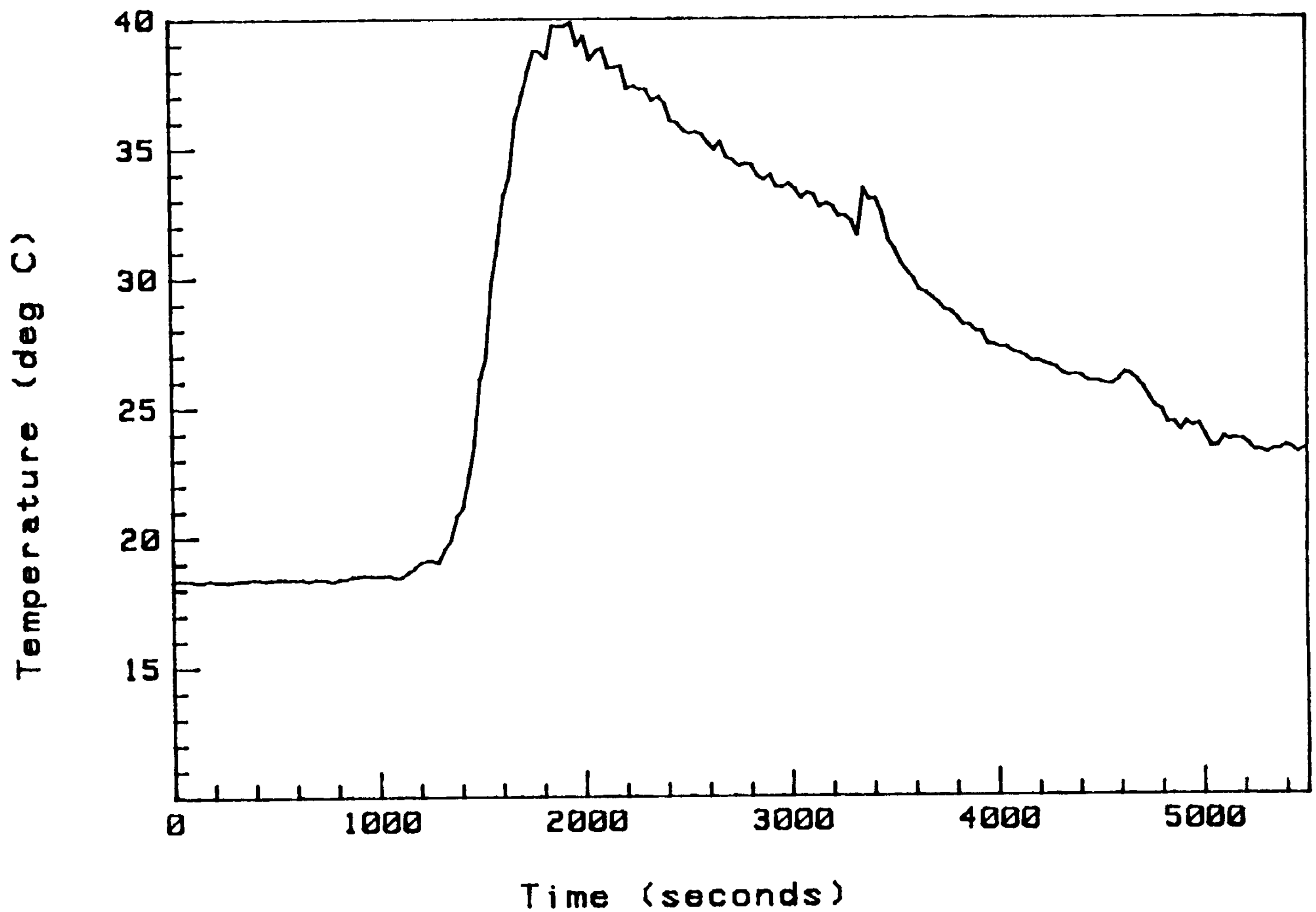


Fig. 31 Temperature Near Counter in Test 4

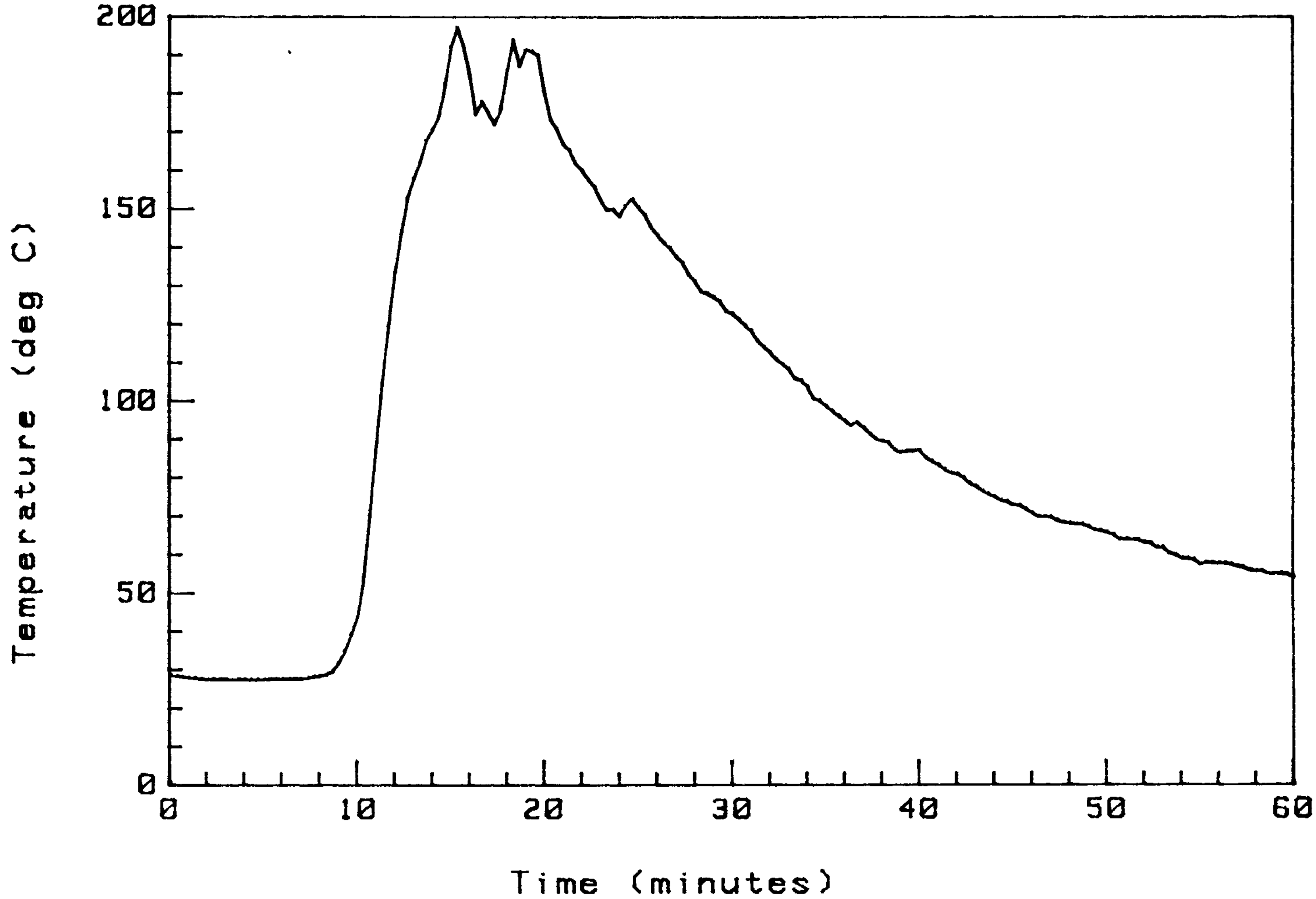


Fig. 32 Temperature Near Power Supply in Test 2

The power amplifier was powered with an input voltage of nominally 1 V and its output was monitored after amplification by 5. The average of the temperatures about 2' above and below the amplifier is shown in Fig. 33. The temperature profile at the amplifier would be close to this average. The amplifier output matched the input (multiplied by five) with an accuracy of better than 0.5% throughout the test. Post-test measurements soon after the test and after several days verified correct operation of the amplifier in both dc and ac applications.

The 4-channel amplifier and power supply was powered with the same nominal 1 V input as the power amplifier. The temperature profile near the 4-channel amplifier is shown in Fig. 34. One channel of the amplifier was set for an amplification of 5 and the output was monitored. As the test progressed, the output signal error increased to about 20% and then was lost. After the test ended, the output returned for about 6 minutes with an initial error of less than 1% but increasing with time to about 16% after which the signal was again lost. After the test, the amplifier power light was found on and the cooling fan was running but no output was being produced. Post-test measurements soon after the test and several days later indicated the amplifier was working on both dc and ac with minimal error. Examination of the plug in unit power supply schematic led to the discovery of a thermal cutout switch which cuts the power off to everything except the on indicator and the cooling fan when the temperature exceeds 58°C (137°F). Fig. 34 shows that the temperature in the vicinity of the amplifier did exceed 58°C, resulting in the cutoff. No instances of similar thermal cutoffs being used in nuclear power plant components are known.

Because the amplifier returned to normal following return to room temperature, the output error was almost certainly a result of thermal drift of subcomponents in the amplifier or power supply. It should also be noted that the cabinet door was open, exposing the amplifier to the direct effects of flame radiation. The thermal cutoff worked as designed to shut the unit down until the temperature returned to normal.

4.1.6.2 Applicability of Data to Other Components

This section describes the expected failure modes of electronic equipment tested and what other components would be expected to experience similar failure modes. Where the electronic equipment did not experience a particular failure mode, the other components would generally also not be expected to experience that failure mode under similar conditions, and conversely.

The power supply, power amplifier, and 4-channel amplifier would be expected to have failure modes similar to the electronics of the strip chart recorders and the counters. These components are in no specific way related to actual components used in nuclear power plants. They were chosen only to reflect the type of subcomponents and potential failure modes that might be related to power plant components. They were all well used prior to testing and were a number of years old, similar to some types of equipment currently found in power plants.

