NUREG/CR-5334
SAND89-0327

Severe Accident Testing of Electrical Penetration Assemblies

Prepared by D. B. Clauss

Sandia National Laboratories

Prepared for
U.S. Nuclear Regulatory Commission

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NUREG/CR-5334
SAND89-0327
RD, R1

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Manuscript Completed: October 1989
Date Published: November 1989

Prepared by
D. B. Clauss

Sandia National Laboratories
Albuquerque, NM 87185

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN A1364

ABSTRACT

This report describes the results of tests conducted on three different designs of full-size electrical penetration assemblies (EPAs) that are used in the containment buildings of nuclear power plants. The objective of the tests was to evaluate the behavior of the EPAs under simulated severe accident conditions using steam at elevated temperature and pressure. Leakage, temperature, and cable insulation resistance were monitored throughout the tests. Nuclear-qualified EPAs were procured from D. G. O'Brien, Westinghouse, and Conax. Severe-accident-sequence analysis was used to generate the severe accident conditions (SAC) for a large dry pressurized-water reactor (PWR), a boiling-water reactor (BWR) Mark I drywell, and a BWR Mark III wetwell. Based on a survey conducted by Sandia, each EPA was matched with the severe accident conditions for a specific reactor type. This included the type of containment that a particular EPA design was used in most frequently. Thus, the D. G. O'Brien EPA was chosen for the PWR SAC test, the Westinghouse was chosen for the Mark III test, and the Conax was chosen for the Mark I test. The EPAs were radiation and thermal aged to simulate the effects of a 40-year service life and loss-of-coolant accident (LOCA) before the SAC tests were conducted.

The design, test preparations, conduct of the severe accident test, experimental results, posttest observations, and conclusions about the integrity and electrical performance of each EPA tested in this program are described in this report. In general, the leak integrity of the EPAs tested in this program was not compromised by severe accident loads. However, there was significant degradation in the insulation resistance of the cables, which could affect the electrical performance of equipment and devices inside containment at some point during the progression of a severe accident.

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PREFACE

The severe accident tests on electrical penetration assemblies (EPAs) described in this report were conducted at Sandia National Laboratories in 1985 and 1986, initially under the direction of Mr. Frank V. Thome and later under the direction of Mr. Jeffrey D. Keck. Thome was responsible for much of the early planning, including the specification and purchase of all three EPAs, and the test of the D. G. O'Brien EPA. Keck led the testing of the Westinghouse and Conax EPAs. These tests were documented by Thome and Keck immediately after the test in the form of Quick Look Reports. Papers on the EPA testing were also prepared for several technical conferences and meetings. This report collects all the information from the Sandia EPA tests into one source. The author was assigned responsibility for this report because Keck and Thome were unavailable for this task. Although the author was not directly involved in the EPA tests at the time they were conducted, he has worked on the NRC Containment Integrity Programs for about five years. The overall objective of the Containment Integrity Programs is to develop and validate methods for predicting the performance of LWR containment buildings subject to severe accident loads. The results of the EPA tests comprise significant input to this activity.

Most of the credit for this work belongs with Thome and Keck. G. Dibisceglie, P. Drozda, R. Padilla, and T. Gilmore were responsible for carrying out the tests and reducing the data. Also, W. Sebrell and C. Subramanian played an important role in the initial planning for the EPA tests. The efforts of Mr. William S. Farmer, who was the NRC Technical Project Monitor for this program, are acknowledged. Farmer worked closely with Thome and Keck in making decisions about critical aspects of the planning and testing.

Finally, the cooperation and assistance of those individuals at D. G. O'Brien, Westinghouse, and Conax Corp. who assisted in this program are gratefully acknowledged.

1.0 EXECUTIVE SUMMARY

Since the Three Mile Island incident, the risk and consequences of severe accidents have been a major focus of reactor safety research. The performance of the containment building has a significant effect on accident consequence, and thus, considerable effort has been directed towards understanding and predicting functional failure of containments. The containment pressure boundary typically includes numerous mechanical and electrical penetrations, each of which represents a potential leakage path past containment.

Several studies completed in the early 1980s indicated that Electrical Penetration Assemblies (EPAs) could be an important potential leak path that merited further study. A report by Oak Ridge National Laboratories on severe accident sequence analysis for BWR Mark I containments concluded that the temperatures in the drywell were high enough to possibly cause failure of the EPA seals, resulting in leakage. In NUREG-0772, EPAs were identified as having "one of the largest uncertainties associated with predicting the amount of radionuclides released." These studies provided the major impetus for NRC to initiate a research program on EPAs. Under the sponsorship of NRC, Sandia National Laboratories managed a program--the Electrical Penetration Assemblies Program--to conduct a background study on EPAs and to recommend and conduct tests to generate data that could be used to assess the leak potential of EPAs subjected to severe accident conditions. The results of the background study and test recommendations were described previously in a report by Sebrell. The severe accident tests that were performed on EPAs are described in this report.

EPAs are used to provide a leak-tight pass-through in nuclear power plant containment buildings for electrical cables with power, control, and instrumentation applications. The design of EPAs has evolved to a modular concept that consists of electrical conductors contained within stainless steel tubes (modules) that are sealed into a modified blank flange called a header plate. The conductors are sealed in the modules by various means including hermetic glass-to-metal seals, epoxy compounds, and polysulfone plugs. The modules are either welded into the header plate, sealed with silicone or ethylene propylene (EPDM) O-rings, or sealed with metal-to-metal compression connectors. The header plate is in turn bolted or welded to a flange on a nozzle that passes through and is welded to the containment wall. Double O-rings, made of silicone, viton, or EPDM, are used to maintain seals in designs where the header plate is bolted to the flange. Typical PWR and BWR nuclear power plants include anywhere from 30 to 70 EPAs in each containment building.

Three full-size EPA designs--one each by Conax, D. G. O'Brien, and Westinghouse[1] --were procured for this test program; all were nuclear qualified and built to meet IEEE 317-1976 and IEEE 323-1974 standards. These three EPAs provide a good representation of the different seal materials used and applications in containments of all major reactor types. Each EPA also included a mix of conductors representing instrumentation, control, and low voltage power modules; the D. G. O'Brien also included a medium voltage power module. These three EPAs represent an "evolved" design, which is used extensively in U.S. nuclear power plant containments.

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1. Mention of specific products and/or manufacturers in this document implies neither endorsement or preference nor disapproval by the U.S. Government, any of its agencies, or Sandia Corp., of the use of a specific product for any purpose.

However, prior to 1971, there were no national standards for design and EPAs were often field manufactured, resulting in a large number of diverse designs. The results of the tests described in this report cannot be extrapolated directly to early EPA designs; they will require separate, individual examination to assess their leak potential under severe accident conditions. Given good information on the containment loads, a heat transfer analysis to determine the temperature profiles in the EPA, knowledge of the time-temperature thresholds for the sealant materials used in the EPA, and the proper exercise of engineering judgement, a reasonable evaluation of the leakage potential of other EPA designs could be made. Certainly, these tests do provide a basis for such an appraisal.

The objective of the severe accident tests was to generate engineering data that can be used to assess the leakage potential of EPAs. As a secondary objective, electrical performance of the EPA cables was monitored. Measurements included leak rate, temperature, and insulation resistance and electrical continuity of the EPA conductors. It is important to recognize that the test conditions were more severe than the design loss-of-coolant accident (LOCA) condition and were therefore not qualification tests; as such, there were no pass/fail criteria. The EPAs were first radiation aged (200 Mrad total; 50 Mrad corresponding to a 40-year service life and 150 Mrad corresponding to LOCA) and then thermally aged to simulate end of service life; they were then exposed to severe accident conditions representative of the "worst-case" loads[2] for either PWR, BWR Mark I, or BWR Mark III containments for a period of approximately 10 days. The severe accident loads were simulated with steam. The EPAs were matched with the severe accident profiles based upon in which containment type a particular EPA design was most frequently used. The effects of chemical sprays, seismic loading, fault currents, preload pressure cycling, thermal cycling, and operating the cables at rated current and voltage were not addressed by these tests.

D. G. O'Brien EPA

The severe accident test of the D. G. O'Brien EPA was conducted in June 1985. This EPA used hermetic glass-to-metal seals between the conductors and the modules. Plugs (also called connectors) were used on each side of the glass-to-metal seals, a unique feature of the D. G. O'Brien EPA. The connectors contain silicon grommets that are compressed around the cables to seal out moisture by applying torque to threaded connector coupling rings. These removable connectors facilitate installation, maintenance, and modifications. The modules were welded into the header plate and two silicone O-rings were used to form a seal between the header plate and the nozzle flange. The D. G. O'Brien EPA was tested to the severe accident test profile for a large PWR containment. The test profile consisted of ramping the temperature and pressure from ambient conditions to 293°F and 60 psia in 30 seconds, then to 361°F and 155 psia in 12 hours using saturated steam, and finally holding at these conditions for the remainder of the 10 day test.

There were no detectable leaks through the EPA during the severe accident test. The module internal gas pressure increased during the test due to seepage on the

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2. These loads represent envelopes of the loads based on what were thought to be the most probable severe accident sequences at the time this program was formulated in late 1983 and early 1984. The loads also reflect certain assumptions regarding the containment shell capability pressure.

order of 10^{-4} standard cubic centimeters per second (scc/sec) past the inboard connectors. The aperture seal (the volume between the two O-ring seals between the header plate and nozzle flange) did not leak. A very small leak, 0.13 scc/sec, was recorded during a posttest air leak rate measurement at ambient temperature and 155 psia. This is not a significant leak from a risk perspective for severe accidents.

The thermocouple data suggest that the temperatures of the EPA and its components "inside containment" are quite uniform under saturated steam conditions. Also, there was a significant temperature gradient along the axis of the EPA nozzle "outside containment". Thus, the outboard module connectors were cooler (about 290°F) than the inboard module connectors (about 360°F).

The electrical performance of the EPA modules degraded over the first 2 days of the test to the point that the insulation resistance to ground for all conductors was less than 1 MΩ, and after 10 days, five out of the eight circuits were passing 0.5 amp to ground, which was the maximum current possible in this test. The earliest short to ground occurred about 13 hours into the test. Insulation resistances fell below 1 kΩ before the shorts to ground occurred. The posttest inspection showed that all but one module was electrically faulty because of moisture that had traveled through the connector and provided a ground between the module pins and the metal mask that surrounds each pin. This bridging with moisture or contaminates is believed to have caused the electrical short to ground.

Westinghouse EPA

The severe accident test of the Westinghouse EPA was conducted in December, 1985. A proprietary system of epoxy compounds developed by Westinghouse was used to seal and support the conductors in the modules at two locations, "inside" and "outside" containment. The modules were clamped and sealed to the header plate with two sets of silicone O-rings. Silicone O-rings were also used to form a seal between the header plate and the nozzle flange. The Westinghouse EPA was tested to the severe accident test profile for a BWR Mark III containment. The test profile called for the temperature and pressure to be increased from ambient conditions over 2 hours to 250°F and 30 psia (saturated steam), then to 400°F and 75 psia (superheated steam) in 12 hours, and then maintaining this pressure and temperature until the end of the 10th day.

No significant leakage through the Westinghouse EPA was detected at any time during the severe accident test sequence or during the air leak tests at ambient temperature before and after the SAC test. Although the pressure in the monitoring space within the EPA modules did increase during the SAC test by an amount greater than that associated with the temperature rise alone, outgassing of the epoxy seals is a more plausible explanation than failure (and leakage) of the module seals. Even if the inside module seals did leak, the outside module seals definitely prevented any leakage past the EPA to "outside containment". Again, the structural and leak integrity of the Westinghouse EPA was maintained during the entire 10-day period of the severe accident test.

Data on the thermal behavior of the EPA was also collected during this test. The data indicated that some temperature stratification can be expected inside the junction boxes of the EPA, and that there is a substantial axial temperature gradient along the EPA nozzle outside containment. This indicates that outboard seals will be subjected to lower temperature than inboard seals and are, therefore, less likely to fail.

The insulation resistances of the EPA conductors were gradually degraded during the SAC test, but electrical continuity was maintained throughout the test. The insulation resistance of all the cables was greater than 1 kΩ for the first four days of the SAC test. The rate of degradation was more dependent on the type of the cable used than on the module design. The insulation resistance of all cables in the Westinghouse EPA recovered significantly during cooling after the SAC test. Although the insulation resistances of the cables in the Westinghouse EPA held up relatively well, conclusions regarding electrical performance based solely on insulation resistance data must be made with caution. A cable's electrical performance also depends on the application, in particular, the voltage, current, and impedance requirements of the equipment or device to which the cable is connected.

The insulation of the thermocouple cables appeared to have been damaged by the high potential applied during measurements made with the Hippotronics Megohmmeter, which applies a potential between 50 and 500 V. This was probably an overtest of the thermocouple cables, since in actual service the cables are normally subject to a potential of less than 0.1 V. Therefore, this data should be interpreted with care.

<u>Conax EPA</u>

The severe accident test of the Conax EPA was conducted in July, 1986. This EPA is very long (~10 feet) and massive; the cables are contained inside stainless steel tubes with polysulfone plugs at each end to seal the conductors in the modules. The modules were sealed into the header plate using Midlock connectors, which are Conax designed connectors that employ a metal-to-metal compression seal. Two silicone O-rings were used to form a seal between the header plate and the nozzle flange. The Conax EPA was tested to the severe accident test profile for a BWR Mark I containment. The test profile required raising temperature and pressure to 640°F and 85 psia in 25 minutes, then raising temperature to 700°F over the next 20 minutes while raising pressure to 135 psia over the next 175 minutes, and finally holding temperature and pressure at 700°F and 135 psia for the duration of the 10 day test. Each of these points represent superheated steam conditions.

The structural and leak integrity of the Conax EPA was maintained during the entire 10 day period of the severe accident test and also during the air leak tests at ambient temperature before and after the SAC test. Although the module seals on the inside containment end failed, the module seals on the outside containment end maintained their integrity and prevented leakage. A significant temperature gradient was measured along the length of the EPA; the header plate and outer module seals reached temperatures of less than 340°F, considerably less than the 700°F to which the inside containment end of the EPA was subjected. At 340°F, the seal materials are within their service limits.

The insulation resistances of several of the EPA cables dropped below 1 kΩ between 5 and 9 hours into the SAC test (the temperature and pressure reached their maximum values, 700°F and 135 psia, about 45 minutes and about 3 hours into the test, respectively). By the end of the test, the insulation resistances of all of the cables were below 1 kΩ. Despite this, the signal from the EPA thermocouples compared favorably with measurements from test thermocouples throughout the duration of the SAC test and afterwards. This is evidence that insulation resistance by itself may not always be a good indicator of electrical performance. The specific voltage, current, and impedance requirements for a given application must also be considered in assessing a conductor's electrical performance.

Conclusions

Three EPA designs were tested under simulated severe accident conditions for a PWR, BWR Mark I drywell, and a BWR Mark III drywell to generate engineering data (leak rate, temperature, insulation resistance, and electrical continuity) to assess their leak potential. None of the EPAs leaked during the severe accident tests, which can be attributed to the use of redundant seals in the EPA designs and to the fact that the outboard containment seals in all three designs were never exposed to temperatures that exceeded the service limits of the seal materials. The exceptional leak integrity of the three EPAs in this program should not be assumed to apply to all other EPAs in use for at least two reasons:

1. There are a large, diverse number of EPA designs in use. In particular, EPAs manufactured prior to 1971 were not subject to national standards and were often field manufactured, whereas the EPAs tested in this program were subject to rigorous quality assurance and were designed to meet the standards of IEEE 317-1976 and IEEE 323-1974.

2. The leak potential is highly dependent on the temperatures to which the EPA is subject. As research continues and more severe accident sequence analyses are conducted, the "worst-case" loads may change. Therefore, the leakage potential of EPAs must be re-evaluated as understanding of severe accident loads is improved. Heat transfer effects must be considered to determine the temperature of the outboard containment seals, which end up controlling leakage potential.

In short, the results of these tests should not be construed as suggesting that all EPA designs will not leak under severe accident conditions; the performance of all components of the containment pressure boundary must be evaluated on a case-by-case basis. The performance of the containment system will be dependent on the loads considered. Given good information on the containment loads, a heat transfer analysis to determine the approximate temperature profiles in the EPA, knowledge of the time-temperature thresholds for the sealant materials used in the EPA, and the proper exercise of engineering judgement, a reasonable evaluation of the leakage potential of other EPA designs can be made. These tests may provide a basis for such an appraisal.

The electrical performance of the EPAs was monitored in these tests by measuring the insulation resistance and electrical continuity of the conductors. The measured insulation resistance degraded rapidly during the severe accident tests, although the rate depended more on the type of cable and loads than on the particular module design being tested. Under the specific severe accident conditions that were simulated, the data suggest that **all** electrical systems supplied in the Westinghouse EPA would have functioned for about 4 days; those supplied in the D. G. O'Brien EPA would have functioned for about 13 hours; and those supplied in the Conax

EPA may have only functioned for about 5 hours[3] (the difference between the performance of the Conax and that of the D. G. O'Brien and Westinghouse is largely attributable to the severity of the loads--the Conax was subject to temperatures up to 700°F compared to 400°F or less for the D. G. O'Brien and Westinghouse). Some cables would be expected to function beyond the times indicated above. However, it must be noted that conclusions regarding the electrical performance of systems inside the containment building based solely on insulation resistance data must be made with caution. The performance of the electrical systems would depend on the specific voltage, current, and impedance requirements for a given application of a conductor. For instance, the thermocouple cables in the Conax EPA continued to transmit an accurate temperature signal throughout the severe accident test even though their insulation resistance had dropped to between 17 Ω to 4 kΩ by 9 hours into the test. On the other hand, the contaminants that seeped into the pins and mask in the D. G. O'Brien module connectors caused a short to ground that would almost certainly have precluded the electrical systems from functioning properly.

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3. The first few hours of a severe accident may be the most critical time from the standpoint of electrical functionality since mitigative action by the operators is generally most effective early in the accident progression.

2.0 INTRODUCTION

In a light water reactor nuclear power plant, the containment building is the last engineered barrier to the release of radioactivity to the atmosphere in the event of an accident. Thus, the leak integrity of the containment building has a profound influence on the safety of a nuclear power plant. In the event of a severe or degraded core (Class 9) accident, a containment building may be subject to internal pressure and temperature levels much greater than its design basis. Knowledge of the performance of the containment building under these conditions is crucial for reliable emergency preparedness, accident mitigation, and risk assessment.

The measures of containment performance of primary interest are the capacity, which determines the timing of failure; the failure mode, which may affect the operability of other safety systems; the failure location, which may or may not involve a release directly to the environment; and the failure size, which determines the rate of release. Many studies in the past have focussed just on the capability of the containment shell. However, a comprehensive, systematic evaluation of containment performance must address all potential failure modes, including structural and seal failures of penetrations.

The U.S. Nuclear Regulatory Commission is sponsoring a number of programs, which are collectively known as the Containment Integrity Programs, that address the issue of light water reactor containment performance for loadings beyond the design basis. Sandia National Laboratories is managing four of these programs, including: (1) scale model tests of containment buildings, (2) tests of seals and mechanical penetrations, (3) tests of electrical penetration assemblies, and (4) analysis and methodology development. The central objective of these programs is to develop methods that can be used to predict the likely failure modes and capacity of a containment building. The tests on scale models, gasket materials, and penetrations have been used to support this objective.

Electrical Penetration Assemblies (EPAs) were a focus for investigation as a potentially important failure mode because of the large number of EPAs used in a typical containment and because they typically use organic compounds or gaskets to make a seal at the containment pressure boundary. These organic materials are subject to failure at high temperatures. Because analytical modelling of EPAs as systems was considered to be too complex and would result in too much uncertainty, testing was necessary.

This report describes the results of tests on three EPAs, which were subjected to simulated severe accident conditions. The primary objective of these tests was to generate engineering data to evaluate the leak behavior of the EPAs. Section 3 provides the background for these tests, such as why EPAs were of concern, how the EPA vendors for this test program were chosen, how the severe accident loads were determined, etc. Sections 4-6 provide detailed information on the tests of the D. G. O'Brien, Westinghouse, and Conax EPAs, respectively. Concluding remarks are given in Section 7.

In addition to this report, the EPA testing was described at several technical meetings and conferences. For additional information see References 1 through 3.

It should also be mentioned that all aspects of this test program adhered to Sandia quality assurance requirements, including purchase orders for the EPAs, calibration of instrumentation, design and use of test apparatus, and testing procedures. Also, in addition to the general test plan [7], detailed test plans were written for each of the three EPAs tested. Each test plan was reviewed and approved by the NRC and the EPA supplier for that particular test.

3.0 BACKGROUND

Electrical Penetration Assemblies (EPAs) are used in nuclear power plant containments to transmit electrical energy for power, control, and instrumentation applications while maintaining a leak tight boundary. EPAs can be divided into four functional categories that are related to the type of service provided. Each category has different design requirements.

Medium Voltage Power (5 to 15 kV)--for the high power demand of reactor coolant pump motors and recirculation pump motors.

Low Voltage Power (up to 1 kV)--for high horsepower motors, fans, heaters, lighting panels, and other equipment.

Low Voltage Control--for control drives, low horsepower motors, reactor protective systems, motor-operated valves, and switching.

Instrumentation--low power sensing applications, such as control rod position, neutron monitoring, environmental sensing, and communication.

A review of these categories indicates that EPAs perform many important safety-related electrical functions and also maintain leak integrity of the containment pressure boundary.

The design of EPAs has evolved to a modular concept that consists of electrical conductors contained within stainless steel tubes (modules) that are sealed into a modified blank flange called a header plate. The conductors are sealed in the modules by various means including hermetic glass-to-metal seals, epoxy compounds, and polysulfone plugs. The modules are either welded into the header plate, sealed with silicone or EPDM O-rings, or sealed with metal-to-metal compression connectors. The header plate is in turn bolted or welded to a mating flange on a nozzle that passes through and is welded to the containment wall. Double O-rings made of silicone, viton, or EPDM are used to maintain seals in designs where the header plate is bolted to the flange.

Typical PWR and BWR nuclear power plants include anywhere from 30 to 70 EPAs per unit. Because of the large number of EPAs used in each plant and because organic compounds and gaskets are used to provide seals in the EPAs, the potential for leakage past EPAs in the event of a severe accident warranted investigation. Based on a severe accident analysis of the BWR Mark I, Cook et al. concluded that high temperatures in the BWR Mark I drywell arise during a severe accident that would fail the sealants in EPAs, resulting in leakage from the EPAs before structural failure of the containment [4]. In NUREG-0772 [5], EPAs were singled out as having "One of the largest uncertainties associated with predicting the amount of radionuclides released." These early studies were a major impetus for the NRC in funding Sandia to investigate the leak potential of EPAs.

Sebrell conducted an extensive background study and review of EPA designs and recommended tests to assess the leak potential of EPAs under severe accident conditions [6]. His report is the basis for the testing described in this report. Some of the important findings of Sebrell's study are summarized in the following paragraphs.

Standards for the design, construction, testing, and installation of electrical penetrations were first established in 1971 and revised in 1976 and 1982. Prior to 1971, there was no specific standard and EPAs were often fabricated in the field. Because of the changes in standards and licensing requirements and also to meet the demands of different types of containment structures, there are a large and diverse number of electrical penetration designs in use.

Eight major suppliers of EPAs to the nuclear industry and up to 13 minor suppliers were identified. Of these, only three vendors were still active: Conax, D. G. O'Brien, and Westinghouse. This affected the availability of EPAs for testing.

The EPA designs used before the mid-1970s, in particular, the field-manufactured units are so diverse in design that they require individual evaluation. These early designs made extensive use of epoxy compounds as all-purpose adhesives and potting materials. This report does not address the issue of these types of EPAs.

The primary leak paths in EPAs are (i) between strands of a multiwire conductor, (ii) between the conductor and its insulation, (iii) between layers of insulation, jackets, or shields, (iv) through gasketed flanges or joints, (v) through voids in sealing materials, jacketing, insulation, or filler materials, and (vi) through voids or pinholes in welded joints. The last two paths listed can be addressed by good quality assurance, while the first four paths are design dependent.

Sebrell concluded that the leakage potential of EPAs used in PWR containments should not be very great because in the worst severe accident sequences, the long time temperature of the containment atmosphere stabilizes at 350°F. Many EPAs have been tested and qualified to this temperature. On the other hand, severe accidents in BWRs produce drywell temperatures much higher than 350°F, and therefore the EPAs in BWRs were thought to have a higher potential for leakage.[4]

The uncertainties associated with efforts to predict leakage from EPAs led to the test program described in this report. Sources of uncertainty included the behavior of sealant materials under severe accident loads, determination of actual temperatures to which sealant materials are exposed, and the calculation of leak rates. The primary objective of these tests was to generate engineering data on leak rate, material performance, and temperature distributions that could be used to evaluate the leakage potential of EPAs under severe accident conditions. As a secondary effort, the electrical performance of the EPAs under severe accident conditions was observed by monitoring the insulation resistance and electrical continuity of the EPA cables. Prior to testing under severe accident conditions, the EPA were irradiated and then thermally aged to simulate end of service life and a loss-of-coolant accident.