Components not tested which might experience similar failure modes are the same as discussed previously for the recorders and counters. The

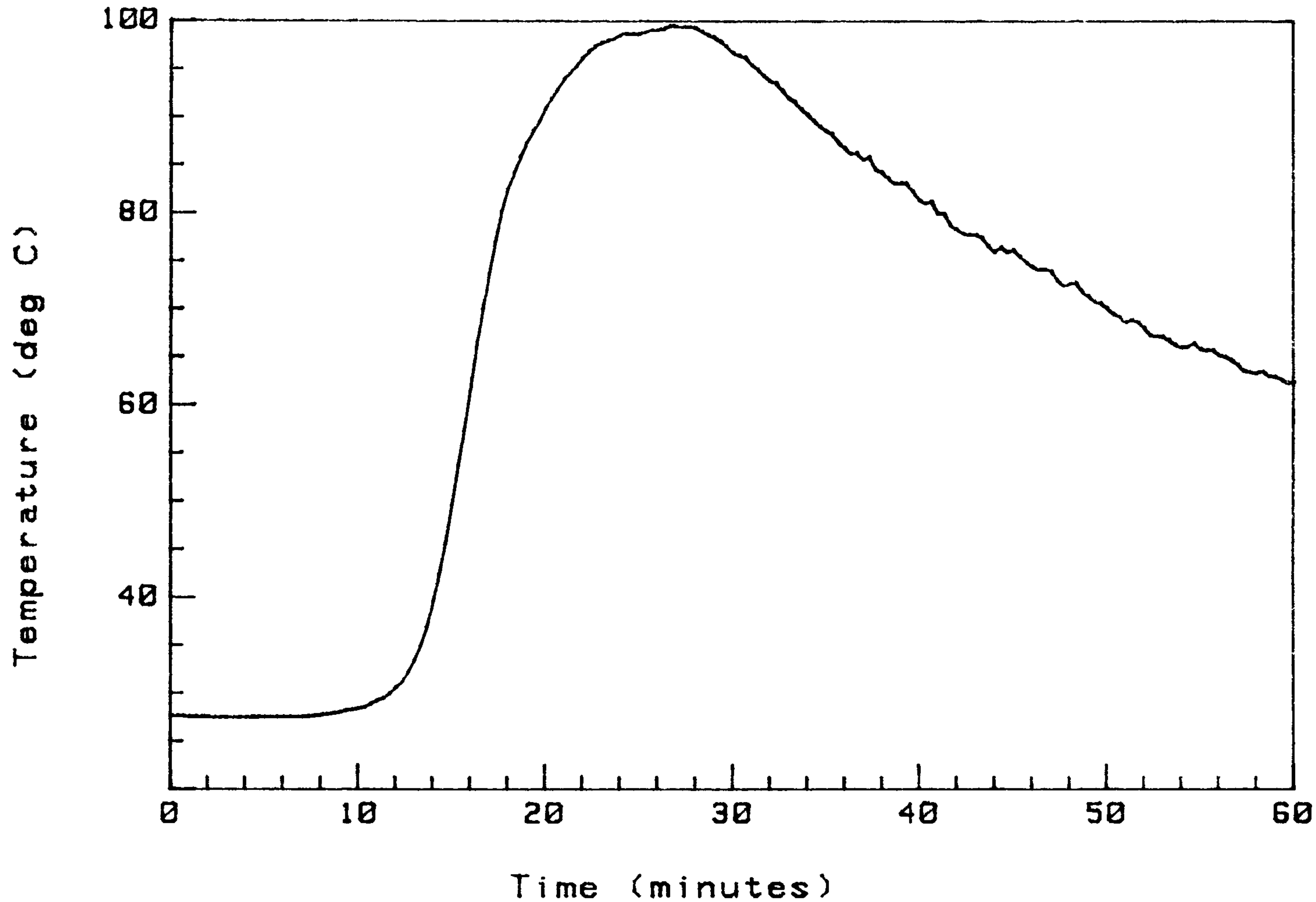


Fig. 33 Average Temperature Near Power Amplifier in Test 2

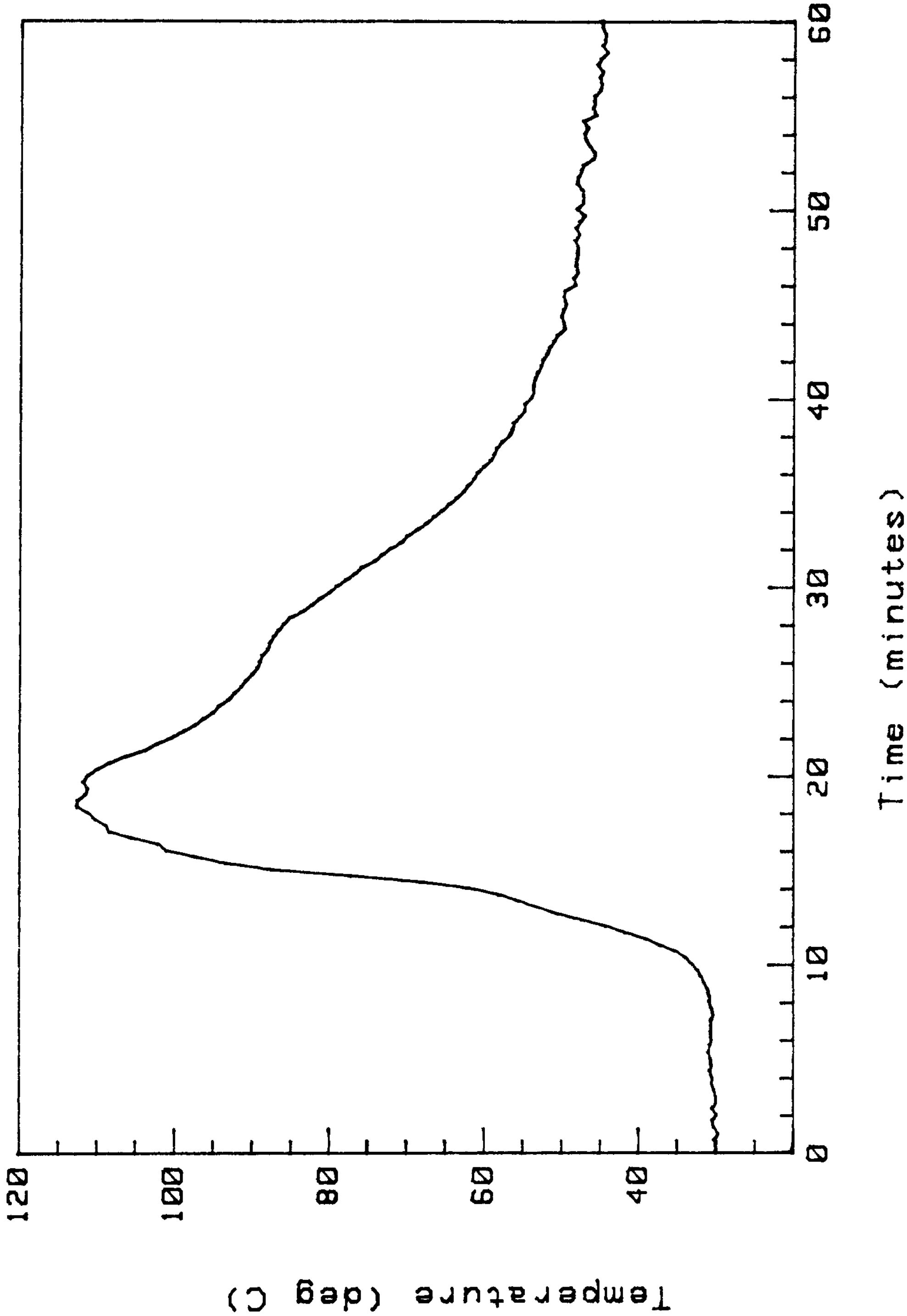


Fig. 34 Temperature Near Oscilloscope 4-channel Amplifier in Test 2

testing of these components was primarily to support the recorder and counter data for older equipment and equipment of more different manufacturers.

4.2 Summary of Component Data Applicability to Other Components

Table 5 summarizes the top ranked components described in section 2.0, some of their potential failure modes, and components tested which might be expected to have similar failure modes. This table demonstrates that although all of the highly ranked components from Section 2.0 were not explicitly tested, other components which were tested have generically similar failure modes which represent many of the failure modes of untested components.

In addition to the listed failure modes, all components would eventually fail if subjected to high enough temperatures. The testing of relays to high temperatures in the test chamber and the temperatures recorded during the cabinet tests give the impression of a large amount of temperature margin for components generically similar to relays, such as switches, MCCs and SG. The high temperature that the counter was exposed to during test 2 also indicates a reasonably high temperature margin for electronic equipment exposed to the relatively short high temperature environment of the cabinet tests. However, the 4-channel amplifier had output errors as high as 20% prior to the thermal cutout operating, indicating the possibility of large temporary errors from electronic components exposed to high temperatures. It should be repeated that the amplifier was located such that it received direct flame radiation effects from the fire. Because no components other than electronics reached temperatures anywhere near their expected damage thresholds based on the tests discussed, most thermal failure modes are not included in Table 5. For example, high temperature failures of MCC or relay coils are not included except for leakage currents/shorts. However, because of the potential temperature sensitivity of some electronics, they are still included in the table.

The primary failure modes (after temperature effects have been considered) are primarily a result of potential corrosive action, particulate deposition, and/or humidity effects. The major expected failure modes include leakage currents/shorts and mechanical binding of moving parts. In some cases, leakage currents may appear to be electronics failures as was noted for the counter from test 3 which was exposed in the humidity chamber. One additional failure mode possibility is the loss of continuity between electrical contacts.

The major failure mode actually observed was the failure of the two strip chart recorders (primarily the one in test 3 when the covers were removed). A second failure observed was a result of leakage currents on the circuit boards of the counter from test 3 after significant exposure to a humidity environment. A third potential failure was the error (as high as 20%) experienced by the 4-channel amplifier in test 2 prior to its thermal cutout operating. The remaining "failures" were specific cases of high contact resistance on relays and switches at the voltage potential used for testing. In no case was the increased contact resistance high enough to prevent correct operation when a small voltage (up to 15 V maximum) was applied across the contacts. The smaller relays with

Table 5 Summary of Component Failure Modes

Component Ranked in Ref. 12	Expected Failure Modes	Components Tested With Similar Expected Failure Modes in Configuration Tested
Recorders	Particulate Buildup Leading to Binding	Recorders *
	Electronics Failures	Recorders, Counters, Amplifiers *, and Power Supply
	Corrosion of moving parts	Recorders
	Low Level Leakage Currents	Counters *, Amplifiers, and Power Supply
	Motor Failure	Recorders
Logic Equipment	Electronics Failures	Same as for Recorders
	Low Level Leakage Currents	Same as for Recorders
Controllers	Electronics Failures	Same as for Recorders
	Leakage Currents/Shorts	Switches and Relays
	Low Level Leakage Currents	Same as for Recorders
	High Resistance Contacts	Switches *, Relays *
Power Supplies	Electronics Failures	Same as for Recorders
	Leakage Currents/Shorts	Same as for Controllers
	Low Level Leakage Currents	Same as for Recorders
Meters	Particulate Buildup Leading to Binding	
	non-sealed meters	Recorders *
	sealed meters	Meters
	Corrosion of Moving Parts	
	non-sealed meters	Recorders *
	sealed meters	Meters
	Leakage Currents/Shorts	Same as for Recorders
Solid State Relays	Electronics Failures	Same as for Recorders
	Low Level Leakage Currents	Same as for Recorders
Electro-Mechanical Relays	Leakage Currents/Shorts	Same as for Controllers
	High Resistance Contacts	Same as for Controllers

Table 5 Summary of Component Failure Modes (cont.)