As described in Reference 7, EPA designs were selected and matched with severe accident profiles for different reactor types, resulting in the following test program:

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4. It must be recognized that these statements are made based on analysis of severe accident loads at the time this program was formulated in late 1983 and early 1984. The severe accident loads at that time also reflected certain assumptions regarding the containment capability. On-going research into containment loads and containment integrity could lead to results that differ with the load scenarios and the test profiles described in this report.

1. A D. G. O'Brien EPA was subjected to loads simulating severe accident conditions in a large PWR containment: As shown in Figure 3-1, the test profile consisted of ramping the temperature and pressure from ambient conditions to 293°F and 60 psia in 30 seconds, then to 361°F and 155 psia in 12 hours using saturated steam, and finally maintaining this temperature and pressure for the remainder of the 10-day test.

2. A Westinghouse EPA was subjected to loads simulating severe accident conditions in a BWR Mark III containment:[5] The test profile called for the temperature and pressure to be increased from ambient conditions over 2 hours to 250°F and 30 psia (saturated steam), then to 400°F and 75 psia in 12 hours, and then maintaining this pressure and temperature until the end of the 10th day, as indicated in Figure 3-2.

3. A Conax EPA was subjected to loads simulating severe accident conditions in a BWR Mark I containment: The test profile, shown in Figure 3-3, required raising temperature and pressure to 640°F and 85 psia in 25 minutes, then raising temperature to 700°F over the next 20 minutes while raising pressure to 135 psia over the next 175 minutes, and finally holding temperature and pressure at 700°F and 135 psia for the duration of the 10-day test.

These test profiles were agreed to by NRC as documented in Reference 8. The EPA severe accident test profiles were based on enveloping the most probable severe accident sequences, which are also indicated in Figures 3-1 through 3-3. This was considered to be a conservative approach. However, it should be emphasized again that the maximum pressure in the severe accident sequence calculations is determined from the assumed containment failure pressure. Also there has been considerable research into severe accident phenomenology since these calculations were made in late 1983 and early 1984, which could lead to changes in the calculated loads.

The selection of EPAs and matching with test profiles were based on several factors:

- A major consideration was availability of EPAs for testing. As stated previously, only 3 EPA vendors were still active at the time this test program was developed. Attempts to locate EPAs manufactured by some of the inactive vendors for testing, such as General Electric, were unsuccessful. Thus, from a practical viewpoint, only the Conax, D. G. O'Brien, and Westinghouse EPAs could be readily obtained for this test program. Fortunately, these EPAs satisfied the other selection criteria also.

- A high potential for leakage, which depends largely on the time it takes to fail the sealants under the temperatures and pressures produced by a severe accident, was important. The Westinghouse EPA uses an epoxy

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5. The original test plan [7] called for the use of a General Electric (GE) epoxy module typical of those installed in BWR Mark III containments. However, at the time preparations for this test were started, GE no longer manufactured this module and had sold manufacturing rights to Westinghouse. Westinghouse subsequently modified the original GE design.

compound and the Conax EPA uses polysulfone plugs to seal the electrical cables in the modules; both materials have relatively low temperature capability. The D. G. O'Brien was thought to possibly have a lower pressure capacity. All three EPAs included in the test program used silicone O-rings to seal the header plate and nozzle flange. The sealant materials used in these three EPAs provide a nearly complete representation of sealant materials in general use, including EPA designs by inactive vendors. Because of the more extreme loads associated with severe accidents in BWR type reactors, EPAs used in these types of containments were of primary interest. Conax and Westinghouse EPAs are widely used in BWR containments, thereby enabling a good match.

In this test program, only internal pressure and temperature loads simulating severe accident conditions were considered. Loads from a loss-of-coolant accident (design basis) were not separately considered, although they were implicitly covered by the initial portion of the test profiles. The effects of chemical sprays, fault currents, preloading (pressure cycles at 100 to 115% of the design pressure), and seismic loads were not included in these tests.

Short circuits can cause short term high amperage currents, known as fault currents, in the EPA conductors that generate very high temperatures and loads even though the condition may exist only for a few cycles. Fault currents were not included because (i) the EPAs tested in this program were qualified to meet the provisions of IEEE 317-1976, which includes requirements and tests for fault currents, (ii) expert opinion on the importance of fault current testing was divided, (iii) the number and location of affected circuits, the magnitude, and the timing of fault currents in a severe accident could not be defined with any precision, (iv) if AC power is not available, which may be the case in some severe accident scenarios (in particular, station blackout sequences), fault currents cannot occur, and (v) a special, high power facility would have had to been built to conduct fault current testing. A more detailed discussion of the fault current issues appears in Appendix B, which is a copy of a letter from Sandia to NRC that documents the results of discussions between Sandia, NRC, and two expert consultants on this issue.

EPAs, as well as other components of the containment pressure boundary, are subject to a number of pressure cycles at ambient temperature during their service life. A typical cycle is associated with either a structural integrity test or integrated leak rate test and involves pressurization to 100% to 115% of the containment design pressure for approximately 24 hours. The effect of preloading on the structural and leak integrity of EPAs was considered to be negligible. Although preloading could have been easily accommodated in the test procedure, it would have significantly increased the time and cost associated with each test and therefore it was not done.

Another consideration in the tests was the interaction of the EPA sleeve or nozzle and the containment wall. The structural deformation of the containment wall was not modelled; however, EPA seals are normally located sufficiently far from the intersection of the EPA nozzle and containment wall to preclude any significant effect on the deformation of the sealing surfaces due to interaction with the containment wall. As described in Sections 4, 5, and 6, a slip on flange and the test chamber mounting plate were used to simulate the heat sink associated with the containment wall.

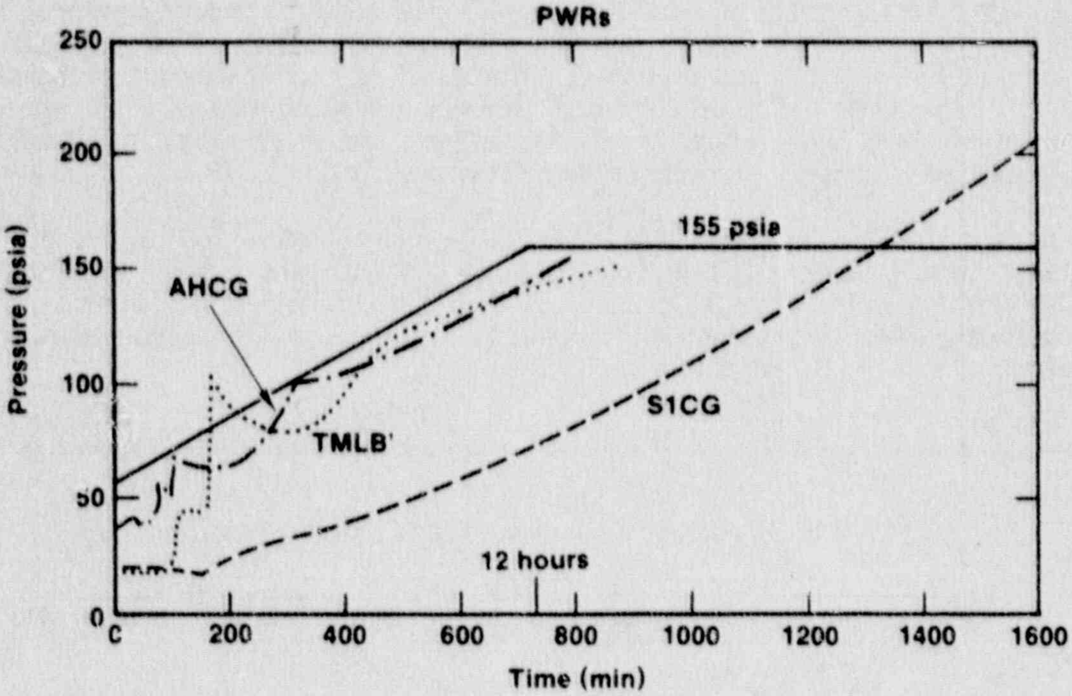
The three EPAs tested in this program were all nuclear qualified components built to IEEE 317-1976 and IEEE 323-1974 standards. The severe accident condition tests were designed to collect engineering data that could be used to assess the leakage potential of EPAs; they were not qualification tests. As such there were no pass/fail criteria for these tests. The primary measurements were leak rate from the aperture seals, module seals, and through the EPAs; temperature distributions; and insulation resistance and electrical continuity of the EPA conductors.

For perspective, the leak rate per EPA that is equivalent to 10% of the primary containment volume per day is given in Table 3-1. A leak rate corresponding to 10% of the primary containment volume per day is a commonly used threshold for determining when the release of radioactive material begins to have significant consequences on the public health and safety.

Table 3-1
Leak Rate Per EPA Equivalent to 10% Volume per Day

Nuclear Plant	Number of EPAs	Leak-rate/EPA (scc/sec)
Browns Ferry	30	328
Watts Bar	53	740
Bellefonte	69	1610

It is important to recognize that this test program included only a limited segment (three) out of the total population of EPA designs used in LWR containments and therefore general conclusions regarding the leak integrity of all EPAs cannot be made based on the test results presented in this report. In particular, older power plants that have field-manufactured EPAs must be evaluated on an individual basis.



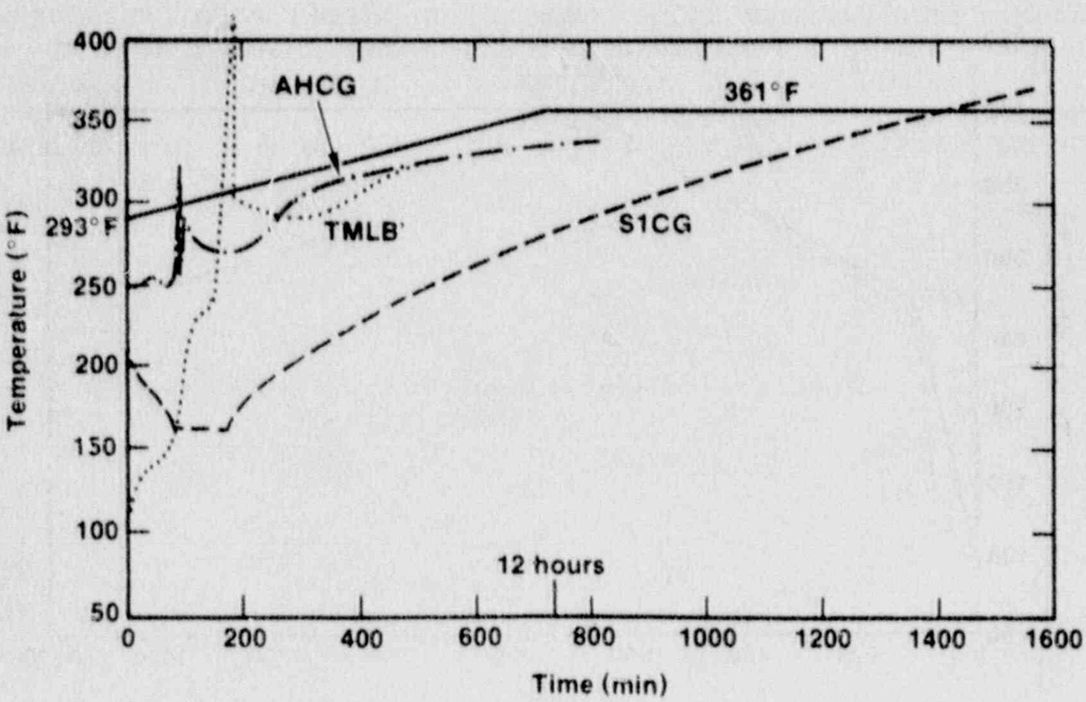


Figure 3-1 Severe Accident Test Profile for a Large PWR Containment

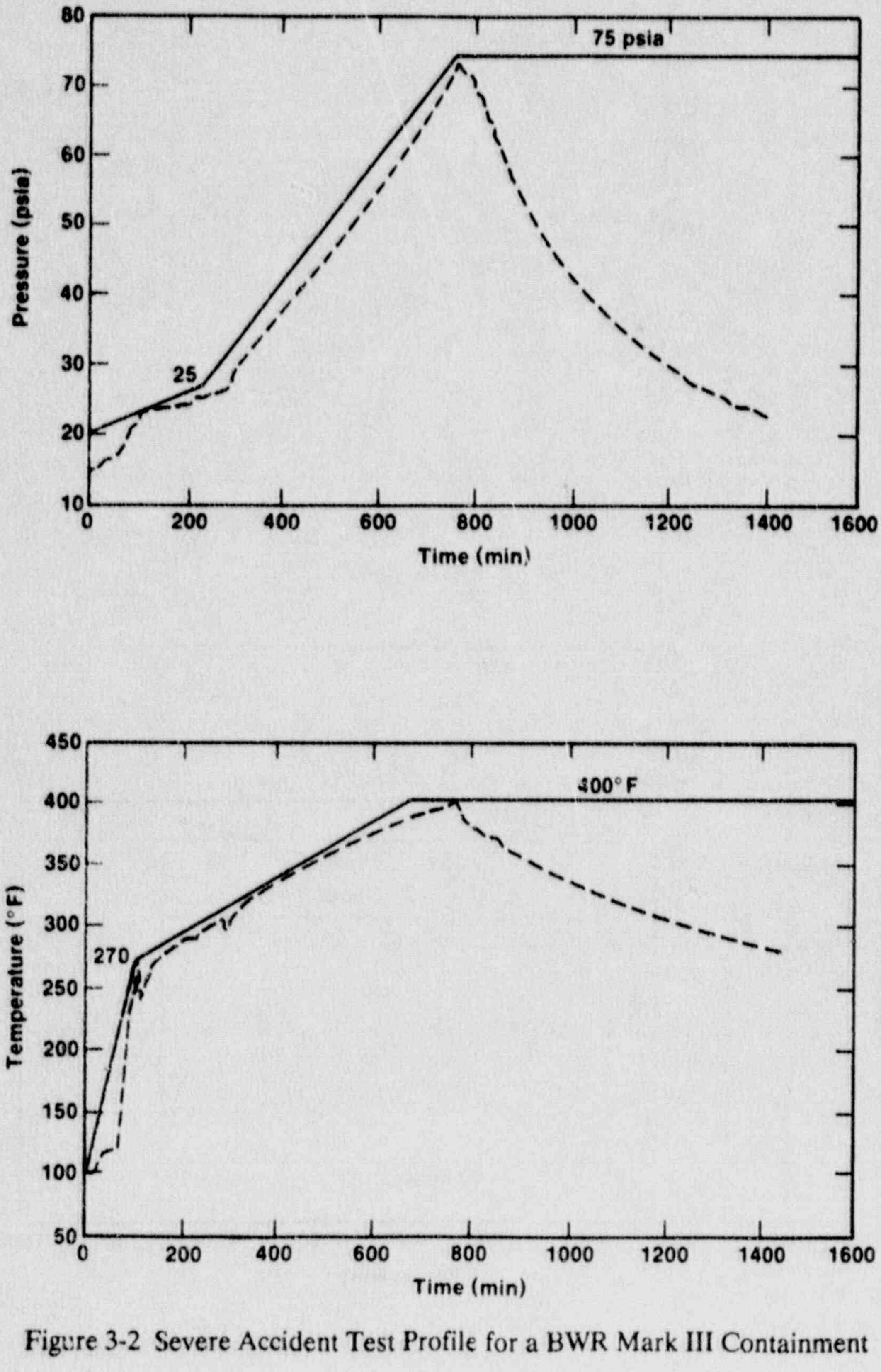


Figure 3-2 Severe Accident Test Profile for a BWR Mark III Containment

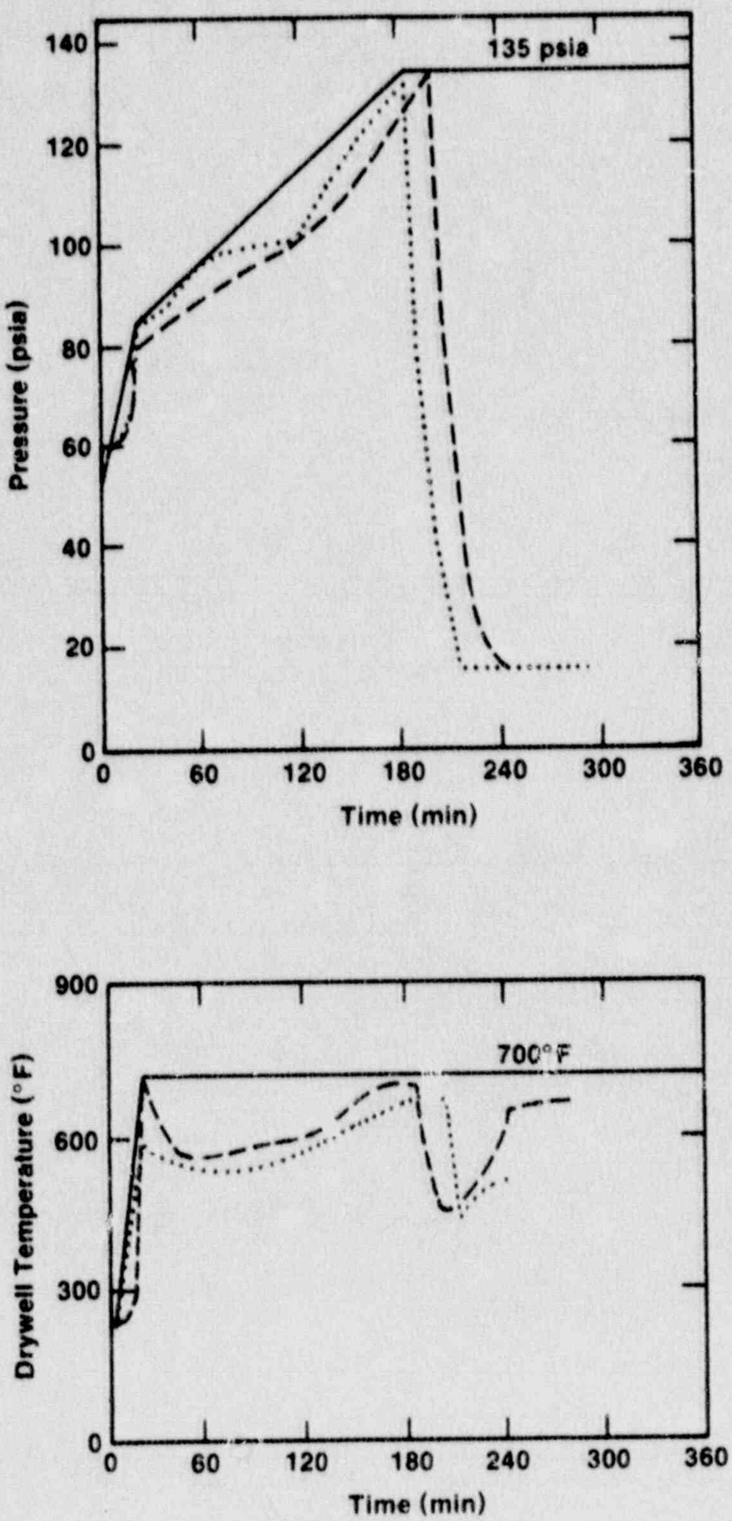


Figure 3-3 Severe Accident Test Profile for a BWR Mark I Containment

D.G. O'Brien
EPA

4.0 D. G. O'BRIEN EPA[6]

4.1 Design and Certification

The D. G. O'Brien EPA tested in this program (serial no. 4473T) was built to essentially the same standards as those used in Duke Power's McGuire and Catawba Unit 1 and 2 stations. The test EPA contained low voltage power (LVP), instrumentation, and medium voltage power (MVP) modules. The qualification standards for the EPAs purchased by Duke Power were IEEE 317-1972, IEEE 324-1971, and IEEE 324-1974 (only for the MVP), whereas for the purchase of D. G. O'Brien EPA serial no. 4473T the newer standards IEEE 317-1976 and IEEE 324-1974 were applied.

The EPA consists of four major components as shown in Figure 4-1: a standard 150#, 12 in. blind flange (referred to as the header plate), a standard 12 in. weldneck flange, a 12 in. Sch 80 pipe (referred to as the nozzle), a junction box on the inside end, and the modules. The other items shown in Figure 4-1 are test fixtures or equipment. The header plate, which is normally mounted on the inboard side of the containment, was fabricated from 304 stainless steel and weighs 102 lbs. The header plate is attached to the weldneck flange with twelve 7/8 in. SAE Grade 8 nuts and bolts torqued to a final value of 150 ft-lbs. Two silicone O-ring seals maintain leak tightness. Pressure was maintained in the area between the two O-rings (the [illegible]) using nitrogen gas to verify seal integrity. The stainless steel, hermetically sealed modules are inserted through bored holes in the header plate and welded in position. The junction box, which is not a leak-tight boundary; is approximately 24 in. deep, 22 in. high, and 22 in. wide. Typically, these boxes are removable to facilitate cable installation in the field and there is also a removable access cover that provides direct access to the connectors.

The EPA nozzle was designed to simulate the arrangement of EPAs in the Catawba nuclear power plant containment building, which is a PWR ice condenser owned by Duke Power. The slip-on flange and the mounting plate in the test chamber approximate the heat sink of the containment building wall. For comparison, a typical EPA nozzle in Catawba is shown in Figure 4-2; note that it is not insulated or covered in the gap between the containment building and the shield building. Consequently, the EPA nozzle used in the test was not insulated. There were a few minor differences between the test nozzle and the EPA nozzles in Catawba:

- Catawba has a junction box outside the containment for a total length of the nozzle and box of 27-3/8 in.; the test nozzle is 34-1/2 in. long.
- The inner diameter of the weldneck flange in Catawba is 11.232 in.; the weldneck flange and nozzle used in this test had an inner diameter of 11.375 in..
- The distance from the center of the containment wall to the junction of the weldneck flange and the nozzle is 7 in. in Catawba as opposed to 8-1/2 in. in this test. The same nozzle was used for both the D. G. O'Brien EPA and the

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6. Mention of specific products and/or manufacturers in this document implies neither endorsement or preference nor disapproval by the U.S. Government, any of its agencies, or Sandia Corp., of the use of a specific product for any purpose.

Westinghouse EPA, for which this characteristic dimension is 10-1/2 in.. Thus, the nozzle used in this test represents a compromise for these two designs.

However, these differences had no apparent affect on the outcome of the test.

Some design parameters for the modules are listed in Table 4-1. Six different designs and a total of ten modules were included in the D. G. O'Brien EPA. Figure 4-3 illustrates the different module designs. The location of each module in the header plate is indicated in Figure 4-4. Each module is made up of two electrical connectors welded on each end of a section of stainless steel pipe to form a pressure vessel. No organic materials are enclosed within this pressure boundary. All of the modules were designed for the following conditions:

- design temperature rating--300°F max LOCA or 330°F MSLB (Main Steam Line Break);
- design pressure rating--65 psig;
- humidity rating--100% RH;
- design life--40 years; and
- maximum integrated radiation exposure in 40 years--200 Mrads.

The design maximum total assembly leakage is specified as less than 10^{-6} scc/sec helium. The modules are pressurized to 15 psig at 72°F with sulfur hexafluoride (SF_6) gas as a means of verifying their gross-leak integrity. The modules are interconnected by pressure lines.

With the exception of the medium voltage power module (M45), the conductors in each receptacle are interconnected by a length of copper, brass, or thermocouple material (pipe or rod) as indicated in Table 4-1. Electrical insulation within the connectors is provided by the circumferential glass seal employed in the hermetic sealing operation. In the case of modules M02, M13, M16, and M19, lateral support for the interconnecting length is provided by two ceramic insulators.

The medium voltage module (M45) has two high voltage ceramic bushings (rather than electrical connectors) welded to each end of the pipe section. The bushings are connected by a 1000 mcm (million circular mils) copper conductor. A glass insulator tube provides insulation and some lateral support of the copper conductor.

The EPA was prewired by D. G. O'Brien using Brand-Rex nuclear qualified cable. Each field cable was stripped, inserted into a contact pin, and crimped. The contact is inserted into a hard insulator that compresses an elastomeric grommet when the coupling ring is torqued to its proper value. This procedure electrically isolates all circuits and provides the environmental seal around each conductor to protect against moisture, steam, etc. The triax plug assemblies differ in that when the plug is terminated to the cable, all components remain as an assembly. Sealing of the triax plug assembly is accomplished with an elastomeric O-ring squeezed at the plug-receptacle interface by engaging the coupling ring. The modules were wired as shown in Figures 4-5 through 4-8. The outboard ends were wired with loops about 1 foot long while the inboard ends were looped to create a net series circuit and a resultant pair of 25 foot long wires for each wire size. These wires exited the test

Table 4-1
Electrical Penetration Design Parameter Summary

Design Parameter	M45	M02	M13	M19	M06	M16
Number of Modules per Flange	1	2	2	1	2	2
Number of Conductors per Module	1 1000 mcm	3#2/0	12#10	3 Coax 33#16	1 75 Triax	14#16 Iron Constan. T/C
Provision for Connection	Test Lead	Mating Plug	Mating Plug	Mating Plug	Mating Plug	Mating Plug
Conductor Size	#12 AWG	3#2/0	12#12	2 RG-59 20#16	RG-11 AU	14#16
Conductor Insulation	XLPE	XLPE	XLPE	XLPE	XLPE	EPR
Connector Conductor Material						
Receptacle	OHFC	TeCu	TeCu	Steel Alloy	Steel Alloy	Iron Constan.
Plug	TeCu	TeCu	TeCu	TeCu	TeCu	TeCu
Calculated Module Weight (lbs)	100	15	8	13	5	5
Total Penetration Weight (lbs)	100	30	16	13	10	10
Minimum Insulation Resistance @ 500 VDC (MΩ)	1000	100	100	100	$1x10^6$	100
Design Continuous Current Rating (amps)	1000	155	35	N/A	N/A	N/A
Short Time Overload Current Rating (amps)	4000	1085	245	N/A	N/A	N/A
Fault Current Overload Rating (amps)	50000	17325	2500	N/A	N/A	N/A
High Potential Test in Production Assemblies (VRMS, 60 Hz)	36000	2200	2200	1500	3000 VDC	1500
Module Volume (in^3)	129	59	24	59	13	16
Penetration Volume (in^3)	129	118	49	59	25	33

chamber through a cable seal system developed by Sandia, which prevents neckdown problems and degradation from high temperature.