Transmitter	Leakage Currents/Shorts	Same as for Controllers
	Low Level Leakage Currents	Same as for Recorders
	Electronics Failures	Same as for Recorders
Switches	Leakage Currents/Shorts	Same as for Controllers
	High Resistance Contacts	Relays *, Switches *
Battery Chargers/ Inverters	Leakage Currents/Shorts	Same as for Controllers
MCCs/SG	Leakage Currents/Shorts	Same as for Controllers
	High Voltage Breakdown	None
Batteries	Leakage Currents/Shorts	Same as for Controllers
Temperature Switches	Leakage Currents/Shorts	Same as for Controllers

* These tested components had actual instances or some indication of the stated failure mode.

enclosed contacts did not experience any high contact resistances. As noted previously, some of the Agastat relays had high contact resistances prior to the test with the voltages used for testing.

Most of the major failure modes for components were not observed in the cabinet tests, with the exceptions noted above. The major failure mode not addressed in the cabinet tests is high voltage breakdown of electrical equipment, most notably MCCs and SG. Failures resulting from particulate (including corrosive effects) and humidity interactions were addressed to some extent by the components put in the humidity chamber. The counter survived over 5 hours at 90% RH followed by an unknown amount of time at 95% RH. The components tested for almost two weeks at 70% RH all survived without any ill effects.

4.3 Chloride Ion Measurements

Chloride ion measurements were made in tests 3, 4, and 5. The intention of the measurements was to establish the chloride ion concentration in the exhaust as a function of time with the hope of relating this value to a chloride ion generation rate and possible corrosion of components. The chloride ion concentrations obtained in test 3 were compared with estimated theoretical values and other experimental work summarized in Ref. [13] and found to be lower by nearly two orders of magnitude. The system was redesigned as explained in Appendix A to eliminate the possibility that a large portion of the sample was lost in the sampling system in test 3. The results of tests 4 and 5 were similar in amount collected to test 3 and were in fact both lower (on a normalized basis) than test 3, indicating that the sample was probably not being lost in the sampling system and the chloride ions were being measured accurately. Because particulate matter can react with vapors in the air (such as reactive hydrogen chloride) and because most of the particulate was effectively filtered out of the sampling system prior to the bubbler (active filtering in test 3; deposited on the sample line or never getting into the sample line which was perpendicular to the flow direction in tests 4 and 5), a particulate sample was taken after test 4 for chloride ion analysis. The particulate sample was taken from the floor of the burn room. The room had been swept prior to the test so contamination of the particulate was kept to a reasonably low level. Another sample for chloride ion analysis was taken from the cable residue to see how much remained after the cable was burned.

4.3.1 Chloride Ion Analysis of the Particulate and Residue Samples

Chloride ion analysis was performed by mercuric nitrate titration on the two samples. The particulate sample contained 33% water soluble chlorides by weight and the residue sample contained 0.7% water soluble chlorides by weight. Other investigators using small-scale apparatus [13] have reported large quantities of hydrogen chloride evolved by heated or burning polyvinyl chloride. Taking the previous small scale results together with the current larger-scale results indicates that a large quantity of hydrogen chloride was probably generated by the cabinet fires, but most of it was deposited on particulate prior to leaving the burn room. These results are consistent in that a significant amount of time is available in larger scale tests for particulate/HCl reactions while in smaller scale tests, less time exists for the reactions. Another possible explanation for the difference noted is that all of the exhaust products, including the particulate, may have been collected in the small scale experiments, resulting in no distinction between vapor phase hydrogen chloride or hydrogen chloride reacted with particulate. Chloride ion analysis after the Brown's Ferry fire [3] found between 14 and 19% chlorides in several soot samples from the first and third floors of Unit 1, further indicating that the HCl and particulate combine in larger-scale fires.

The major implications of HCl combining with soot are 1) particulate generated from burning PVC and deposited on components will likely contain a large quantity of chloride ions and 2) hydrogen chloride vapor in the air in condensing concentrations is probably less likely than small scale data would imply. HCl condensed on components would be expected to react or evaporate after the ambient concentrations were reduced. However, chloride ions combined with particulate are expected to remain on the components until physically removed. Corrosion resulting from the chloride ions is worst when the humidity is high as evidenced by the counter which was exposed to high humidity and suffered significant corrosion (see Fig. 30).

4.3.2 Chloride Ions in Exhaust as a Function of Time

The chloride ions measured in the exhaust gas as a function of time for test 3 are shown in Fig. 35. This figure was obtained after first processing the raw data to filter the signal, but the data is still somewhat variable for two major reasons: 1) the chloride ion concentration is found by using the derivative of the total chloride ions collected as a function of time and derivatives of experimental data greatly amplify errors in the measurement and 2) the amount of chloride ions collected was far below what was expected so the chloride ion probe did not work in its optimal range, causing further difficulty in obtaining the derivative of the signal. The data does give an indication of the levels observed as a function of time. The variation of chloride ion concentration as a function of time for test 4 was not recorded because of a problem encountered with the datalogging system. For test 5, the amount collected was so small that derivative data was impossible to obtain with any accuracy. Consequently, only the total amounts collected are presented for the last two tests. These totals, along with other pertinent data for each test is given in Table 6.