Two types of connectors or plugs are used with each module, again, with the exception of the M45 module. The C32 plug, shown in Figure 4-9, was used "outside of containment" and the C42, shown in Figure 4-10, was used "inside containment". Prior to shipment, D. G. O'Brien personnel torqued each plug to 20% of its recommended value, which is listed for each module in Table 4-2. Full torque values were applied with the special spanner wrenches supplied by D. G. O'Brien after the radiation and thermal aging but prior to severe accident testing. The medium voltage power module, M45, is not listed in Table 4-2 because it is a hard wired terminal rather than a plug.

Table 4-2
Recommended Torque for Coupling Rings

Module	(ft-lbs.)
M02	20-25
M06	10-15
M13	10-15
M16	5-10
M19	20-25

4.2 Test Preparations and Procedures

Test Objectives and Overview

The primary purpose of this test was to generate engineering data to evaluate the leak behavior of the EPA under severe accident conditions. The test profile for the D. G. O'Brien EPA was representative of the severe accident conditions in a large pressurized water reactor (PWR), which was simulated with saturated steam at temperatures and pressures to 361°F and 155 psia. As a secondary effort, the electrical degradation of the EPA cables was observed by monitoring the insulation resistance (IR).

Since this was not considered a qualification or a verification test, there was no pass/fail criteria. The effects of chemical sprays, seismic loading, fault currents, preload pressure cycling, thermal cycling, and operating the cables at rated current and voltage were not addressed. The EPA was not subject to the normal LOCA qualification test profile prior to the SAC test. It must be emphasized that the SAC test is much more severe than the LOCA test.

The significant dates in the test sequence (in 1985) were:

Initial Inspection and baseline measurements	April 12-17
Assembly and Instrumentation	April 17-19
Radiation--200 Mrad dose (air)	April 22 - May 2
Inspection and IR measurement	May 27 - June 4
Thermal Aging at 275°F for 168 hours	June 5 -12
Inspection and IR measurement	June 12-17
Air Leak Test at 60-100°F and 150-160 psia	June 17
Severe Accident Test (steam)	June 17-27
Staircase rampdown	June 27-28
Air Leak Test at 60-100°F and 150-160 psia	July 1
Inspection and IR measurement	July 1-5

Test Equipment

The SAC loads were applied in an environmental chamber, which was modified by adding the mounting plate that accepted the EPA fixture, as shown in Figure 4-1. The boiler in conjunction with an accumulator tank was capable of delivering 245 lbm/hr of steam at 200 psig and 388°F.

The N_2 and SF_6 pressure lines were designed to detect leakage into the gap between the two O-rings on the header plate and into the modules, respectively. However, these systems monitor leak-integrity of components of the EPA; failure of these components does not necessarily indicate a loss of containment integrity. Therefore, a system to measure the total leakage to outside of the containment boundary was developed.[7] Leakage past the EPA would have had to flow into the chamber formed by the EPA nozzle where it would then have been piped through condensing equipment. The measurement technique relied on measuring condensate over a known period of time. This system proved accurate and reliable for the range of approximately 1 scc/sec to 10 000 scc/sec. Since leakage past the EPA was not detected during the steam (SAC) test, details of this measurement system are not included in this report.

Thermocouples were installed on the EPA connectors and inside the flange to monitor the temperatures during irradiation. Twenty-two thermocouples, including sixteen intrinsic gages, were installed inside the nozzle and on the connectors of module 2 and 16 as shown in Figure 4-11. The intrinsic thermocouples were installed approximately every 6 in. along the axis and every 90° radially. Before thermal aging, an additional 50 thermocouples were installed on the junction box, the header plate, the weldneck flange, and the test chamber mounting plate. The approximate locations of these gages are indicated in Figure 4-12.

Each cable circuit was matched with a separate electrical power supply and a monitoring circuit, which are collectively referred to as the load bank. By observing the voltage drop in the monitoring circuit, the insulation resistance and continuity of each cable circuit could be determined, as described later in this section. A direct

7. This system has been documented in a draft report available in the NRC PDR by J. W. Grossman, F. V. Thome, and G. M. Dibisceglie, "Flow Measurement Techniques for Evaluating Leak Behavior Through Electrical Penetration Assemblies Under Severe Accident Conditions," Sandia National Laboratories, Albuquerque, NM, February 1987.

current of 1/2 amp from the 28 volt power supply was maintained on all cables throughout thermal aging (but not radiation aging) and during the severe accident condition test. A wiring schematic for the load bank is shown in Figures 4-13 and 4-14. The output from the monitoring circuit was recorded on an automatic datalogger. In addition, insulation resistance was measured at 50 to 500 VDC several times per day with a Hippotronics Megohmmeter to back up and check the continuously recorded data.

Initial Inspection

The EPA was received at Sandia on February 7, 1985; it was inspected for damage and parts were inventoried. The EPA setup at this time is shown in Figure 4-15. The module pressure (SF_6) was read and recorded at 17.9 psig. When this value is appropriately compensated for temperature and atmospheric pressure, it compares favorably with the pressure in the modules at the time of shipment. The close agreement indicates that the modules were leak tight. The EPA was stored inside; the room temperature varied between 60-100°F. There was no attempt to control humidity. The module pressure was monitored periodically from receipt through preparation for installation in the nozzle and there was no indication of any leakage.

A set of insulation resistance and loop resistance (continuity) measurements were made before the unit was uncrated. All cables in this baseline measurement had insulation resistances between $3x10^{10}$ to $1x10^{13}$ Ω.

The torque on the connectors in each model were checked and compared to the recommended value. Most of the connectors were found to be overtorqued for the 20% value specified by D. G. O'Brien but none exceeded the 100% value recommended for the steam test. None of the connectors were removed.

Five small weld beads, which probably resulted from splatter when the modules were welded into the header plate, were observed in the O-ring grooves in the header plate (mostly on the side walls). These beads could not be easily removed and did not affect the test results.

Assembly

Before radiation aging, the mating surfaces on the header plate and the weldneck flange were repeatedly cleaned with acetone and alcohol to remove all scratches and grit. The silicon O-rings were lubricated and installed in the proper grooves and the header plate bolts were torqued to their specified value. The header plate and weldneck flange were not disassembled until after the steam tests were completed.

The aperture seals was pressurized with dry nitrogen to 15 psig. All fittings and seals were soap tested; no leakage was observed. A pressure drop test was also conducted. The initial pressure and temperature were 15.0 psig and 72.5°F; after 24 hours the pressure and temperature were 13.8 psig and 68.1°F. Using these values in Equation A.1 (see Appendix A), the calculated leak rate was $4x10^{-5}$ scc/sec.

Radiation Aging

The EPA was exposed to a total dose of 200 Mrad using a cobalt source as measured at the outside of the header plate. An end view of the EPA header plate showing the condition of the modules, connectors, and cables before irradiation is shown in

Figure 4-16. The dose rate ranged from about 0.5 to 1.0 Mrad/hr over the entire EPA and inside connector. The total exposure time was 227.3 hours. During the irradiation period, the cobalt was lowered 4 times to conduct maintenance of the facility for a total downtime of 8.4 hours. No unintentional cobalt lowering took place during this period. Figures 4-17 and 4-18 illustrate the location of the EPA relative to the cobalt array. The 1/4 in. thick chamber wall liner was used for flux mapping and also helps to reduce the radiation gradients. A continuous air flow between the barrel and the EPA nozzle was maintained to keep the temperature below 120°F. The thermocouple readings (gages on the nozzle at positions 1B, 2D, and 3D and on the inside end of modules M02, position 10, and M16, position 6, were connected to a datalogger during this time) during the irradiation never exceeded 105°F.

The O-ring aperture seal pressure was also monitored during radiation aging. This was important in order to verify that the pressure was sufficient to maintain adequate force on the seals, which holds them in their "normal" position. The aperture seal pressure varied between 10.9 and 16 psig during irradiation. Several pressure drop tests were conducted during irradiation and the leak rates were calculated to be between 10^{-5} and 10^{-4} scc/sec. An attempt was made to determine if the leak was from the inner or outer O-ring using a portable "sniffer", but this was unsuccessful. The leak remained near constant at approximately 10^{-4} scc/sec.

Insulation resistance and continuity measurements were made immediately before and after irradiation. Unfortunately, the Hippotronic Megohmmeter was connected improperly and the only reliable insulation resistance measurements made at this time were for the RG-11 triax and RG-59 coax cable. The load bank was not attached during the radiation aging. The insulation resistance for the triax cable and coax cable dropped by about two and four orders of magnitude after irradiation as shown in Table 4-3.

Table 4-3
IR Measurements on the Triax and Coax Cable Before and After Irradiation

Cable Type	Module	Position	Description	Insulation Resistance Ω Before	After
Triax	MO2	3,10	Center to inner shield	$4.0X10^{12}$	$4.8x10^{10}$
			Inner to outer shield	$1.9x10^{11}$	$2.3x10^{9}$
Coax	M19	8	Center to shield	$3.0x10^{12}$	$1.3x10^{8}$

The cables inside the vessel hardened noticeably but were still elastic. Note that the 25 foot cabling attached to the inner connectors was not exposed to the high dose rate as it was coiled and tied in the corner of the cell away from the cobalt.

The torque on the header plate bolts and the connectors were checked after irradiation. The torque on the header plate bolts was essentially unchanged. However, the torque on both the inner and outer connectors was significantly less than the 20% preradiation values. Four of the inside connectors (on both of the M13 and M16 modules) had torques that were higher than the 20% preradiation values. The inside M19 connector was found to be hand loose. All connector torques were reset to their proper values, as given in Table 4-2.

Thermal Aging

Thermal aging was conducted in the same chamber as the SAC test in order to minimize handling between these two phases of the test. The junction box was mounted to the header plate for the first time. Since it was important to maintain a reasonably uniform temperature during thermal aging, some seventy-two thermocouples were installed inside and outside the junction box and along the EPA nozzle as shown in Figures 4-11 and 4-12. It was fortunate that such a large number of thermocouples were installed because many of the thermocouples failed during the SAC test.

In order to install the EPA in the test chamber, the SF_6 monitoring system for the modules was depressurized and the line was cut. The N_2 line (to monitor the aperture seal pressure) and SF_6 line were fed through the test chamber cover plate (see Figure 4-1) and reconnected. Pressure gages were also installed on these lines at this time. The SF_6 line was evacuated and backfilled and then isolated for the remainder of the testing. Both systems were pressure-drop tested for leaks; there were no detectable leaks from the modules and the leakage from the aperture seal was less than 10^{-4} cc/sec

Insulation resistance and continuity measurements were taken; the test chamber was not connected to earth ground and thus the problems experienced with the measurements taken before and after radiation aging were not repeated. The triax (MO2 positions 3 and 10) and the coax (M19 position 2) had the lowest insulation resistances to ground. The insulation resistance of the triax outer shield to ground was about 100 MΩ and the insulation resistance of the coax shield to ground was about 7 MΩ. The insulation resistance for module M16 (positions 5 and 6) had dropped to about 1200 MΩ.

At 11:35 on June 4, 1985, the heaters and recirculation blower were turned on. The controller was set to maintain temperature at 275°F. Initially, the controller did not work as expected. After 18 hours, the temperature inside the junction box at its centerline leveled off at about 250°F. The controller was reset at 07:30 on June 5, and the temperature inside the junction box quickly rose to the desired set point of 275°F. Thermal aging was uninterrupted over the next 7 days and temperature control was normal. Although temperature fluctuations inside the junction box from point to point were greater than expected, the average temperature inside the junction box did not fluctuate much with time as shown in Figure 4-19. The actual temperatures recorded at nine locations inside the junction box are plotted in Figures 4-20 and 4-21. Again, the temperature differs from point to point but for a given point, temperature is relatively constant with respect to time once thermal aging started. It is important to closely control these fluctuations because degradation of organic materials is very sensitive to temperature. As indicated in Figure 4-22, there was also some difference in the temperatures of modules M02 and M16. However, the header plate temperature, Figure 4-23, was quite uniform.

The remaining thermocouple data recorded during thermal aging is plotted in Figures 4-24 through 4-32. Note that not all of the thermocouples shown in Figures 4-11 and 4-12 were connected to the datalogger during thermal aging. The only observation of interest is that a significant axial temperature gradient existed along the EPA nozzle, as seen in Figures 4-27 through 4-30. (It should be noted that data from day 2 through day 6 was not saved properly on disk and is therefore not included on the temperature plots for thermal aging. However, the temperatures are recorded on paper tape, and no significant deviations in temperature occurred during this time period.)

When the load bank was turned off to take insulation resistance and continuity measurements during thermal aging, the control temperature oscillated slightly before settling back to the set-point temperature. This was apparently caused by insulation resistance **heating** from the cables. During the severe accident test, the additional energy due to electrical heating raised the steam temperature inside the junction box about 20 to 30°F above the saturated condition over a two day period. This phenomenon should also be expected to occur in an actual LOCA or severe accident. In Sandia's test the additional power was about 5 kW assuming a total cable resistance of 20 Ω and a current of 0.5 amps. This level of power is representative of a typical control application.

The load bank and insulation monitoring system were operated for the first time during the thermal aging of the D. G. O'Brien EPA. The power supply was observed to be extremely stable; as a result, insulation resistance could be measured with good resolution using the load bank. This provided an important back-up system to the Hippotronics Megohmmeter during the severe accident condition test. An equation for converting the voltage drop, ΔV (in volts), to insulation resistance, IR (in Ω), was derived:

$$IR = 393.3 \cdot (\Delta V^{-0.96}) \qquad (4\text{-}1)$$

The load bank is not accurate for measuring insulation resistances greater than about 50 MΩ, which is equivalent to a voltage drop of roughly 0.005 mV. Since the insulation resistance of all cables remained above 50 MΩ during thermal aging, the load bank data during thermal aging is not provided in this report.

The pressures in the monitoring volumes for the modules and aperture seal are plotted in Figure 4-33. Note that the graph of the module pressure closely mirrors the graph of the average header plate temperature. For a fixed mass and volume with initial pressure and temperature of 19 psig and 70°F, the pressure calculated from the ideal gas law for a temperature of 240°F is 29 psig, which agrees closely with the measured value. There was no measurable leakage from the modules. The aperture seal pressure does not correlate as well with the average header plate temperature, but this is not surprising because a large fraction of the volume consisted of copper tubing that was outside the test chamber. Therefore, the nitrogen gas probably did not heat up much from ambient temperature.

The condition of the modules, the junction box, and the cables were inspected after aging. The outer jacket of one of the triax cables, M06 position 9, was split for 12 in. as shown in Figure 4-34. All the cables had hardened further from their condition after radiation aging, so the cables were moved as little as possible before the severe accident test.

The torques on the connector coupling rings were checked for all of the EPA modules. The inside connector for M06 position 2 and the outside connector for M06 position 9 were jammed and could not be moved in either direction; the spanner wrench was broken while trying to do so. D. G. O'Brien personnel indicated that there was past experience with connectors jamming in this way, and that the applied pressure during the planned air leak test would probably seat the grommet material if it wasn't already adequately torqued earlier. Rather than using a heavier tool to free them, which could possibly have damaged the glass-to-metal seals, these two connectors were left as they were. The outside containment connectors that were found loose after radiation aging were also loose after thermal aging. The inside containment connector on M19 was hand loose again. Except for the two M06 modules described above, all connectors were torqued to the recommended value (see Table 4-2) at this point.

The torques on the header plate bolts were not checked because it would have required complete removal of the junction box and the thermocouples. Since these torques did not change after radiation aging, it did not seem necessary to check them after thermal aging.

Air Leak Test

At this time the coupling rings on the connectors were torqued to the recommended value, the SF_6 and N_2 lines were drop-tested, the cable penetrations through the test chamber were filled with epoxy, and a complete set of insulation resistance and continuity measurements were taken. Two orifices were installed in order to check the leak measurement system.

The test chamber was sealed and pressurized to 50 psig with air. At the cable penetrations into the test chamber where the epoxy seal was used, leaks were detected from five cables. This indicates leakage through crack and/or split cable insulation or leakage by the silicon grommet in the connector: :

- Triax cable--M06 position 9; at outer jacket to test chamber penetration around the epoxy seal system.
- Coax cable--M19 position 8; both cables leaked between the jacket and shield. The jacket swelled.
- #2/0 wires--M02 positions 3 and 10; a large leak was observed between the conductor and insulation.

Note that leakage from the cable penetrations in the test chamber could not be measured with any of the leak detection systems. Several attempts were made to seal these leaks with epoxy and rubber grommets, but these efforts were unsuccessful.

The air pressure was increased to 143 psig and leakage through the EPA, into the modules, and at the header plate aperture seals was measured. After four minutes, the N_2 pressure (aperture seals) increased by 4 psig, indicating a leak past the outer O-ring. In 3.5 hours, the N_2 pressure was 125 psig. The SF_6 pressure was unchanged; there was no evidence of leakage into the modules. The leakage through the EPA was measured at 0.024 scc/sec using conventional air flow meters.

The test chamber was then depressurized and a second set of insulation resistance and continuity measurements were taken. The NRC Program Manager was briefed regarding the cable splits, leaks, and coupling ring seizures (see description of thermal aging). Based on the discussion, it was determined that Sandia should proceed with the severe accident test without any modification or replacement of the test apparatus.

4.3 Conduct of the Severe Accident Test

The severe accident condition test began at 15:45 on June 17, 1985 when saturated steam was admitted to the test chamber. In 30 seconds the pressure had reached 48 psig; over the next 12 hours the pressure was raised by 2 psig every fifteen minutes until the maximum test pressure of 143 psig was attained. The PWR accident profile, which represents the intended loads for this test, and the actual temperature and pressure profile applied to the EPA in the severe accident test are shown in Figure 4-35. The differences are explained below. The inside of the junction box may have overheated during the first two days of the test by 20 to 30°F. There are several factors that may have led to overheating:

- An unusually high number of thermocouples failed;
- The datalogger was erratic due to shortcomings in the software; and
- Because the test conditions involved saturated steam, the heat losses were low and the in-flow of steam was minimal. Thus, the test chamber environment was relatively stagnant, which magnified the effect of insulation resistance heating from the cables inside the junction box.

At 13:00 on June 19, the test chamber was depressurized in order to improve the steam circulation. The necessary modifications to the steam piping took about 25 minutes, after which the test chamber was pressurized back to 143 psig in about 15 minutes. The changes solved the overheating problem for the remainder of the test. The last deviation from the specified test profile occurred on June 20 at 03:50 when the test chamber was depressurized for repairs to a flange in the test chamber that was leaking. The repairs were completed in about 25 minutes.

The test was terminated following the steps specified in the test plan. Pressure was reduced in steps; every four hours the steam pressure was decreased about 25 psig in fifteen minutes and then held constant for 225 minutes while the EPA temperature was allowed to equilibrate at saturated conditions. Steam was shut off to the test chamber at 11:45 on June 28, and the chamber pressure was reduced to 0 psig over 15 minutes with the vent.

The cable leaks that were detected during the air leak test effectively "disappeared" at the beginning of the high pressure test; only a few water drops were observed from these cables. A large amount of water escaped from the #12 wire in the M45 module, but this also leakage stopped later in the SAC test. It must be noted that this wire did not have a sealing system at the module since it was a wire in place to monitor the module electrical degradation.

The Hippotronics Megohmmeter was not connected properly during the first few days of the test and insulation resistance measurements made with this device during the SAC test prior to 10:15 on June 20 are not valid. However, the load bank provided good insulation resistance measurements (below 50 MΩ) throughout the test.

A summary of important events in the SAC test is presented in Table 4-4.

Table 4-4
Milestones in the SAC Test

Date	Time	Elapsed Time (hrs)	Event
June 17	15:45	0.	Started SAC test
June 18	3:45	12	Reached 143 psig
	4:40	12	Ground lifted for coax cable, M19
June 19	13:00	45.25	Overheating problem in junction box identified. Inlet valve. Steam piping modified to improve circulation.
	13:42	45.97	Returned to operating pressure (143 psig)
June 20	2:14	58.48	Ground lifted for M16 positions 5 and 6.
	3:50	60.08	Depressurized chamber to repair steam leak
	4:25	60.67	Returned to operating pressure (143 psig)
	8:45	65.	Ground lifted on #16 wire, M19
	10:00	66.25	Determined Hippotronics Megohmmeter was being used incorrectly.
June 24	8:50	161.08	Power supply #5 ground lifted (M06, RG-11)
June 27	15:45	240	Began lowering pressure in 25 psi steps
	20:10	244.42	Power supply #3 ground lifted (M13, position 7).
June 28	11:45	260	Reduced pressure from 13 psig to 0 psig; test concluded.
	14:45	263	Shutdown instrumentation and data acquisition systems.
July 1			EPA returned to ambient temperature and pressure conditions. IR and continuity measurements taken. Air leak rate test conducted.
July 2			Opened test chamber and junction box cover.
July 5			Completed initial inspection and post-mortem.

4.4 Test Data and Results

Data collected during the test consisted of leakage measurements (including the SF_6 and the N_2 monitoring pressure for the modules and aperture seal, respectively, and condensate collection of leakage through the EPA), insulation resistance and continuity of the cables, and temperature at various locations.

Leakage Measurements

The pressure histories in the monitoring spaces for the modules and aperture seal are is plotted in Figure 4-36. For the first 30 hours of testing, the pressure graph mirrors the graph of the average header plate temperature; the measured pressure during this period correlates well with the pressure calculated from the ideal gas law for a fixed mass and volume at the temperature of the header plate. However, at about 30 hours into the test, the module pressure suddenly began to increase again, even though temperature was stable. The slow nearly constant rate of increase in pressure after the first day suggests that the leak could be characterized as slow seepage. The volume of the module monitoring space was not known. However, as indicated in Equation (A-1) in Appendix A, the leak rate varies linearly with volume. If the volume of the module monitoring space is assumed to be on the order of 10000 cm^3, then the average leak rate from the second to the ninth day of the SAC test was on the order of 0.03 scc/sec. This is a very small leak rate, and involves leakage into the modules and not past the EPA.

The N_2 pressure at the start of the SAC test was about 75 psig; leakage past the outer O-ring during the air leak test had raised the seal aperture pressure considerably from its nominal value. As shown in Figure 4-36, the N_2 pressure fell steadily for the first two days of the test and bottomed out at 13.6 psig at 17:30 on June 20. After this point the N_2 pressure oscillated in a fairly narrow range for the duration of the high pressure test. The data suggest that the aperture seal performance was actually better in the SAC test than in the air leak test. This is plausible; the header plate is pressure-seating, so that high contact forces are maintained during pressurization and, furthermore, the elevated temperature would tend to soften the organic O-ring material, which could cause the material to flow and form a better seal. Certainly, it seems clear that there was no significant leakage past the aperture seals during the SAC test.

Although it appears that there was seepage into the modules, no leakage through the EPA (outside containment) was detected at any time during the SAC test.

Electrical Measurements

Insulation resistance determined from the load bank measurements using Equation (4-1) are graphed for power supplies 0 through 7 in Figures 4-37 through 4-44 and summarized in Table 4-5. Readings from the digital multimeter (those taken after 10:15 on June 20) are also shown in these figures. The insulation resistance of larger wires (#12 wire, #2/0 wire) degraded more slowly than the #16 wire, the coax cable, and the triax cable. Continuity was also monitored; five of the eight cables passed 0.5 amp to ground before the end of the SAC test (the time at which continuity of the cables was first broken is indicated in Table 4-5). As can be seen in Figures 4-37 through 4-44, the break in continuity was accompanied by a sharp drop in insulation resistance, as expected. When continuity was lost, the insulation resistance of the cables dropped below 1 kΩ.

Table 4-5
Summary of Load Bank Data Taken During SAC Test

Module:Position:Cable	No. of Hours into Test When IR Dropped Below 1MΩ	0.1MΩ	0.01MΩ	No. of Hours into Test When Ground Lifted (1/2 amp to ground)
M19:8:Coax	1	1	1	13
M19:8:#16 Wire	8	15	61	65
M13:4:#12 Wire	6	52	70	did not lift
M13:7:#12 Wire	7	52	59	244
M16:5&6:#16 TC Wire	11	56	56	58
M06:2&9:Triax	12	39	52	161
M02:3&10:#2/0 Wire	12	61	232	did not lift
M45:1:1000mcm/#12	12	-	-	did not lift

Temperature Measurements

The thermocouple data is plotted in its entirety for completeness in Figures 4-45 through 4-61. As mentioned earlier, a large number of the thermocouples inside the test chamber (including those inside the junction box) gave erroneous or noisy readings during the SAC test. The problem was apparently caused by a chemical attack on the thermocouple sheaths as described in the next section. As a result, the thermocouple data must be interpreted with caution.

The following general observations are made from these Figures:

- The test chamber and all components of the EPA inside the test chamber or inside the junction box were at or close to the steam saturation temperature (about 360°F) at 155 psia, i.e., there was little or no difference between the steam temperature and the skin temperature (Figures 4-45 through 4-56).

- The outboard module connectors, which extend into the EPA nozzle, were considerably cooler than the inboard module connectors. The maximum temperature of the outboard connectors was about 290°F, while that of the inboard connectors was about 360°F (Figure 4-55).

- There is a significant axial temperature gradient along the EPA nozzle (Figures 4-57 through 4-60). There is less of a gradient in the air along the centerline (Figure 4-61).

4.5 Posttest Observations

The test chamber cooled naturally to ambient temperature over the weekend (June 29 and 30). A reservoir was installed on the N_2 system by inserting a 50 foot length of 1/2 in. copper tubing on June 28. The N_2 pressure dropped from 15.0 psig to 10.3 psig in 69.3 hours, which indicates a leak rate of approximately 0.01 scc/sec.

The same type of air leak test that was conducted before the severe accident test was repeated at this time. With the test chamber at 143 psig, the leak rate through the EPA was about 0.13 scc/sec, which is still very small, but about an order of magnitude larger than the air leak rate at this pressure before the SAC test (0.024 scc/sec).

Insulation resistance and continuity measurements were made before and after the air leak test. Except for the M45 module, which had an insulation resistance of about 24 MΩ at both times, all of the module loop circuits still had insulation resistances of less than 0.1 MΩ.

When the test chamber was opened and the junction box was removed, test technicians found that all but one of the fifty-eight thermocouples had been badly damaged; there were splits in the stainless steel sheaths at approximately one inch intervals along the length of each damaged thermocouple. This behavior was unexpected as it had not been observed in a large number of previous severe accident tests on seal and gasket material that had been conducted at Sandia. There was little or no difference between the damage experienced by thermocouples inside the junction box and those outside the junction box. Thome has speculated that exposure of the EPA connectors to the SAC environment produced an acid that attacked the 310 stainless steel sheath. Metal (either galvanized or zinc) cable clamps used in the bottom of the junction box also indicated a chemical attack; they had essentially dissolved and were found in small pieces in the bottom of the test chamber as shown in Figure 4-62.[8] It is important to note also that there was very little steam circulation inside the test chamber because the only in-flow was that necessary to compensate for heat losses, which are small for saturated steam conditions.

As indicated in Figures 4-63 and 4-64, a white material, similar to an epoxy, had extruded out the back of the coupling ring and from between the module and the plug skirt on the C42 series connectors, which were used "inside containment". This material may be a decomposition of the polysulfone used as a sealing material in the connectors; other products of such a decomposition could be responsible for the damage to the thermocouples. Speculation aside, the white material seized up the coupling rings and prevented removal of the inside connectors on both of the M02 and M13 modules.

Many of the remaining connectors were removed with a pipe wrench because sufficient torque could not be generated with the spanner wrenches provided by D. G. O'Brien. Of the five inside connectors that could be disassembled, most had signs

8. Recent tests conducted at Sandia by M. Jacobus demonstrate that chloride is released by Hypalon cable conductors in a saturated steam environment, which can lead to chloride stress corrosion of stainless steel. It is possible that some or all of the insulators and/or jackets may have contained chlorine. In subsequent tests, this problem was circumvented by using Inconel sheaths and higher rates of steam circulation.

of moisture intrusion as shown in Figures 4-65 through 4-67. Tracks between the pins and ground were observed in the M16 and M19 modules and confirmed with an ohmmeter.

4.6 Summary and Conclusions

A D. G. O'Brien EPA typical of those used in containment buildings of PWR nuclear power plants was tested under severe accident conditions simulated by saturated steam at temperatures and pressures up to 361°F and 155 psia. This test includes conditions beyond the design basis of the EPA. The EPA was first irradiated and then thermally aged. The primary objective was generate engineering data that could be used to evaluate the leak integrity of the EPA. A secondary objective was to investigate the EPA's electrical performance.

There were no detectable leaks through the EPA during the severe accident test. The module pressure increased during the test due to seepage on the order of 10^{-4} scc/sec past the inboard connectors. The aperture seal did not leak. A very small leak, 0.13 scc/sec, was recorded during a posttest air leak rate measurement at ambient temperature and 155 psia.

The thermocouple data suggest that the temperatures of the EPA and its components "inside containment" are quite uniform under saturated steam conditions. Also, there is a significant temperature gradient along the axis of the EPA nozzle "outside containment". Thus, the outboard module connectors were cooler (about 290°F) than than inboard module connectors (about 360°F).

The electrical performance of the EPA modules degraded over the first 2 days of the test to the point that the insulation resistance to ground for all conductors was less than 1 MΩ, and after 10 days, five out of the eight circuits were passing 0.5 amp to ground, which was the maximum current possible in this test. The earliest short to ground occurred about 13 hours into the test. Insulation resistances fell below 1 kΩ before the shorts to ground occurred. The posttest inspection showed that all but one module was electrically faulty because of moisture that had traveled through the connector and provided a ground between the module pins and the metal mask that surrounds each pin. This bridging with moisture or contaminates is believed to have caused the electrical shorts to ground.

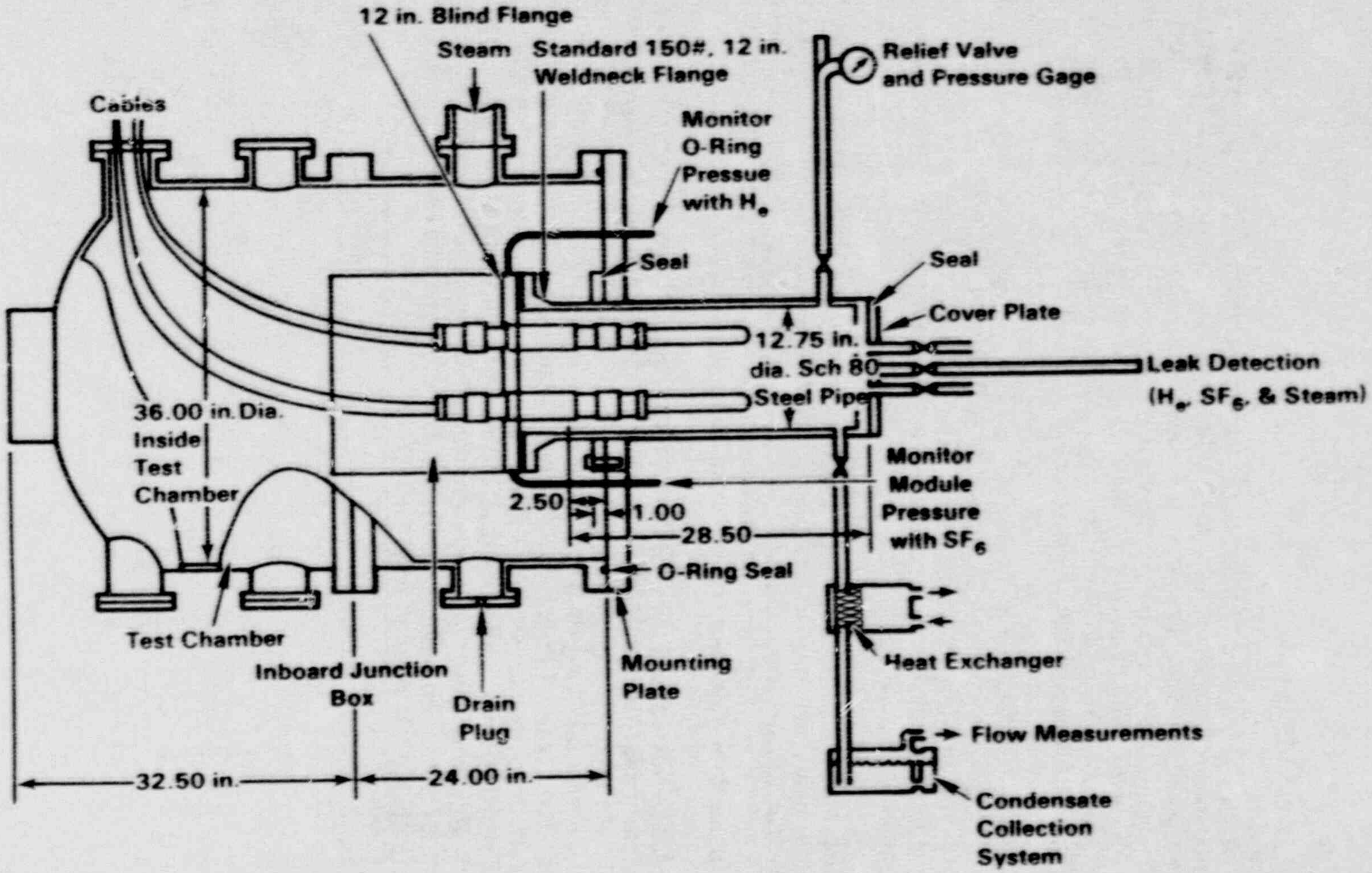


Figure 4-1 D. G. O'Brien EPA Test Assembly

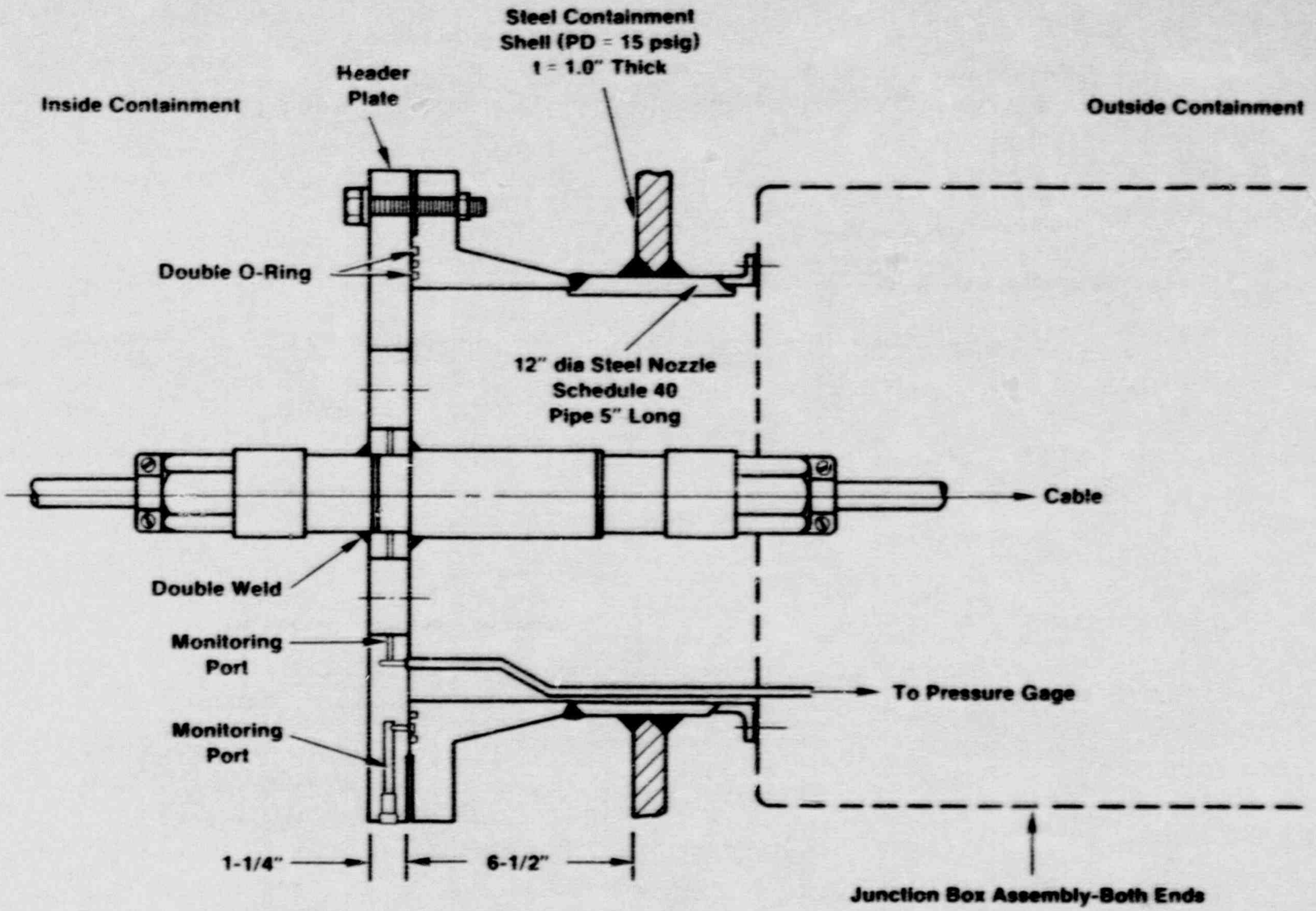


Figure 4-2 EPA Nozzle Design Used in Catawba Nuclear Power Plant

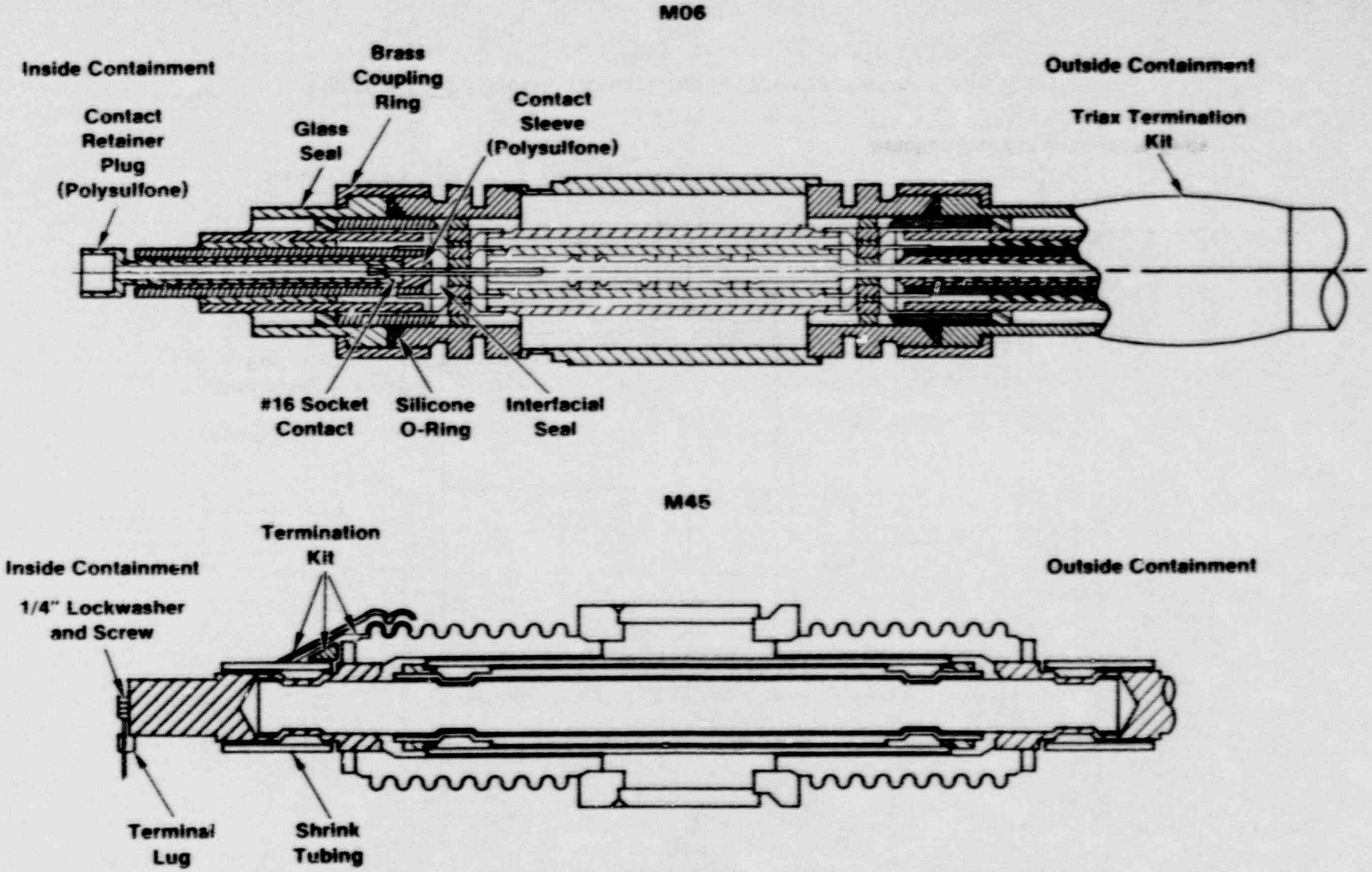
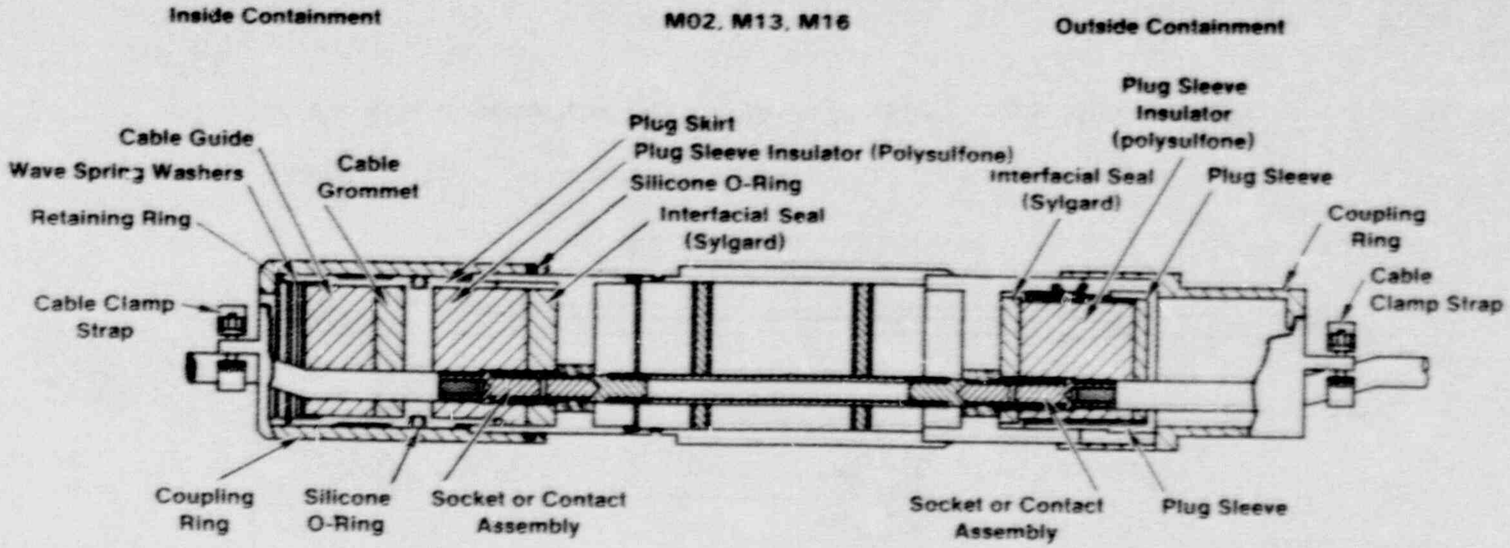


Figure 4-3a Schematic of D. G. O'Brien Module Designs M06 and M45



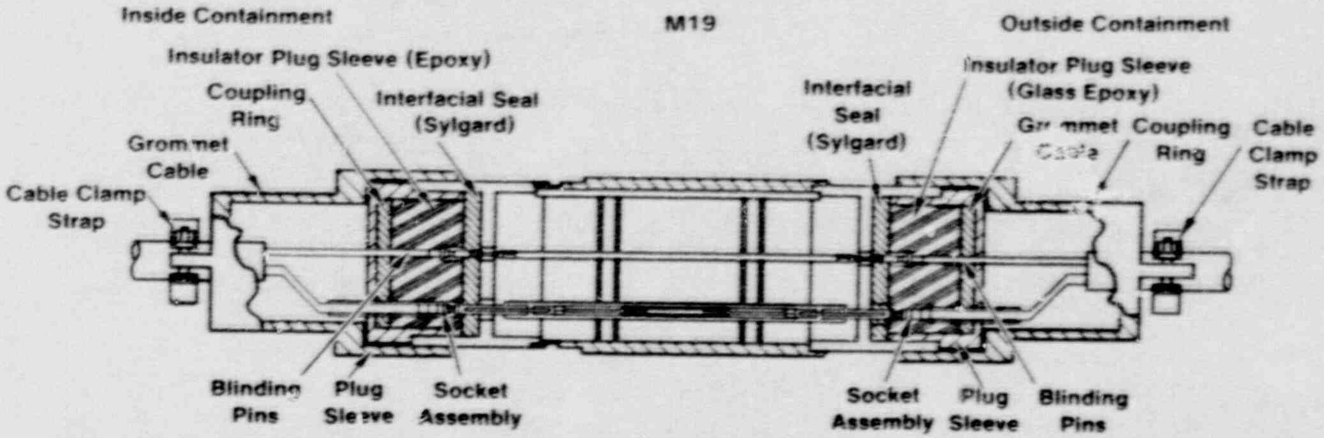
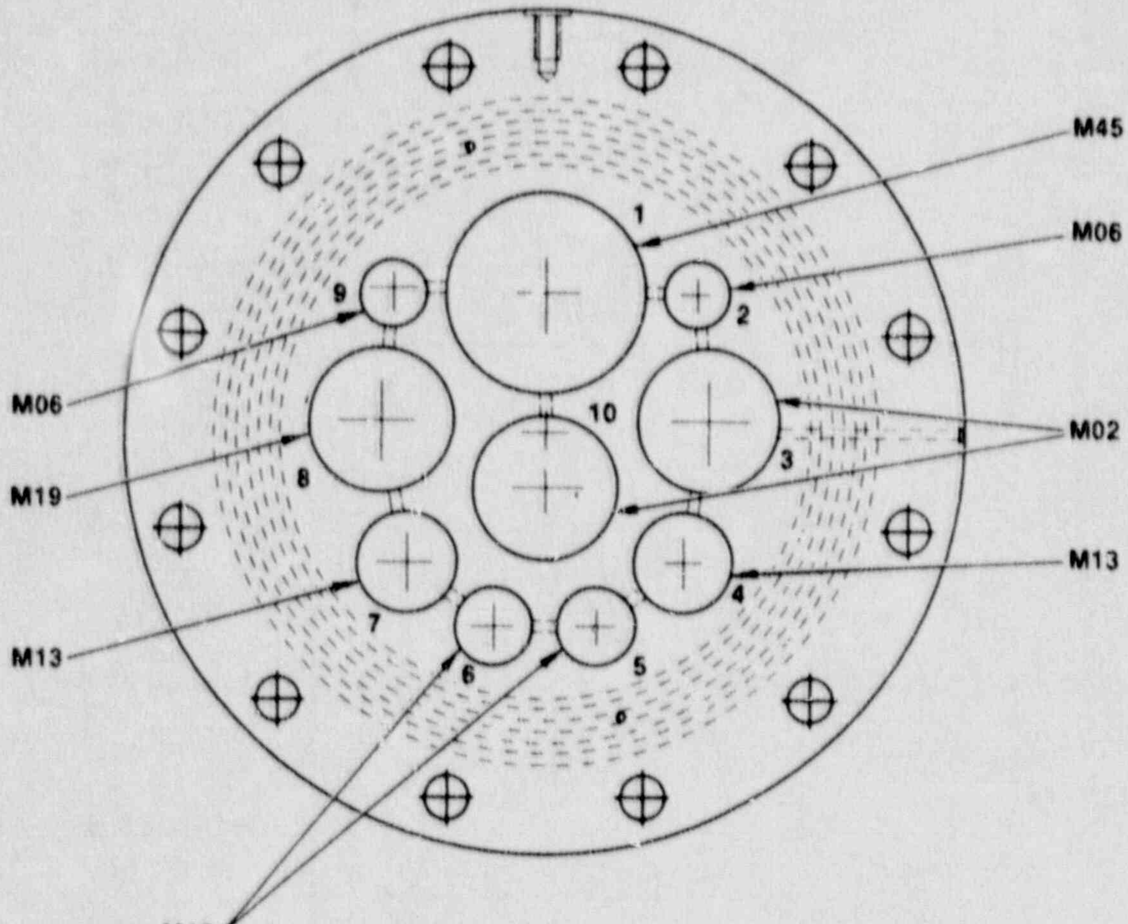