Table 6 shows the low percentage of theoretical chloride ions collected in all the tests. The data also shows that as the ventilation rate (expressed in air changes per hour) is increased, the percentage of theoretical chloride ions increases. Another likely conclusion is that the smaller the room, the larger the amount of chloride ions collected. Both these observations seem to make sense. As the ventilation rate is increased, less time is available for hydrogen chloride/particulate reactions, and hence more chloride ions are collected. Also, the higher ventilation rates tend to clean out the room more quickly at the end of the test, leaving fewer chloride ions lost in the room environment at the end of the test. For example, with one room change per hour, the exponential decay time constant for reducing the chloride ion concentration in the room is one hour if the concentration is assumed uniform at all times. Obviously uniform concentration is not a good

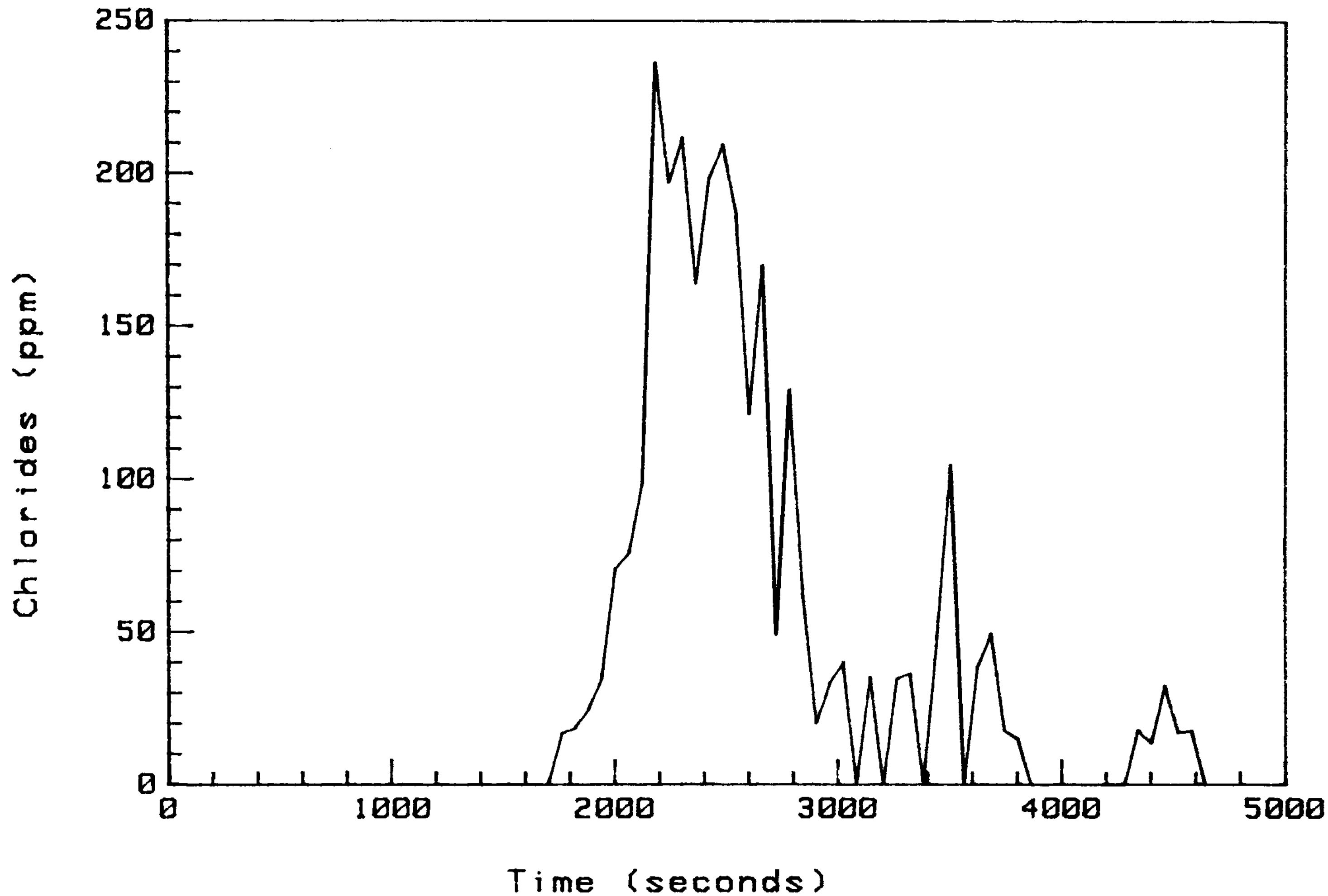


Fig. 35 Chloride Ion Concentration in Exhaust Duct vs. Time for Test 3

assumption, but it does convey the idea. With larger rooms, more surface area is available for particulate deposition for a fixed size fire, resulting in less collected.