Figure 4-[illegible] Schematic of D. G. O'Brien Module Designs M02, M13, M16 and M19



Location of Modules in Header Plate
(view from inside containment end)

Figure 4-4 Location of Modules in Header Plate

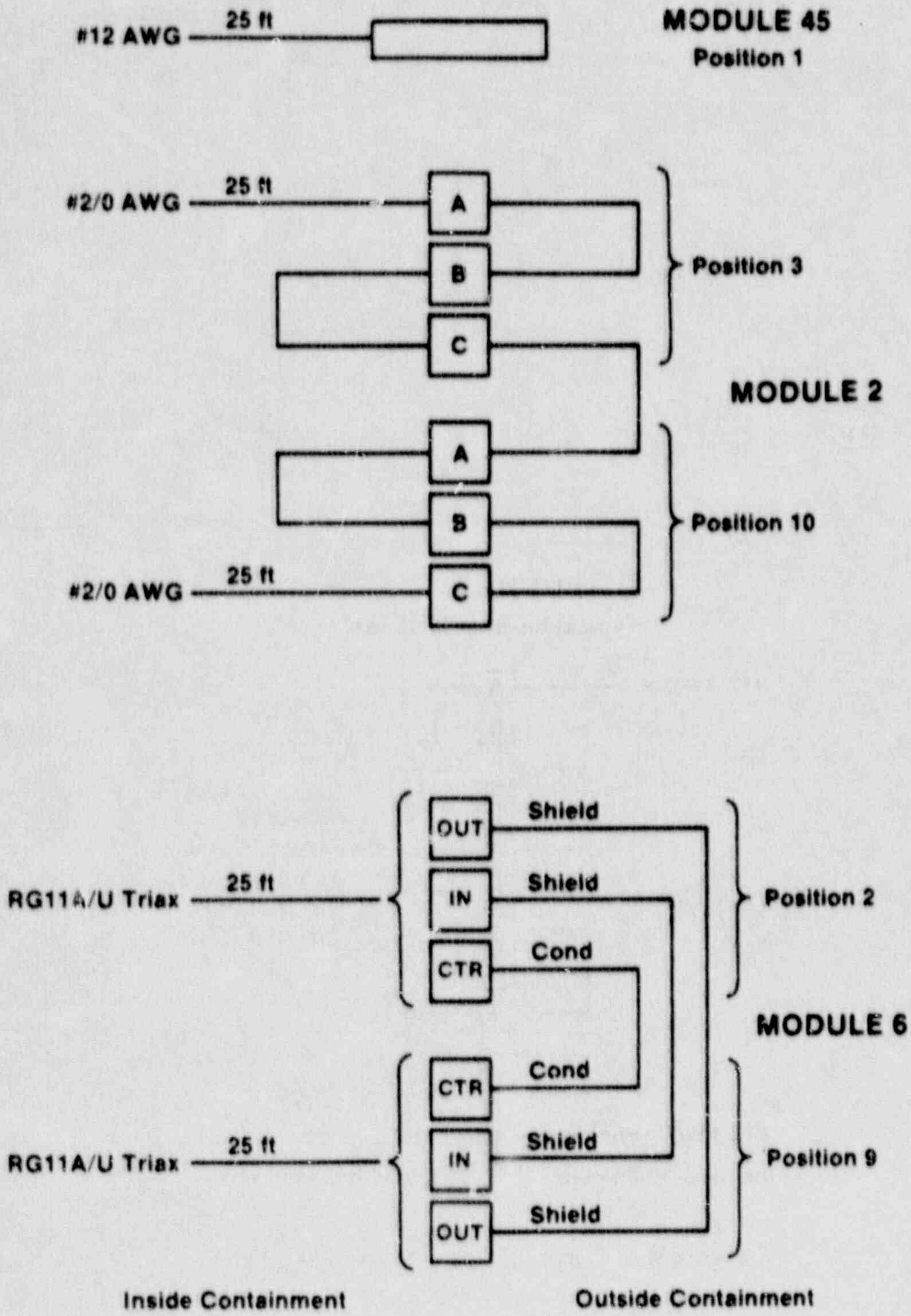


Figure 4-5 Wiring Schematic for Modules 45, 2, and 6

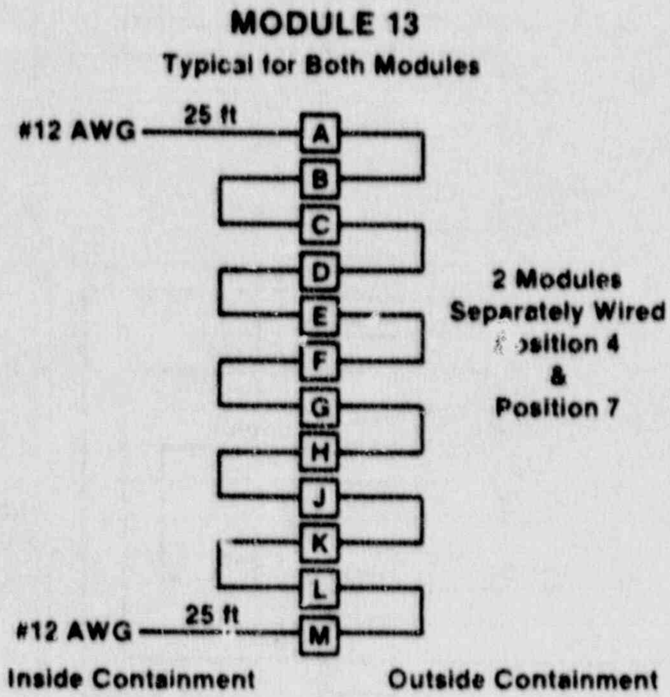


Figure 4-6 Wiring Schematic for Module 13

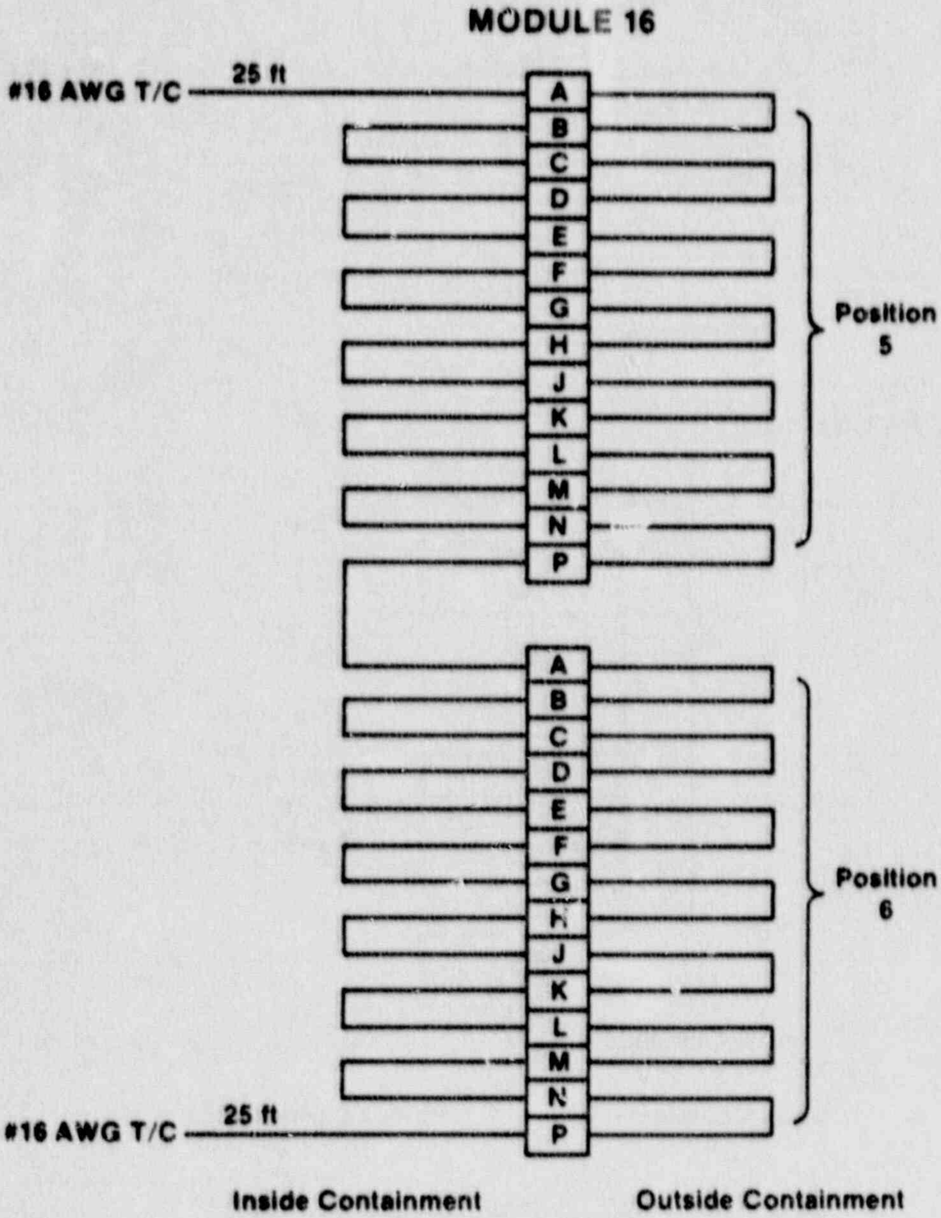


Figure 4-7 Wiring Schematic for Module 16

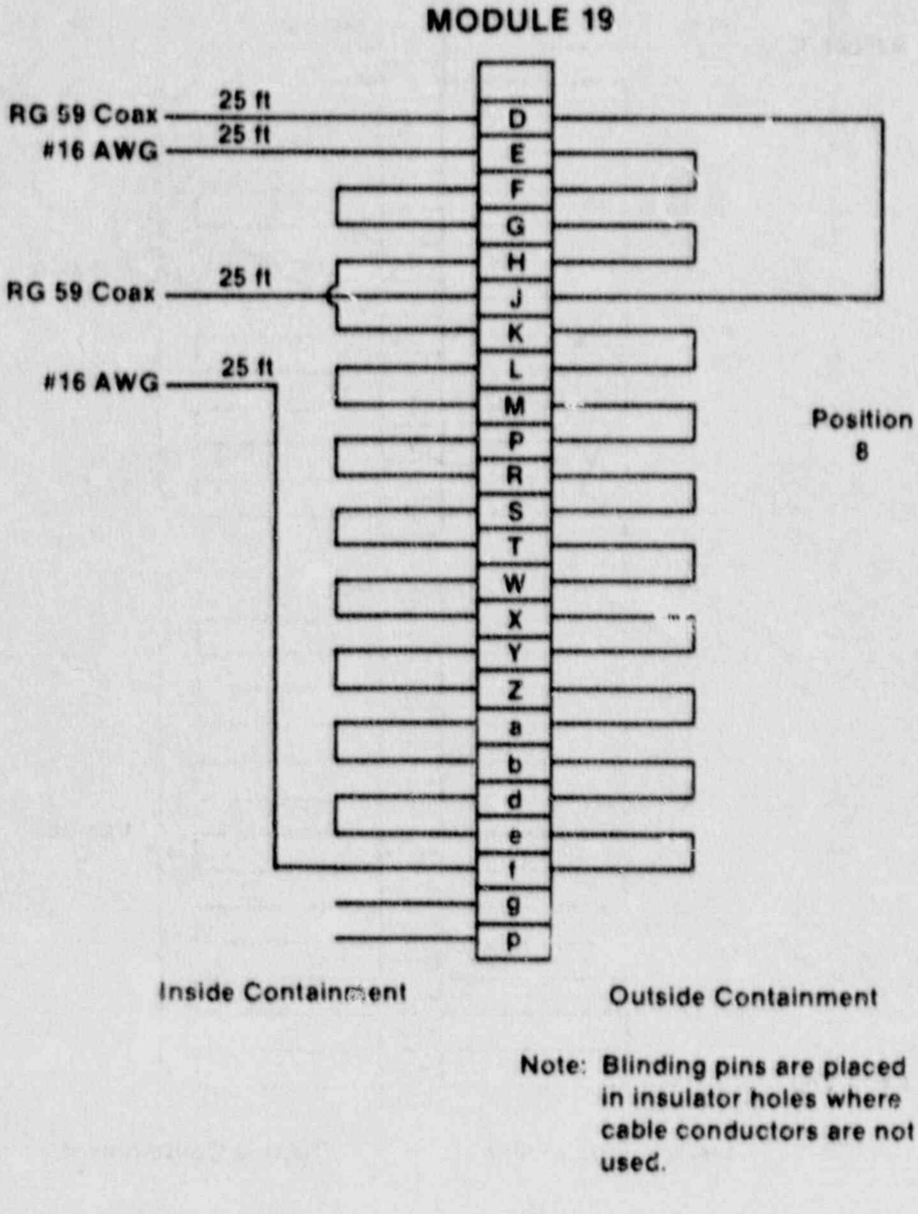


Figure 4-8 Wiring Schematic for Module 19

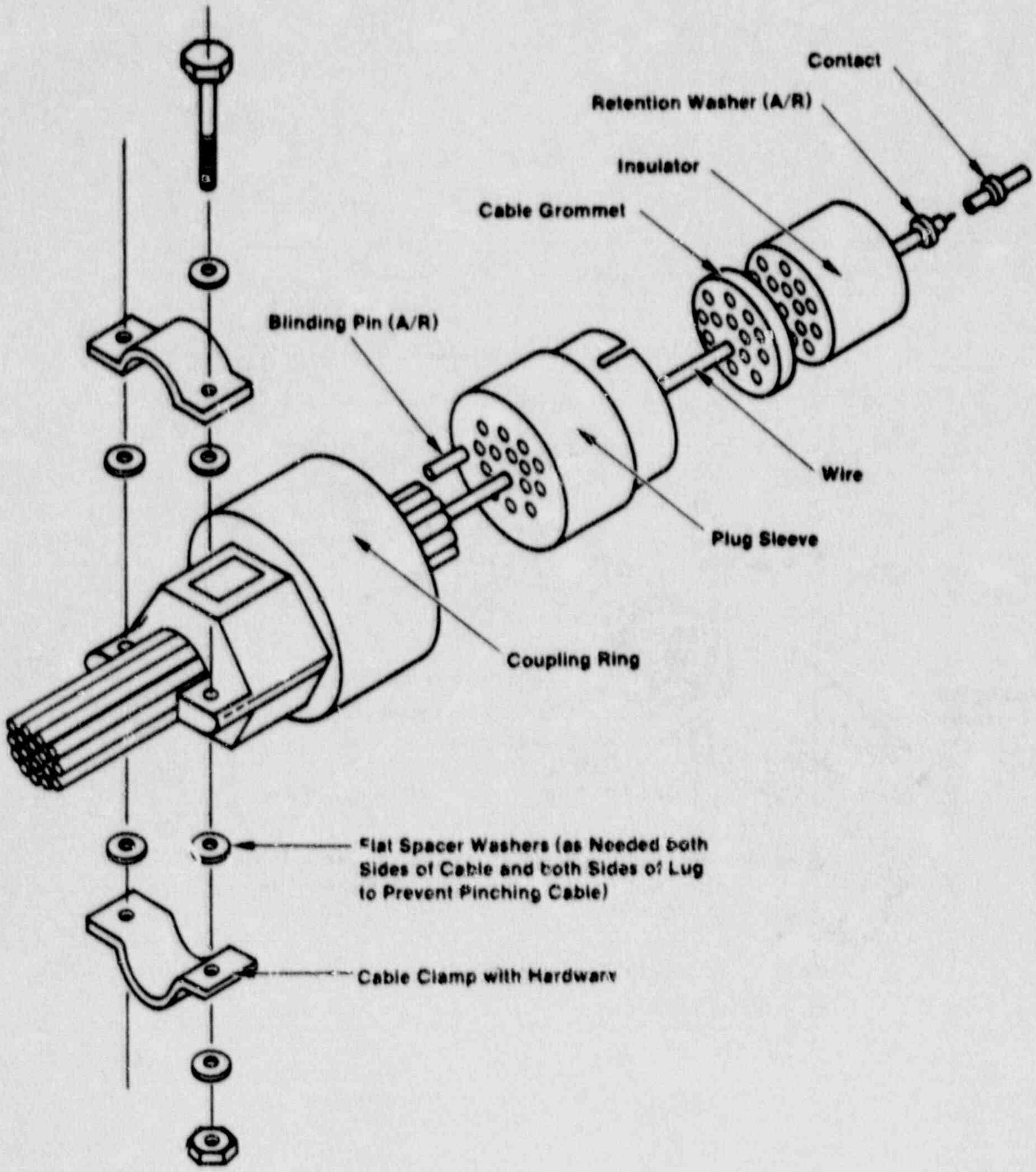


Figure 4-9 C32 Series Plug (Used Outside Containment)

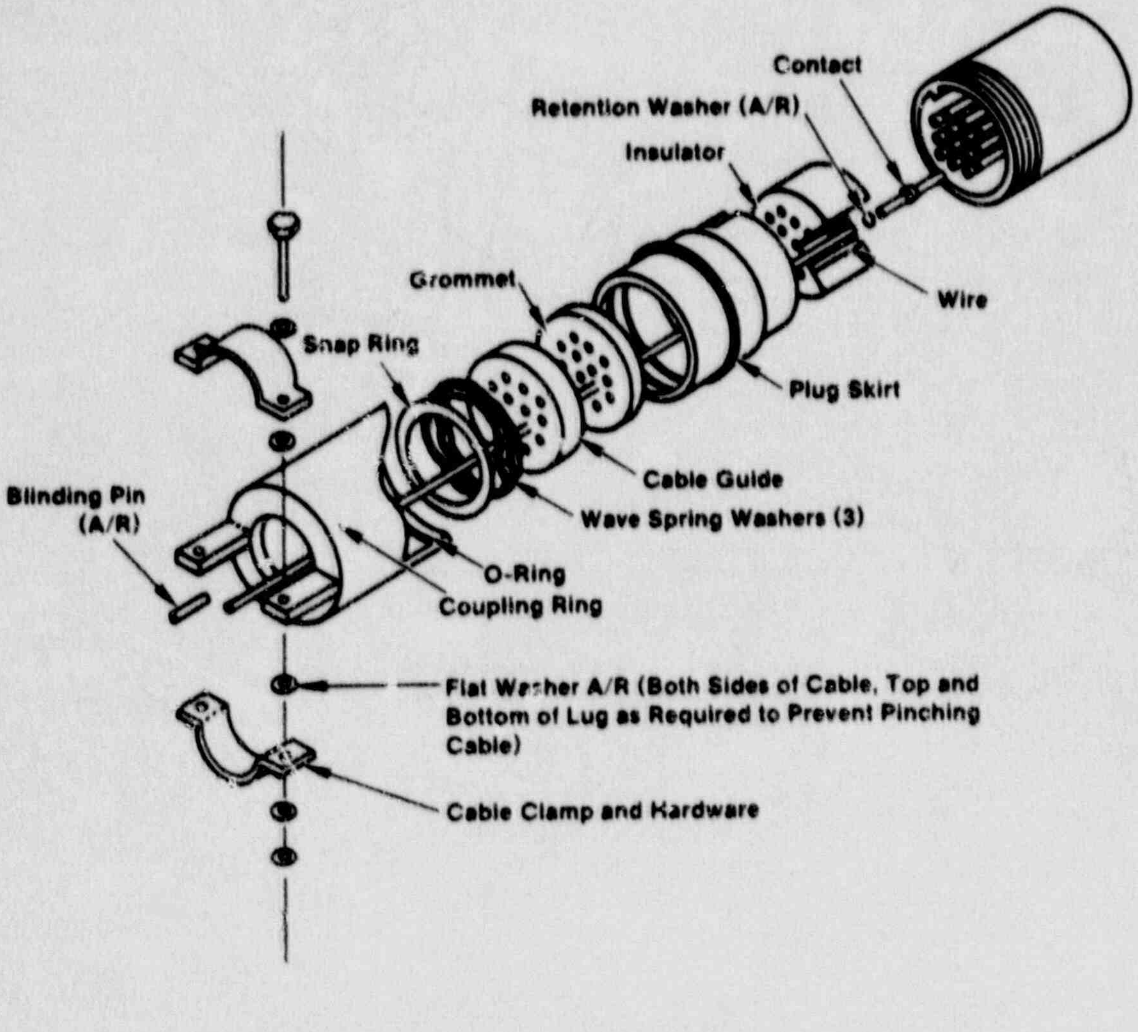


Figure 4-10 C42 Series Plug (Used Inside Containment)

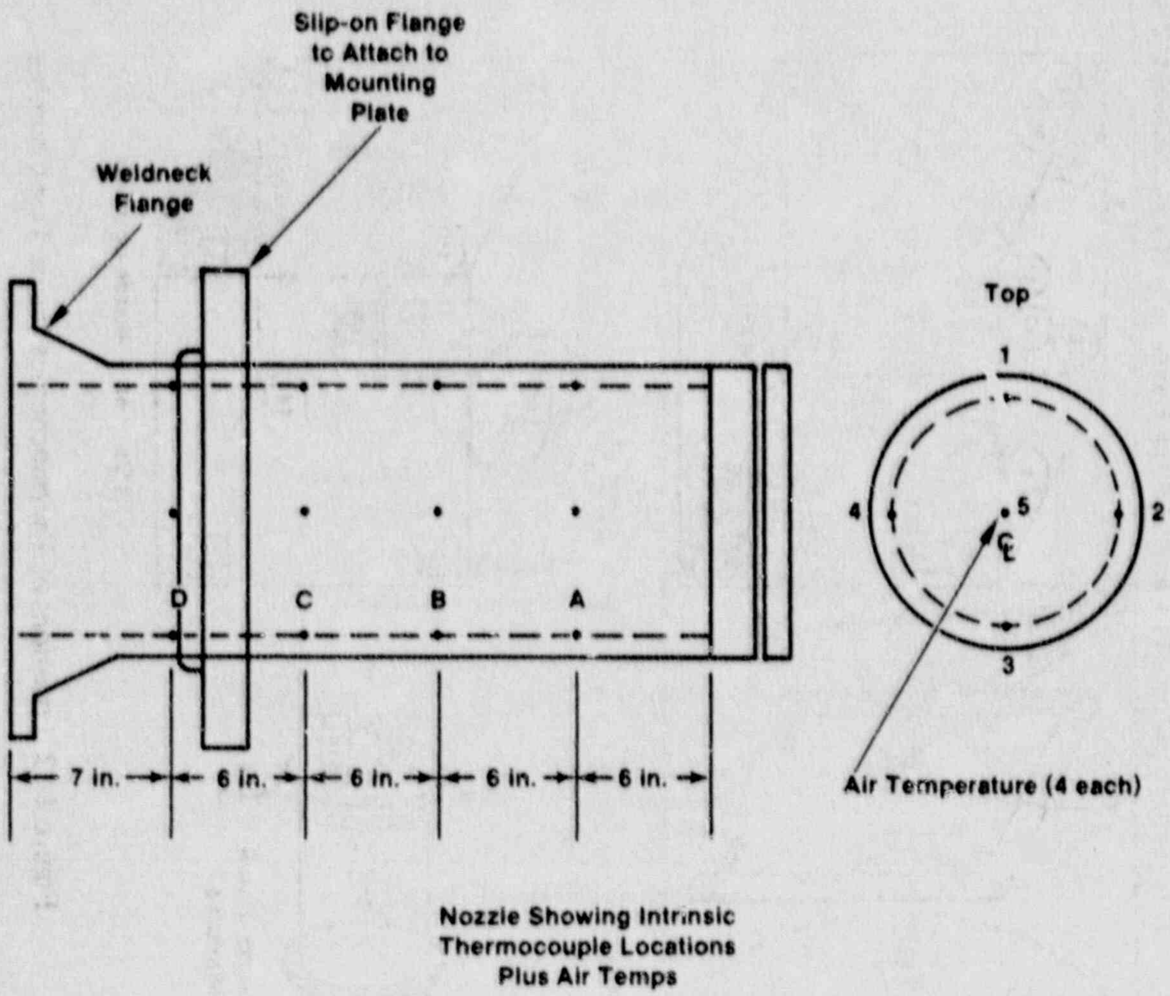


Figure 4-11 Locations of Thermocouples on Nozzle

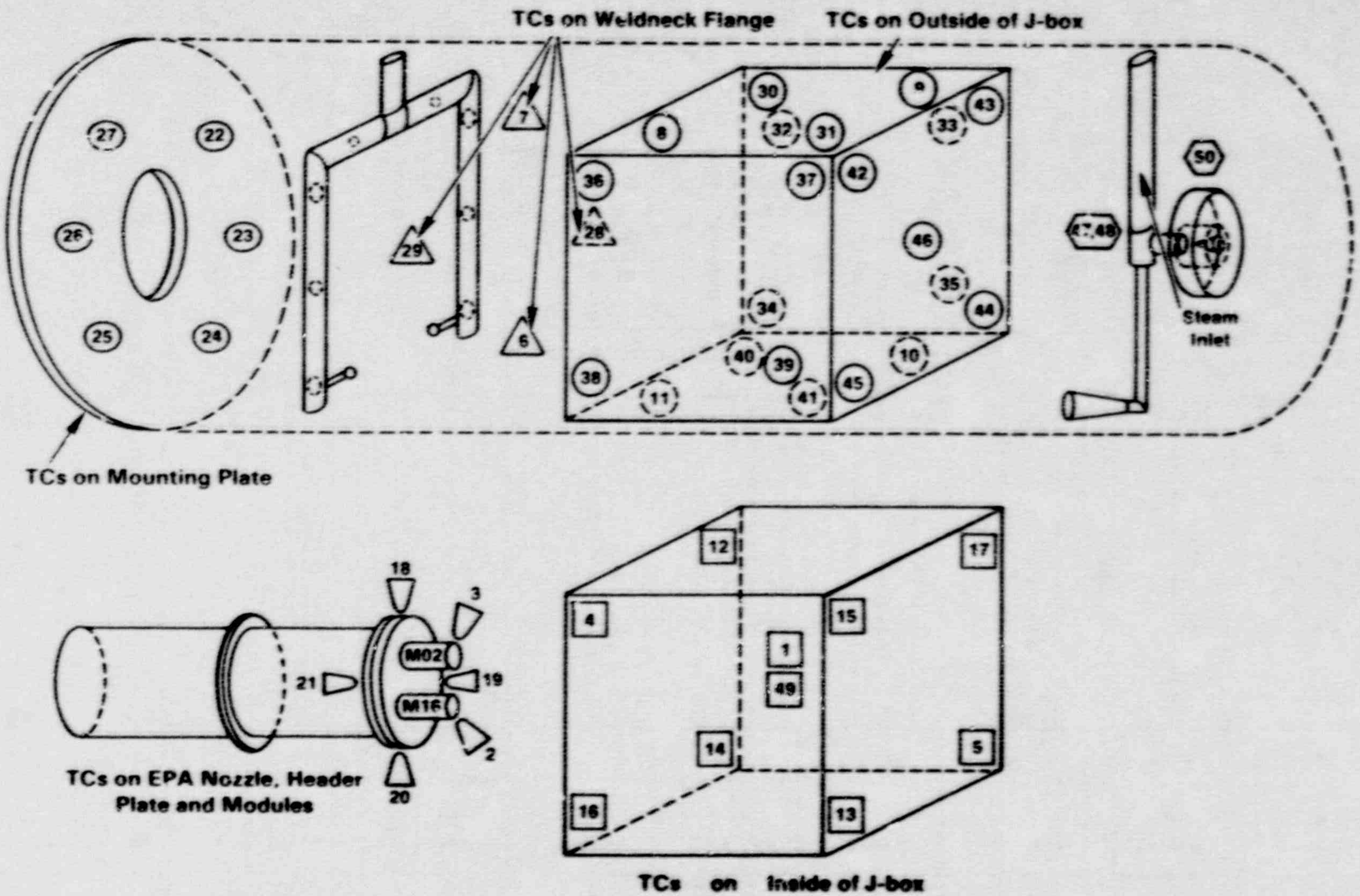


Figure 4-12 Locations of Thermocouples Inside Test Chamber

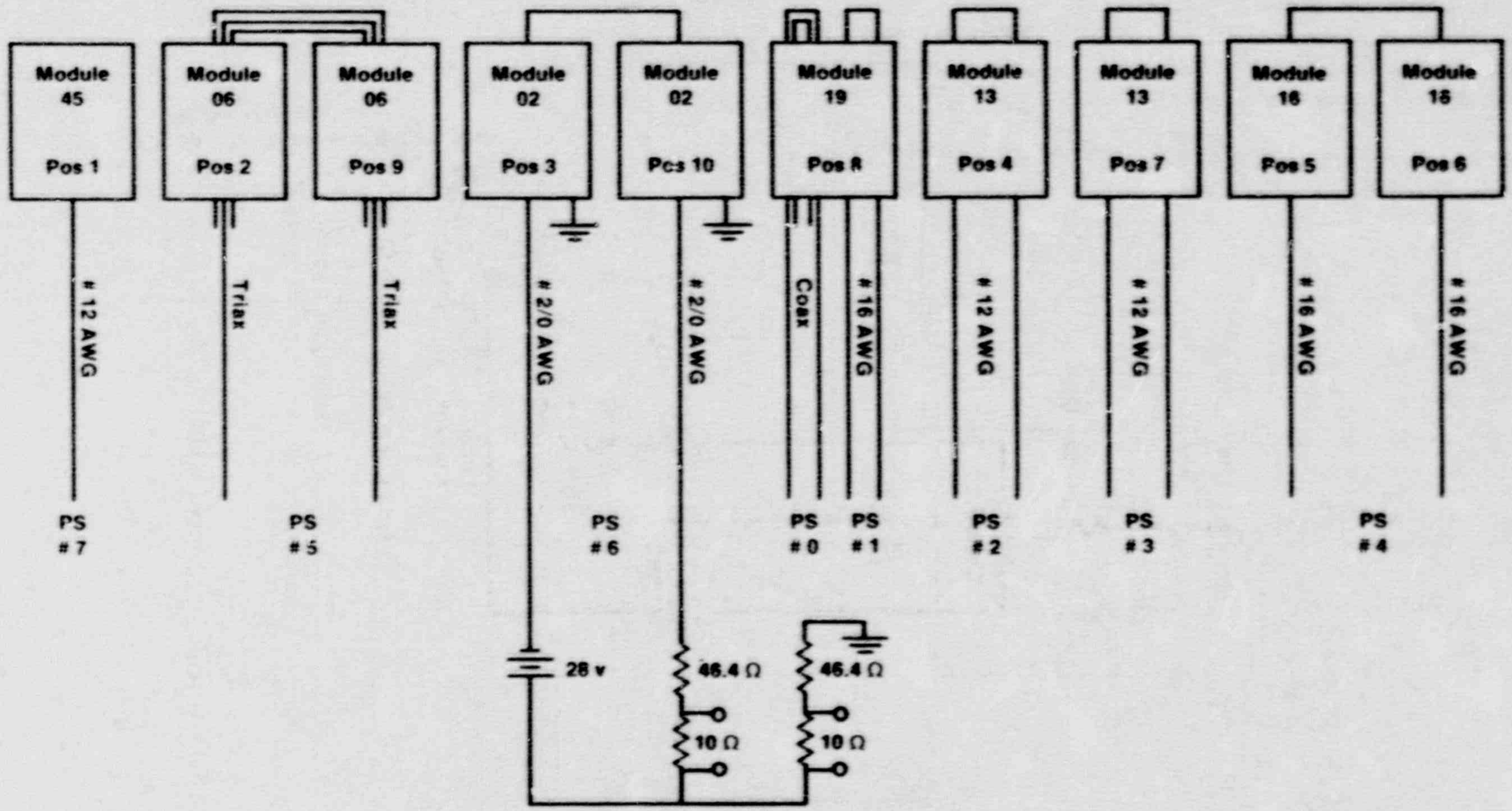


Figure 4-13 Wiring Schematic for Load Bank

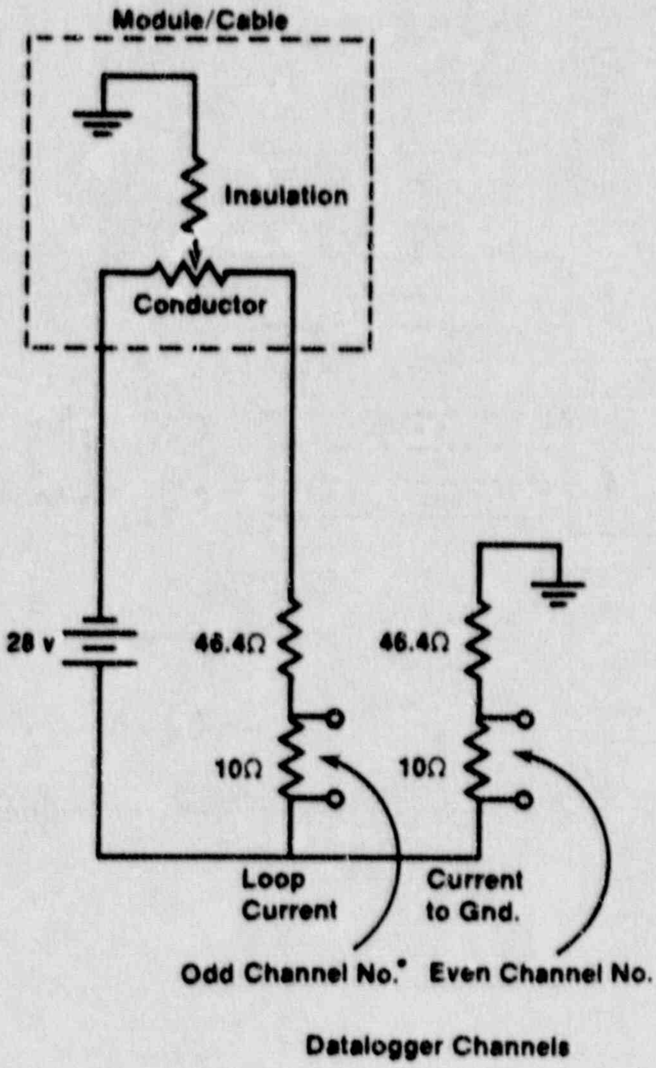


Figure 4-14 Circuit for Monitoring Continuity and Insulation Resistance

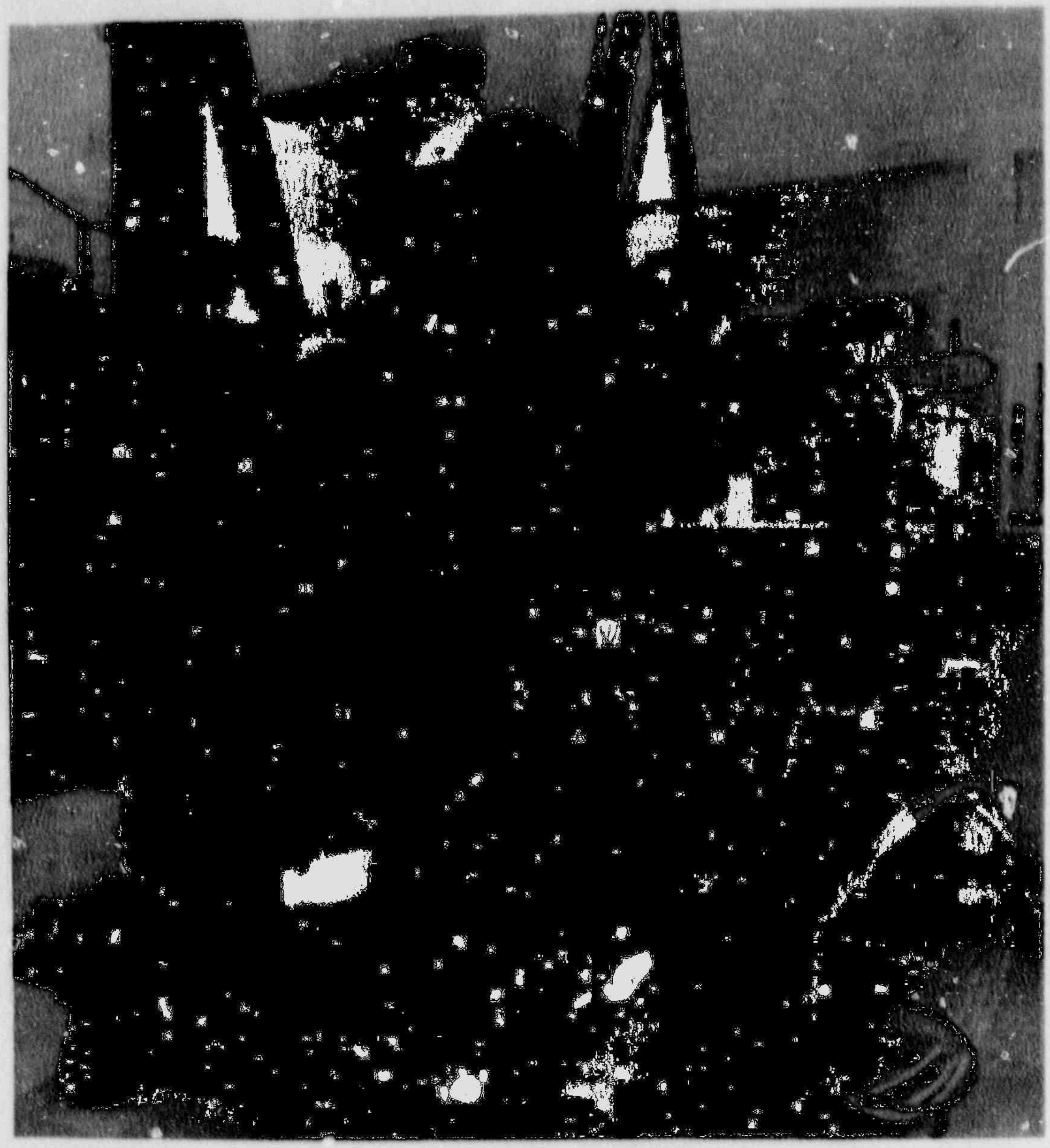


Figure 4-15 EPA Setup for Initial Inspection

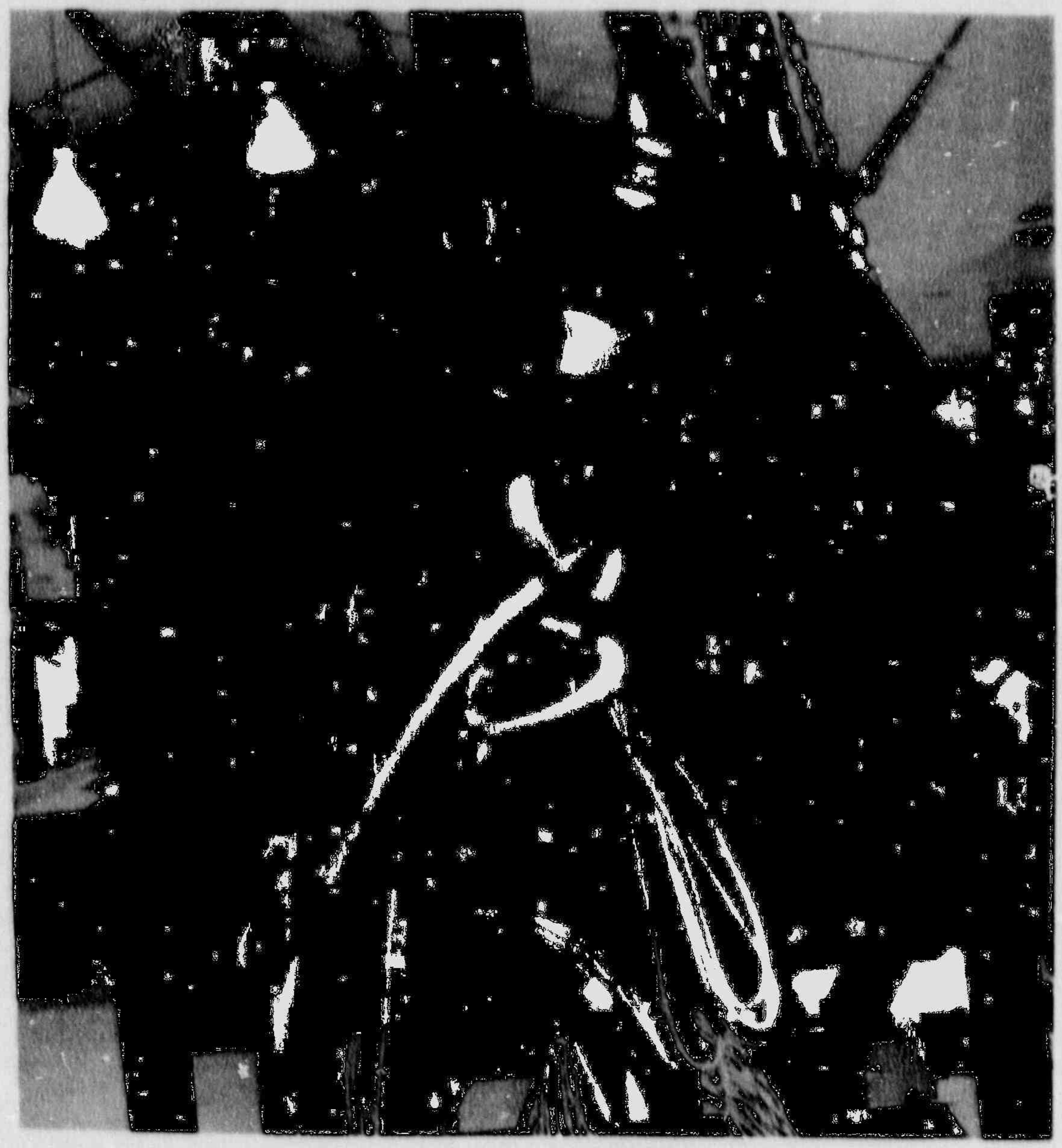


Figure 4-16 EPA in Nozzle Before Irradiation

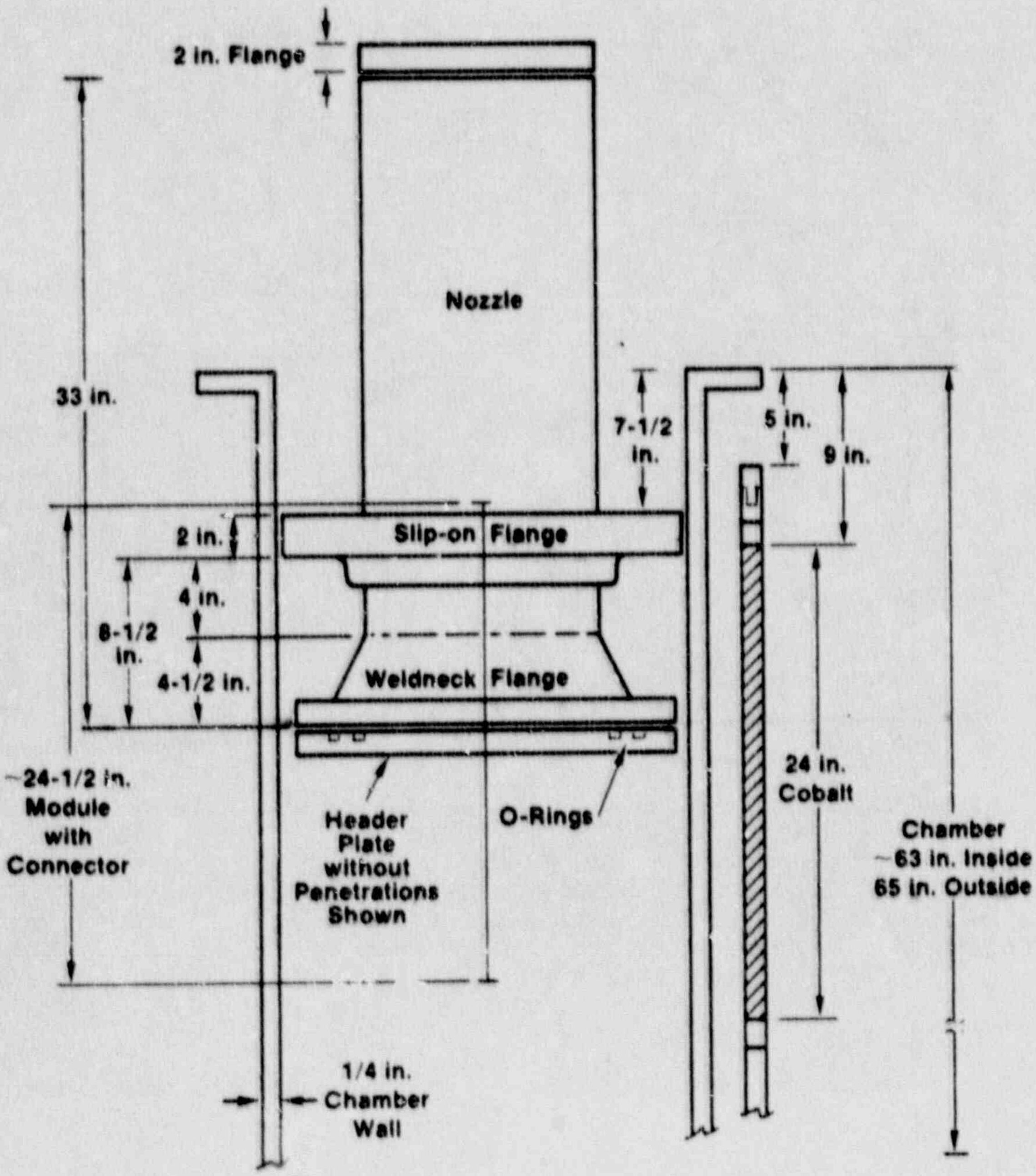


Figure 4-17 Location of EPA Relative to Cobalt Array

Figure 4-18 EPA and Nozzle Positioned for Irradiation

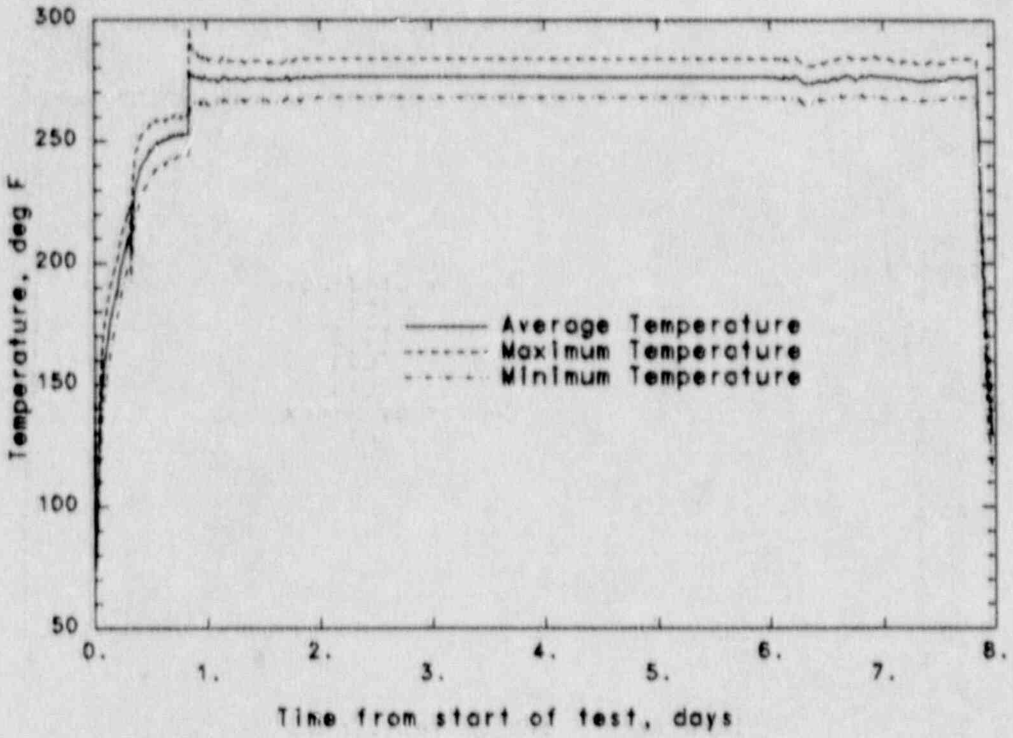


Figure 4-19 Temperature Extremes on Inside of Junction Box During Thermal Aging

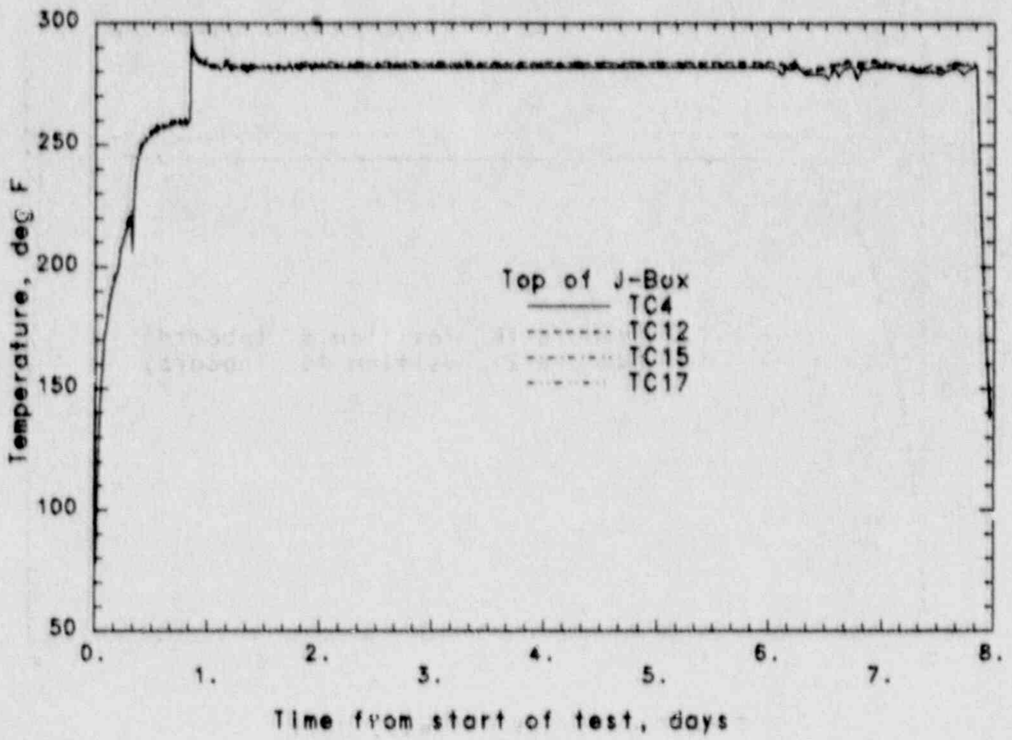


Figure 4-20 Temperature Inside Junction Box (Top) During Thermal Aging

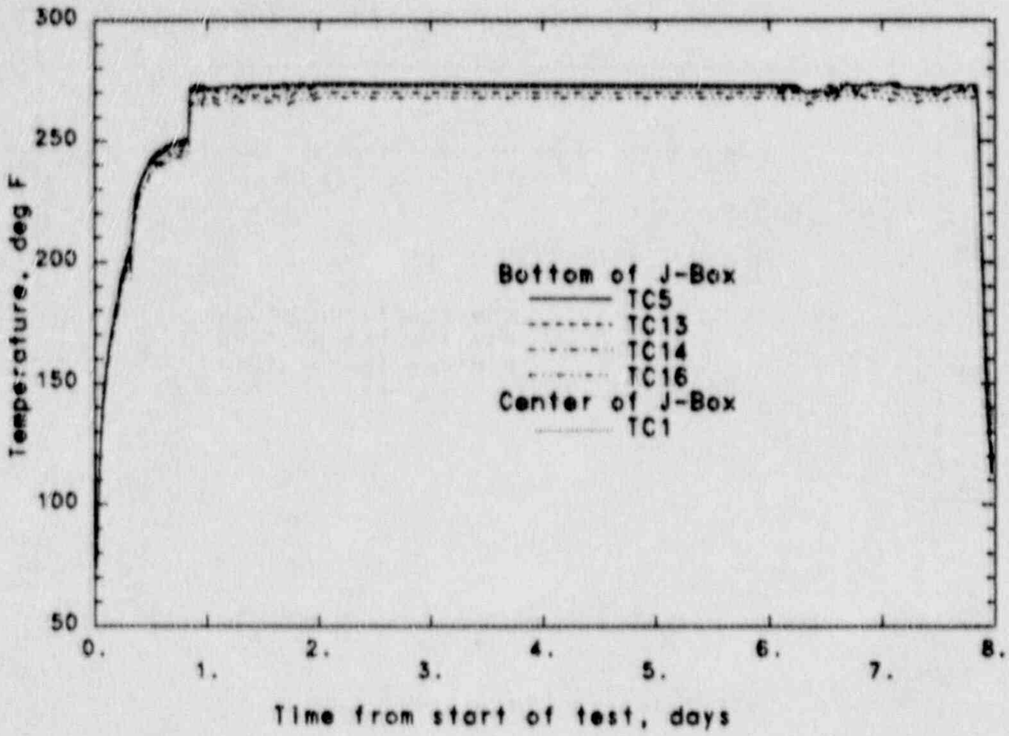


Figure 4-21 Temperature Inside Junction Box (Bottom) During Thermal Aging