Table 6 Pertinent Data for Chloride Ion Collection

Test Number	3	4	5
Total Chloride Ions Collected (mg)	3.02 *	3.44	0.60
Approximate Weight Burned (kg)	45	50	35
Ventilation Rate (m^3/min)	68	23	181
Air changes per hour	14.4	1.0	8.0
Room Size (m^3)	283	1360	1360
Amount collected x (ventilation rate/ sample flow rate)/amount burned (mg/g)	4.56	1.57	3.20
Percent of Theoretical Chloride Ions **	1.6	0.55	1.1

* Corrected for actual sample flowrate which was not constant at 1 liter/minute.

** Assuming about 50% of the cable weight is PVC [13] and 57% of PVC is chlorides (based on the chemical formula).

5.0 CONCLUSIONS

The results of this test program show actual failure or some indication of failure for the strip chart recorders, the electronic counters, the oscilloscope amplifier, and the switches and relays. Most of the expected failure modes of the highest ranked components from section 2.0 were tested either directly or indirectly in this test program. The major exception is high voltage breakdown of components. It should be emphasized that the environmental stresses used in the cabinet tests were limited to those created by the tests. Several fire environments remain to be addressed: 1) direct spray from suppression activities, either manual or automatic, 2) response of cool components to steam exposure resulting from from suppression activities (although high humidities were addressed by the humidity exposures, relatively cool components were never exposed to rapidly changing humidity which would likely cause condensation, and 3) hydrogen chloride/humidity interactions (condensation) which could occur prior to the chlorides combining with particulates. In addition, this test effort did not address failures from direct fire effects which could cause undesired effects in a power plant, such as spurious operations of equipment.

The following specific conclusions may be drawn from this study:

1. The counter tested in test 3 and then exposed to high humidity conditions failed electrically twice. Both failures were apparently a result of leakage currents on the circuit boards caused by corrosive action of the chloride containing particulates in a high humidity environment. The counter had the covers removed during the fire test and was located where a significant amount of particulate was deposited on the circuit boards.

2. Two strip chart recorders failed mechanically when particulates were deposited on the pen slider mechanisms. The first recorder had the covers removed and failed grossly; the second was cabinet mounted, had the covers intact, and only one of the three pens failed. No signs of electrical failures were noted in either case.

3. The 4-channel amplifier experienced errors as high as 20% prior to its thermal cutout operating and cutting off the output. The degradation mode of the amplifier was apparently thermal drift because its operation returned to normal shortly after the test was over.

4. Several instances of high contact resistances were noted for some switches and relays at the low test voltages used. However, small voltage stresses were sufficient to overcome the high contact resistances. In addition, similar high contact resistances were noted on some of the relays prior to testing.

5. Relays tested to thermal failure failed at temperatures considerably higher than the temperature levels observed in this series of tests at typical component locations, such as inside cabinets (other than the burning cabinet).

6. Chlorides generated in the large scale cabinet tests were almost completely combined with particulates before being exhausted from the room. The amount of combined chlorides appears to increase with lower ventilation rates and larger rooms. Consequently, particulate generated from burning PVC and deposited on components contains a significant quantity of chlorides.

7. Hydrogen chloride vapor in the air in condensing concentrations may be less likely than small scale data would imply.

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Appendix A--Chloride Ion Measurement System

The system used to measure the chloride ion concentration in the exhaust duct of some of the cabinet fire tests consisted of the system shown in Fig. A.1. A sample of the exhaust gas was taken from the ventilation exhaust duct and bubbled through a cylinder containing deionized water stirred gently by a magnetic stirrer. The bubbler was made by punching a series of small holes in the end of the Teflon line to keep the bubble size small while also preventing plugging due to particulate accumulation. The sample temperature and pressure were then measured and the sample was run through a flow controller which maintained the correct flowrate as long as excessive plugging did not occur. A nominal flowrate of 1 liter/minute was maintained in all tests. A chloride ion electrode and a reference electrode monitored the chloride ion concentration in the deionized water solution as a function of time. The chloride ion electrode was shielded from generated bubbles by a glass tube over the electrode reaching below the level where the bubbles were generated. The bubble protection was needed for the membrane on the ion specific electrode; the reference electrode works differently and did not need to be protected. The detrimental effect of the glass tube was an increase in the response time of the system to allow for a uniform chloride ion concentration to be established in the cylinder. Two additional factors in the system contributed to a relatively high overall response time. These include 1) the time for the generated chloride ions to get from the fire, into the room and the ventilation exhaust duct, and through the approximately five-foot long sample line, and 2) the response time of the chloride ion electrode which can be up to about one minute.

The system as shown was used in two Factory Mutual Tests. The one test at Sandia where chloride ions were measured used an earlier version of this design where the flow controller and pump were upstream of a beaker used for collection. This eliminated the need to seal all the equipment which had to go into the beaker (thermocouple, electrodes, and sample line). The earlier version also had materials other than Teflon in the sample line prior to the bubbler and a fritted glass bubbler was used to generate small bubbles. The system was changed because it was believed that the equipment and sample lines may have been removing many of the chloride ions prior to their reaching the bubbler. The bubbler was changed to prevent clogging by particulate. The system was therefore modified such that no material was in contact with the sample, other than Teflon, prior to the bubbler. The length of Teflon line was also limited to five feet.