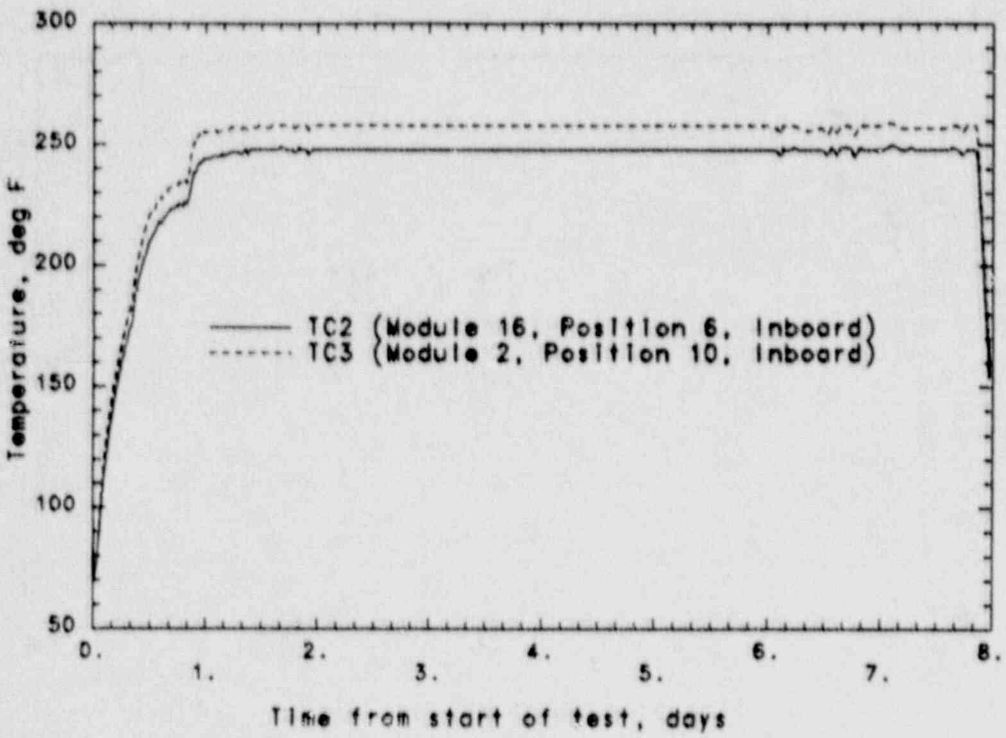


Figure 4-22 Temperature of Module Connectors During Thermal Aging

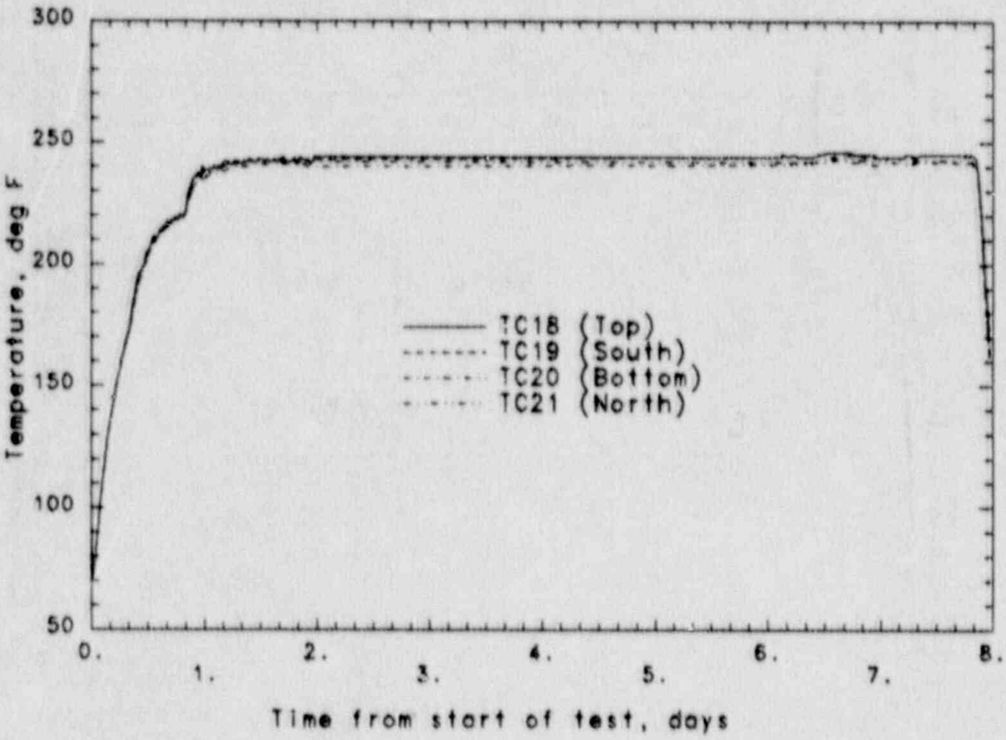


Figure 4-23 Temperature of Header Plate During Thermal Aging

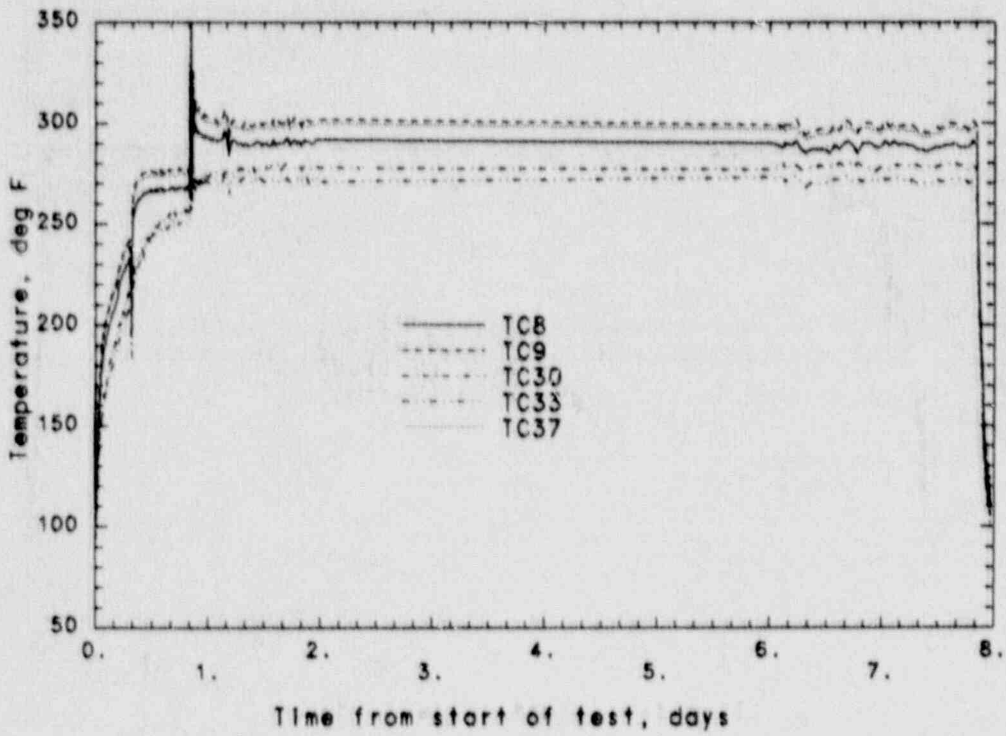


Figure 4-24 Temperature Outside Junction Box (Top) During Thermal Aging

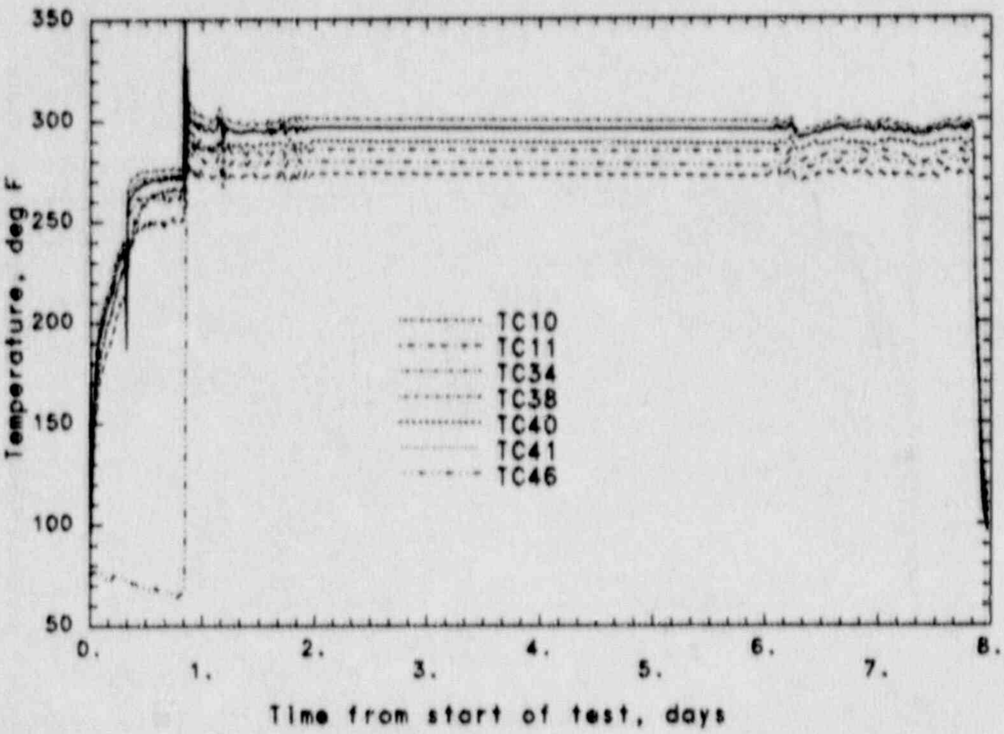


Figure 4-25 Temperature Outside Junction Box (Bottom) During Thermal Aging

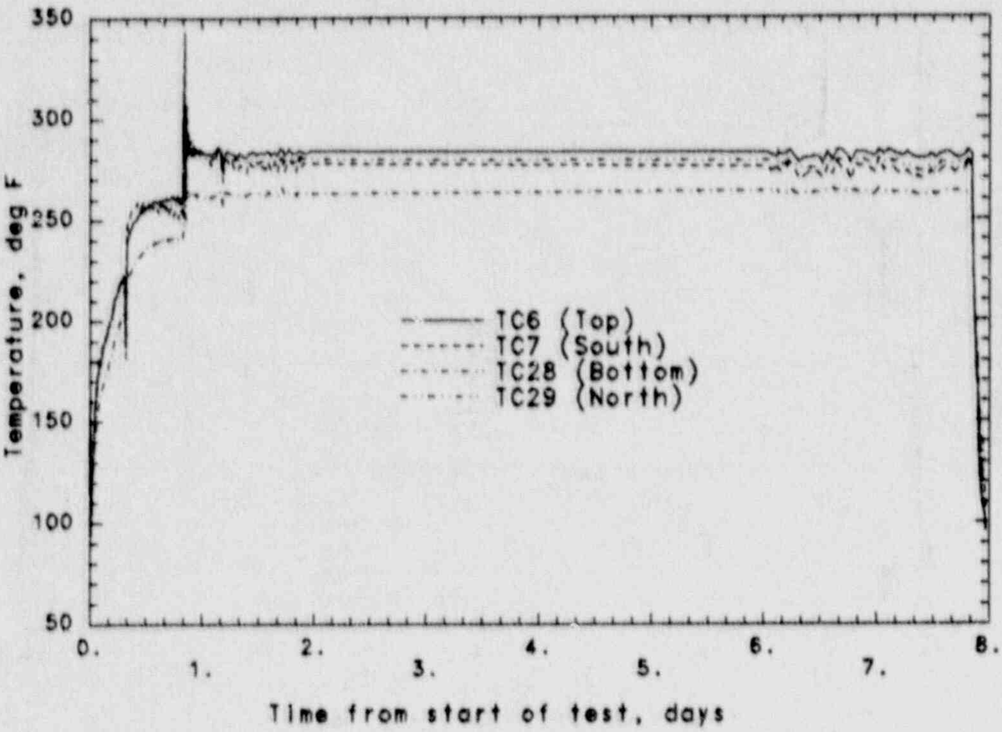


Figure 4-26 Temperature of Weldneck Flange During Thermal Aging

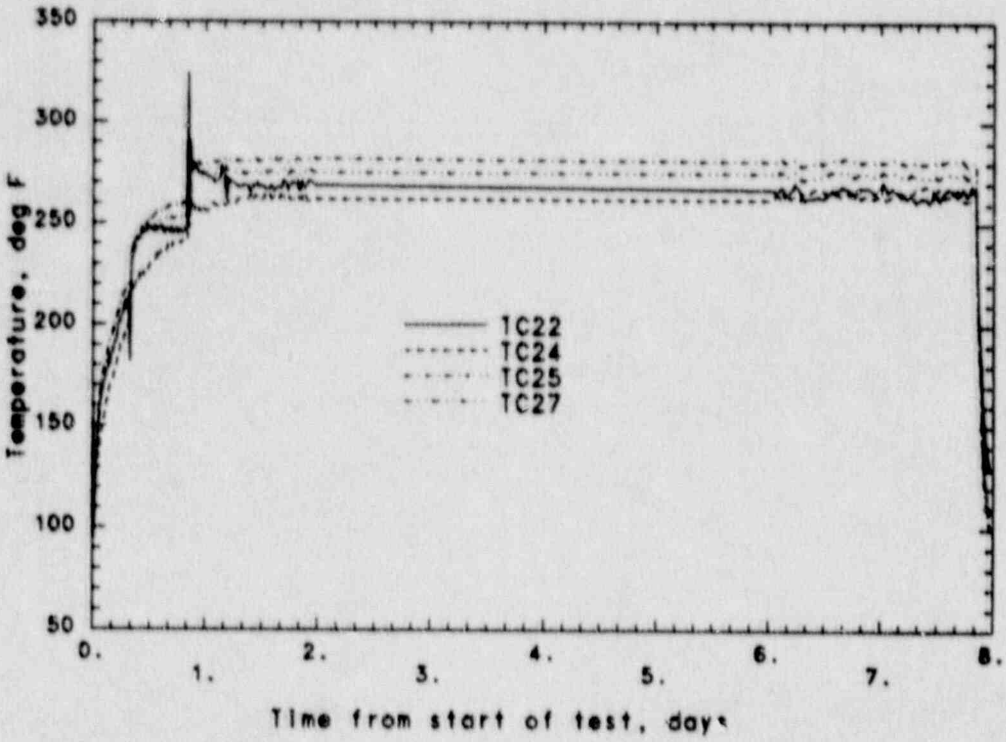


Figure 4-27 Temperature Near Mounting Plate During Thermal Aging

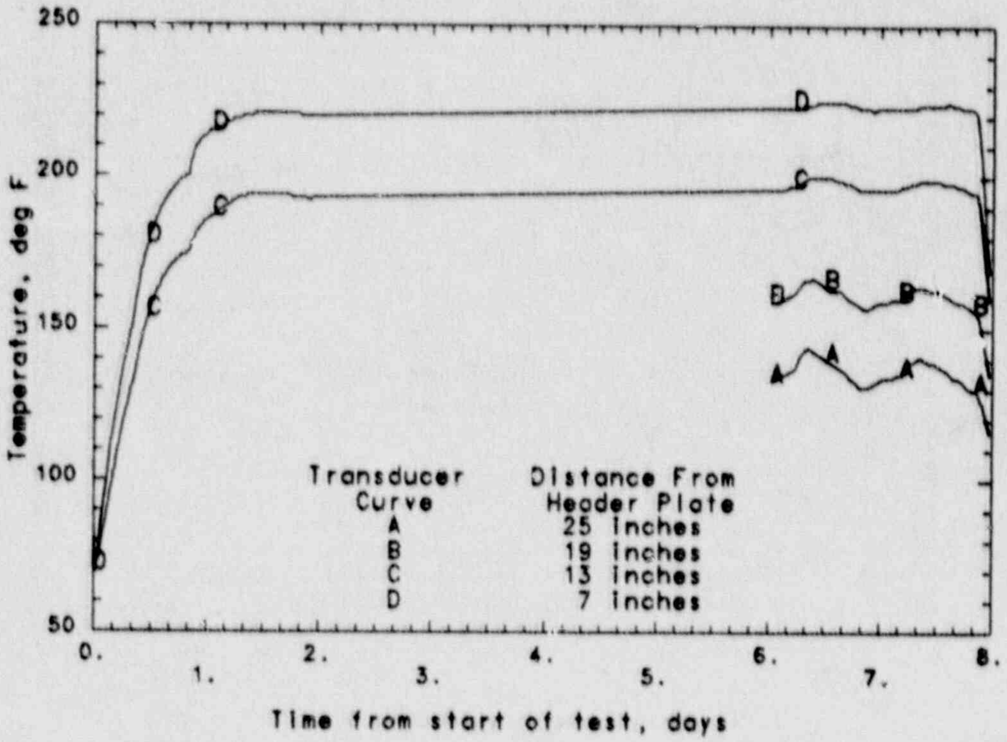


Figure 4-28 Nozzle Temperature at Position 1 During Thermal Aging

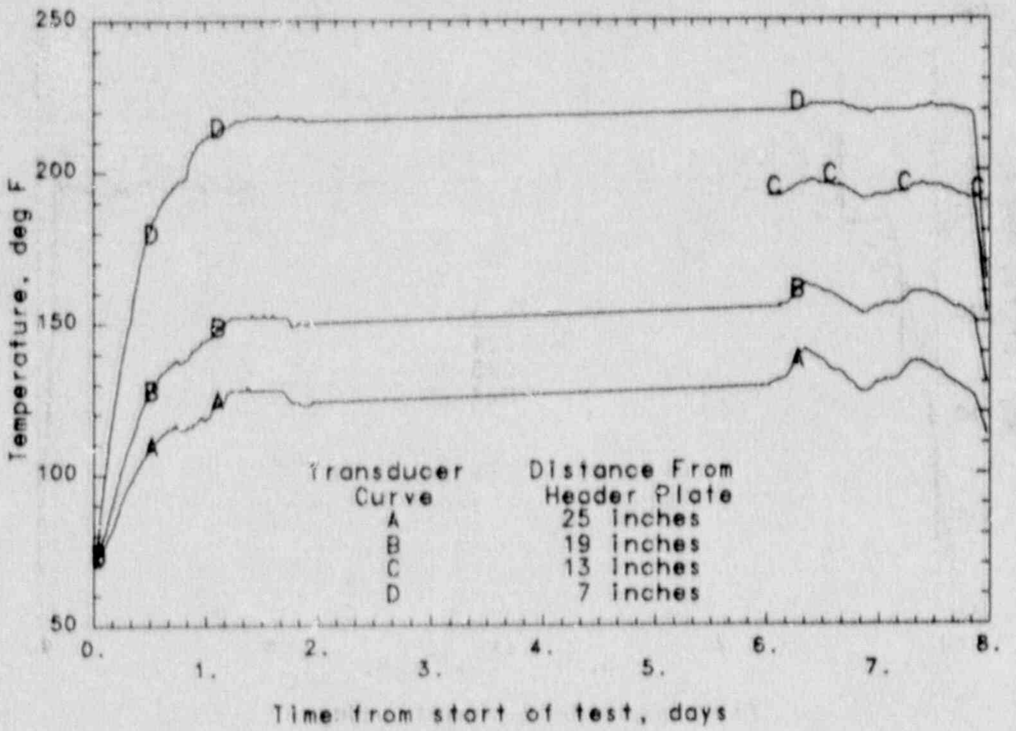


Figure 4-29 Nozzle Temperature at Position 2 During Thermal Aging

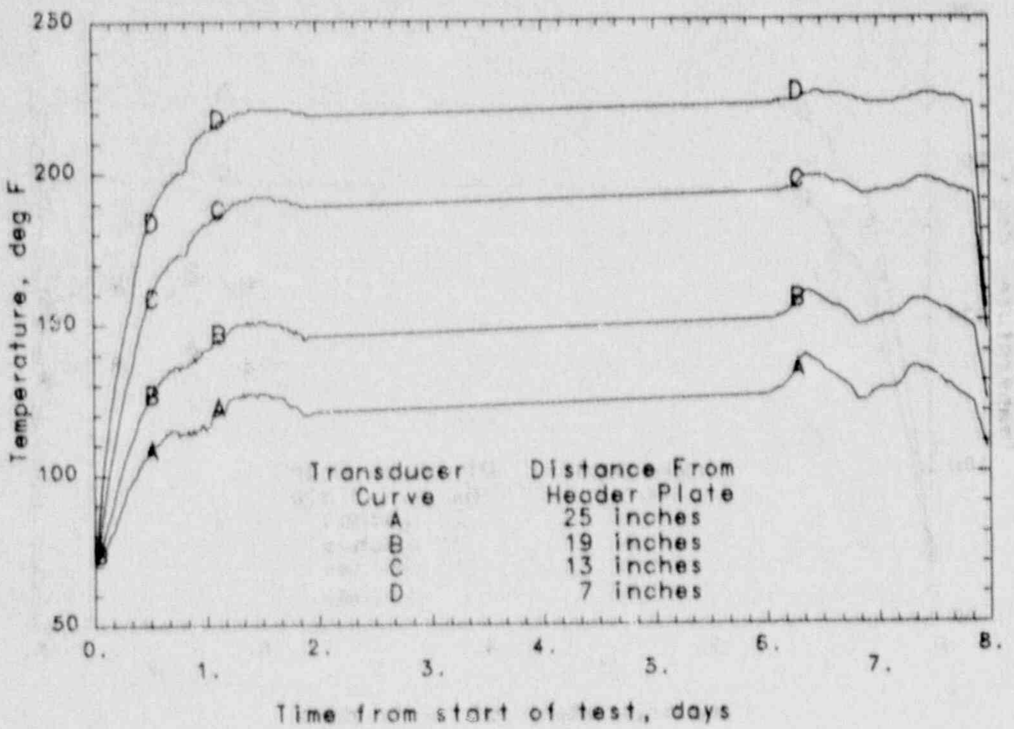


Figure 4-30 Nozzle Temperature at Position 3 During Thermal Aging

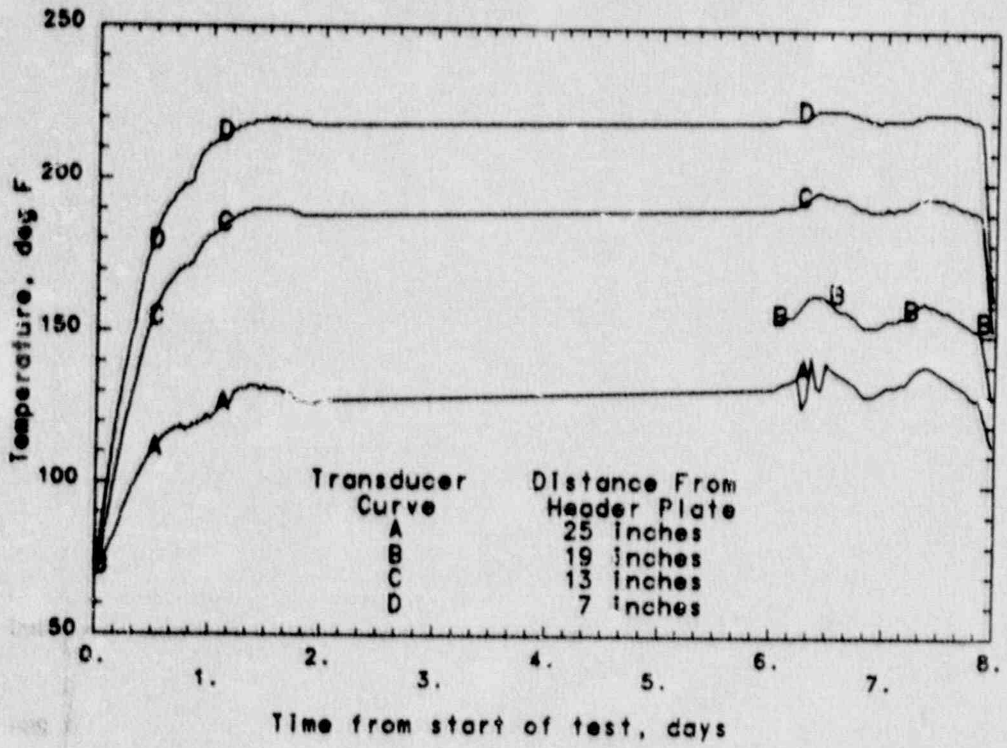


Figure 4-31 Nozzle Temperature at Position 4 During Thermal Aging