Both configurations of the chloride ion measurement system were checked for collection efficiency using hydrogen chloride ion sources. The original system was checked using bottled anhydrous hydrogen chloride and the modified system was checked using hydrogen chloride generated by a heated cable specimen. Two bubblers were used in series and the amount of chloride ions collected in the first bubbler divided by the amount collected in both bubblers was taken as the collection efficiency. The efficiency for the first system with the small bubbles was found to be much greater than 99% up to concentrations on the order of 10^{-1} molar while the second system using somewhat larger bubbles had an efficiency much greater than 99% up to chloride ion concentrations of about $5x10^{-4}$ molar and an efficiency of at least 99% up to concentrations of $2x10^{-2}$ molar.

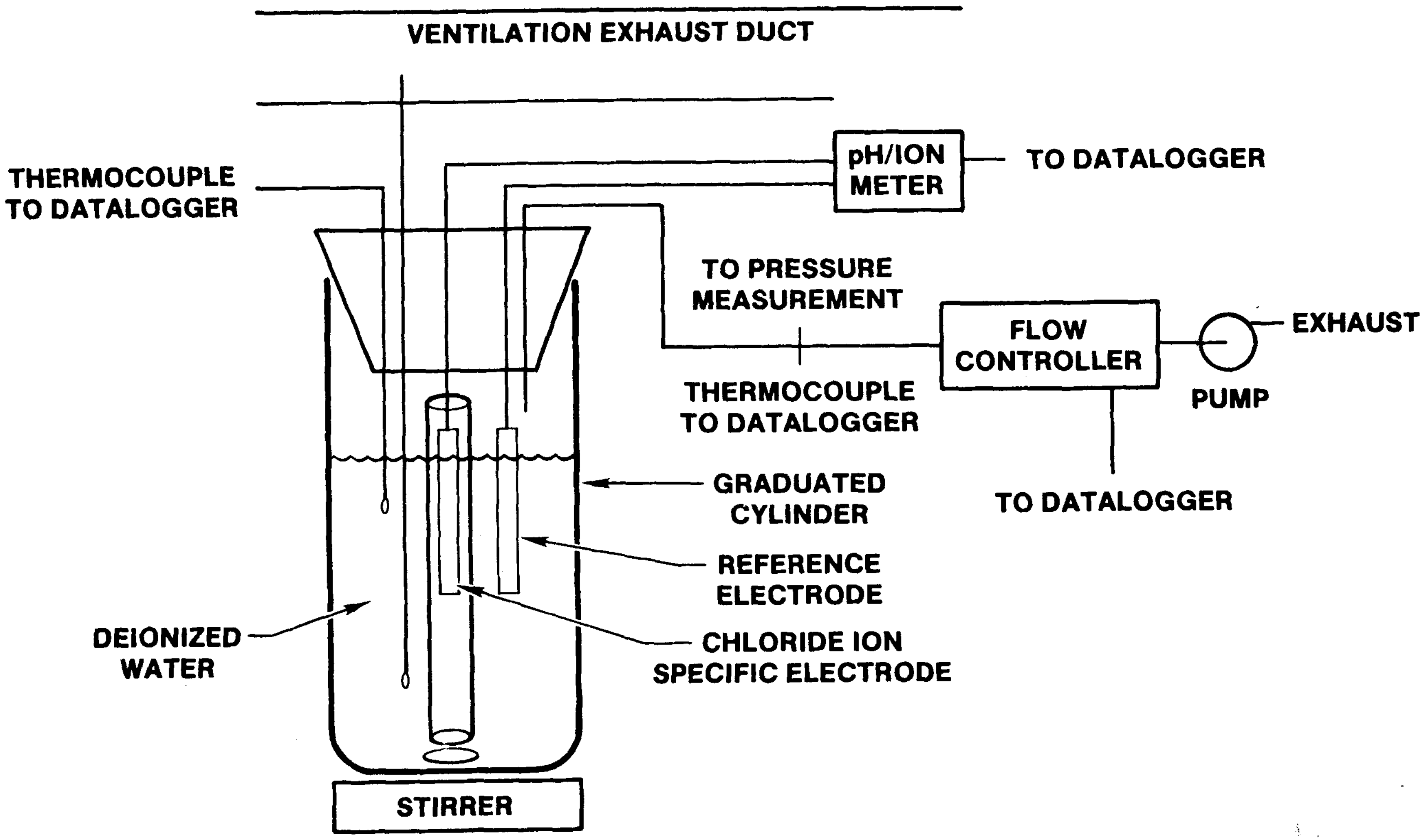

Fig. A-1 Chloride Ion Measurement System

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12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

This report presents results of screening tests to determine component survivability in secondary environments created by fires, specifically increased temperatures, increased humidity, and the presence of particulates and corrosive vapors. Additionally, chloride concentrations were measured in the exhaust from several of the tests used to provide fire environments. Results show actual failure or some indication of failure for strip chart recorders, electronic counters, an oscilloscope amplifier, and switches and relays. The chart recorder failures resulted from accumulation of particulates on the pen slider mechanisms. The electronic counter experienced leakage current failures on circuit boards after the fire exposure and exposure to high humidity. The oscilloscope amplifier experienced thermal-related drift as high as 20% before thermal protective circuitry shut the unit down. In some cases, switches and relays experienced high contact resistances with the low voltages levels used for the measurements. Finally, relays tested to thermal failure experienced various failures, all at temperatures ranging from 150°C to above 350°C. The chloride measurements show that most of the hydrogen chloride generated in the test fires is combined with particulate by the time it reaches the exhaust duct, indicating that hydrogen chloride condensation may be less likely than small scale data implies.

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