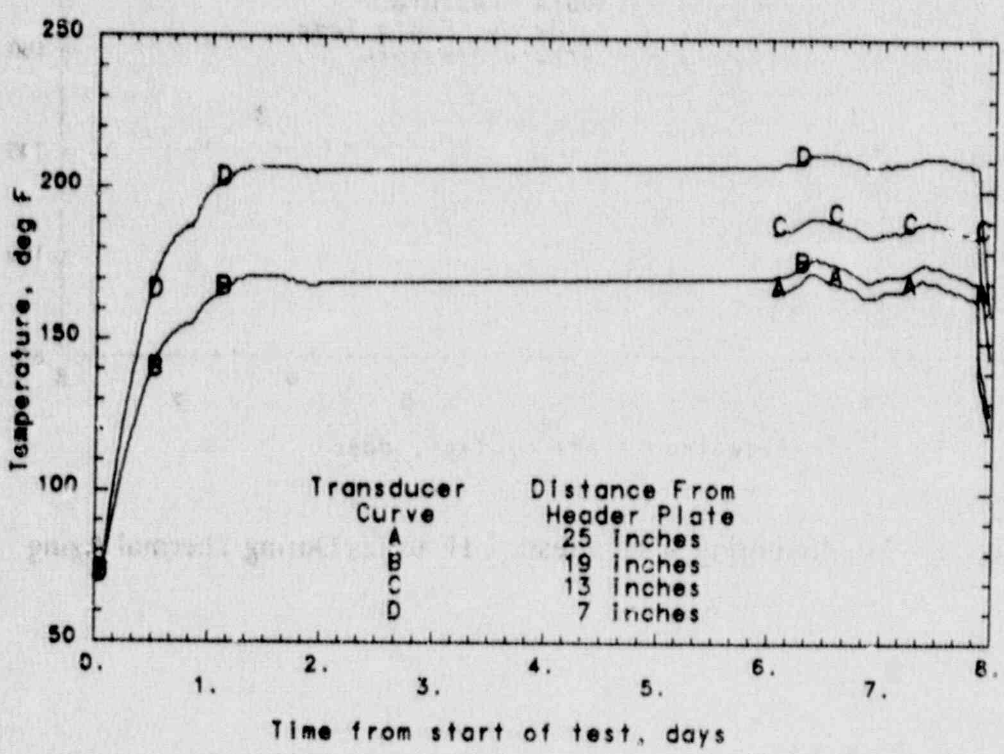


Figure 4-32 Air Temperature Along Nozzle Centerline During Thermal Aging

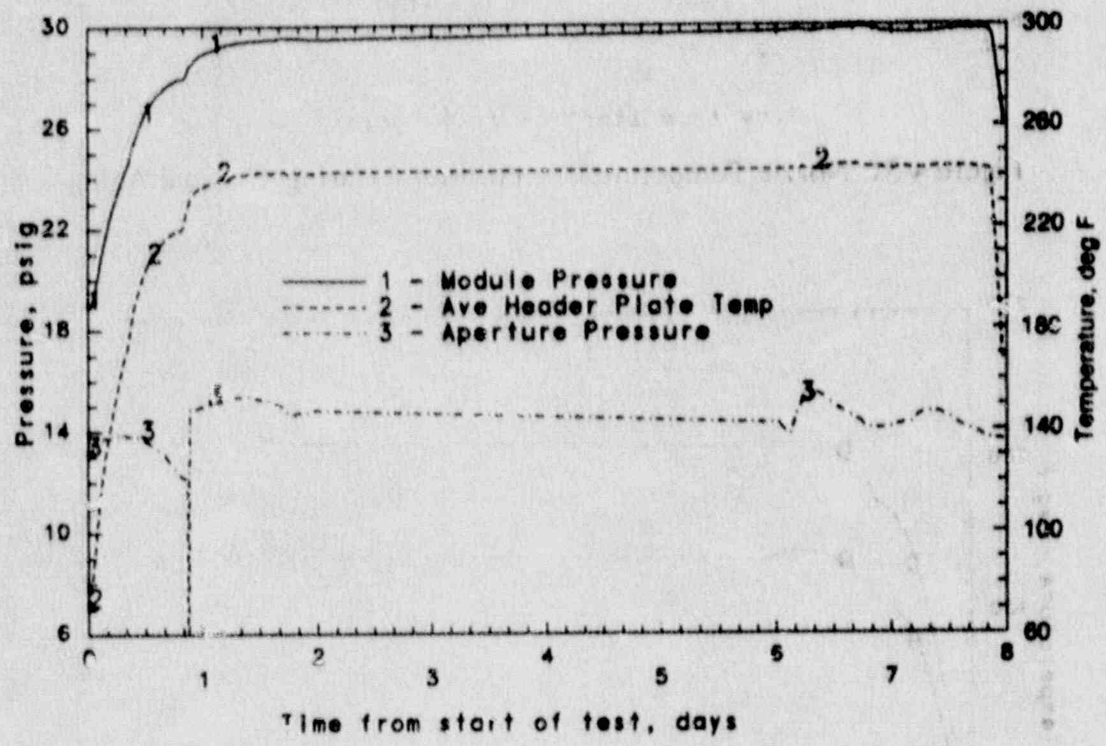


Figure 4-33 Monitoring Space Pressure Histories During Thermal Aging

Figure 4-34 Damage to Triax Cable After Thermal Aging

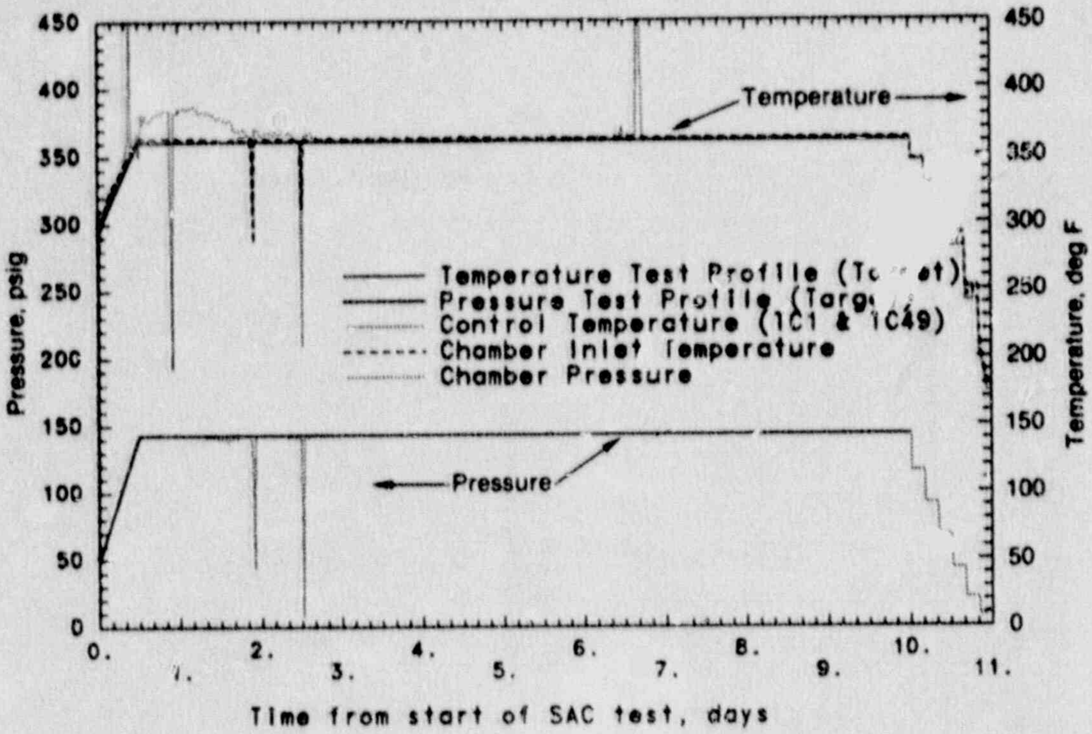


Figure 4-35 SAC Test Pressure and Temperature Profiles

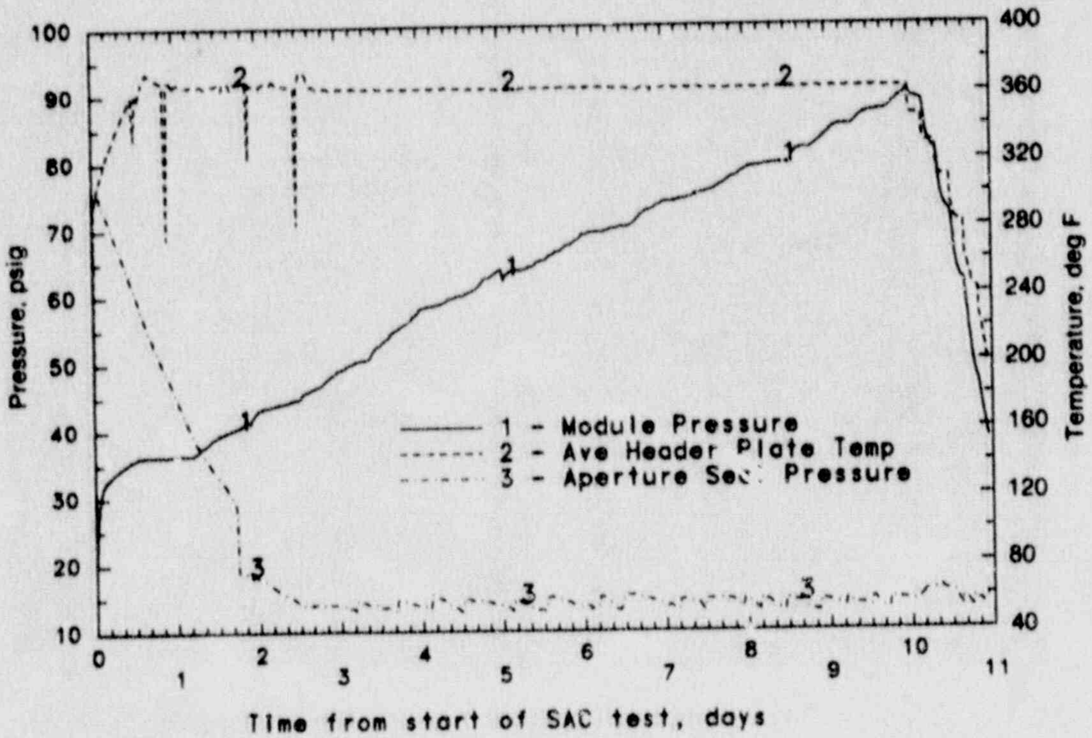


Figure 4-36 Monitoring Space Pressure Histories During the SAC Test

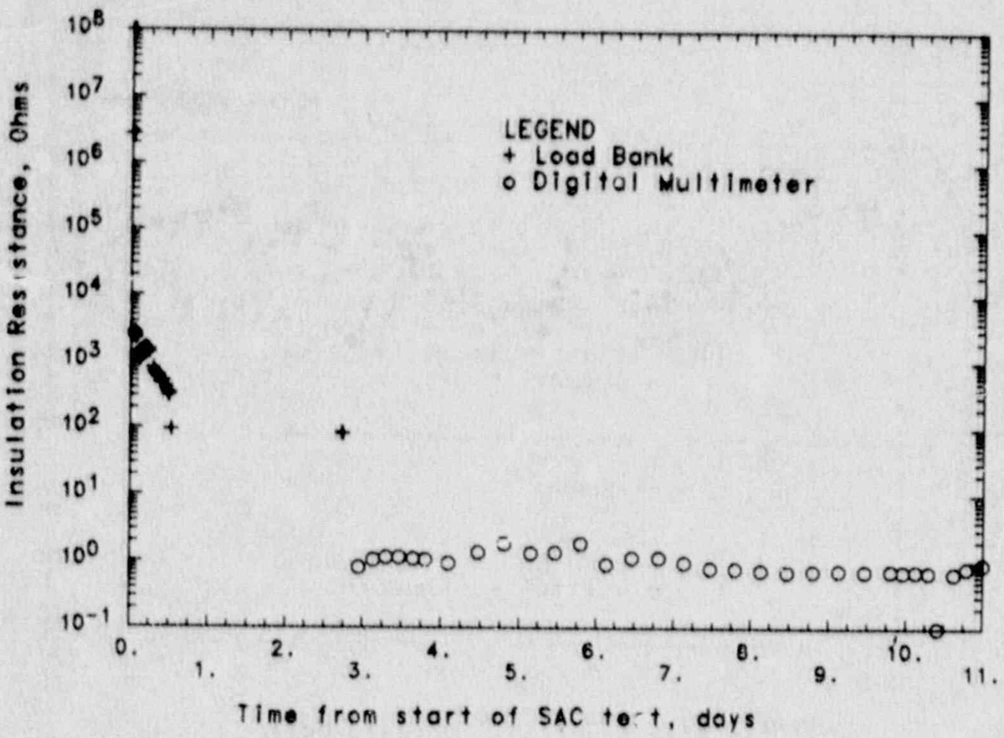


Figure 4-37 Insulation Resistance for Module 19, Position 8, Coax Cable

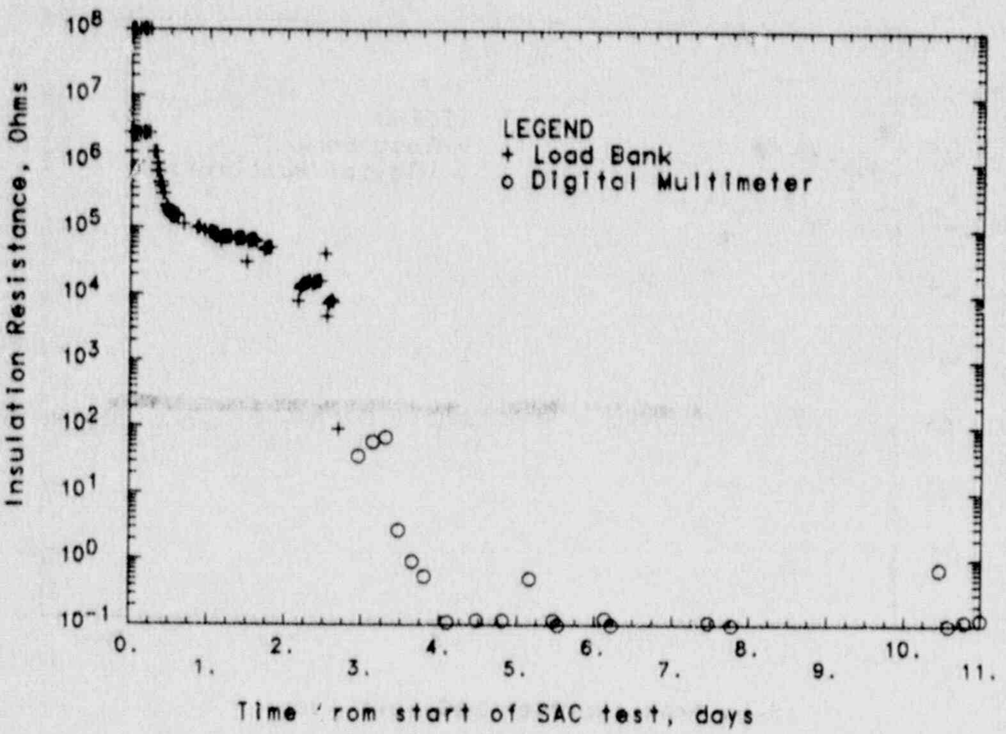


Figure 4-38 Insulation Resistance for Module 19, Position 8, #16 Cable

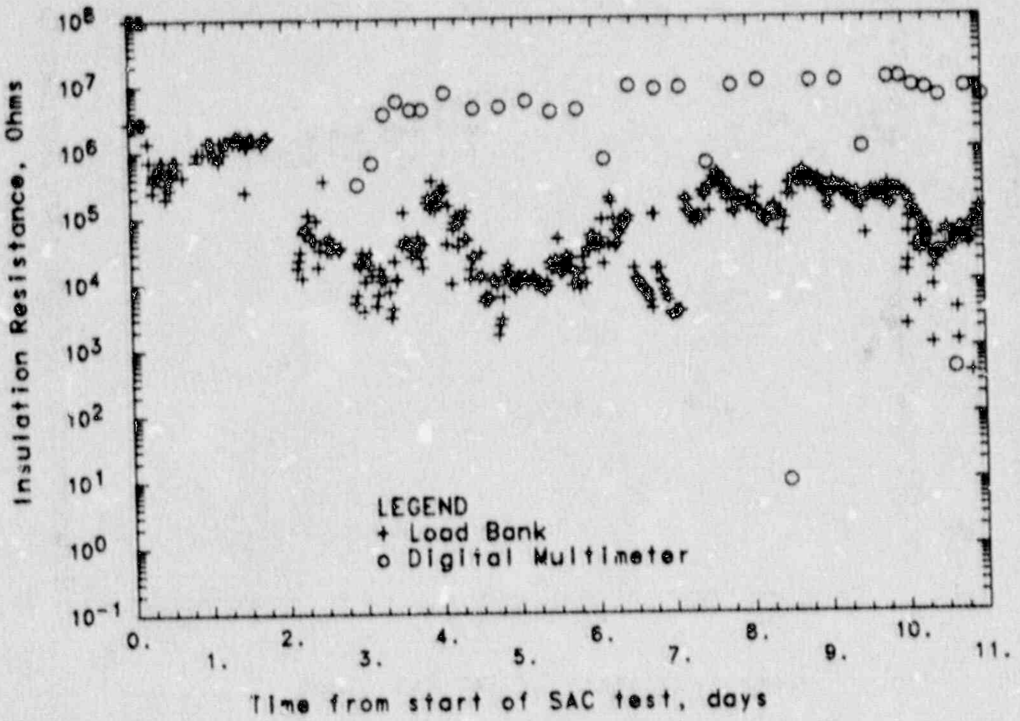


Figure 4-39 Insulation Resistance for Module 13, Position 4, #12 Cable

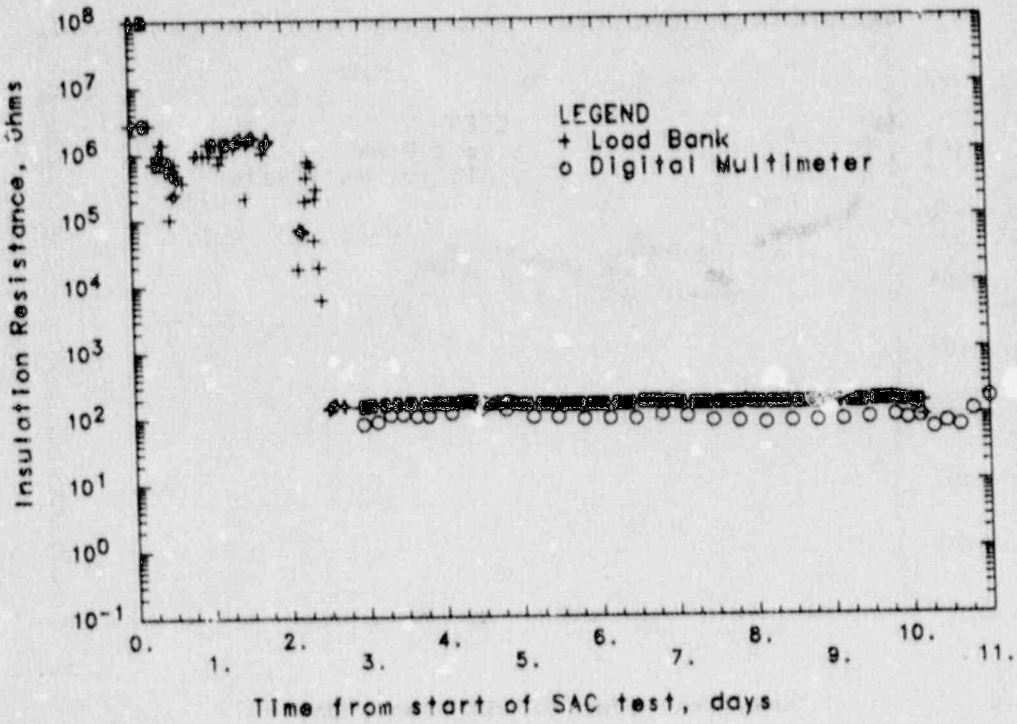


Figure 4-40 Insulation Resistance for Module 13, Position 7, #12 Cable

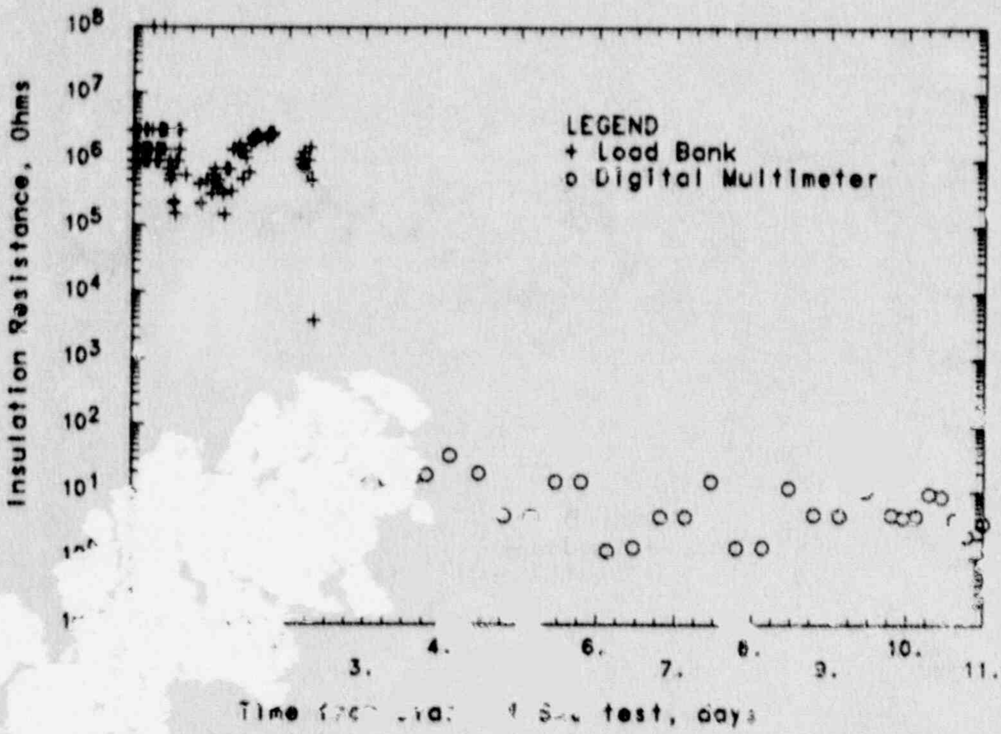


Figure 4-41 Insulation Resistance for Module 16, Positions 5 and 6, #16 TC Cable

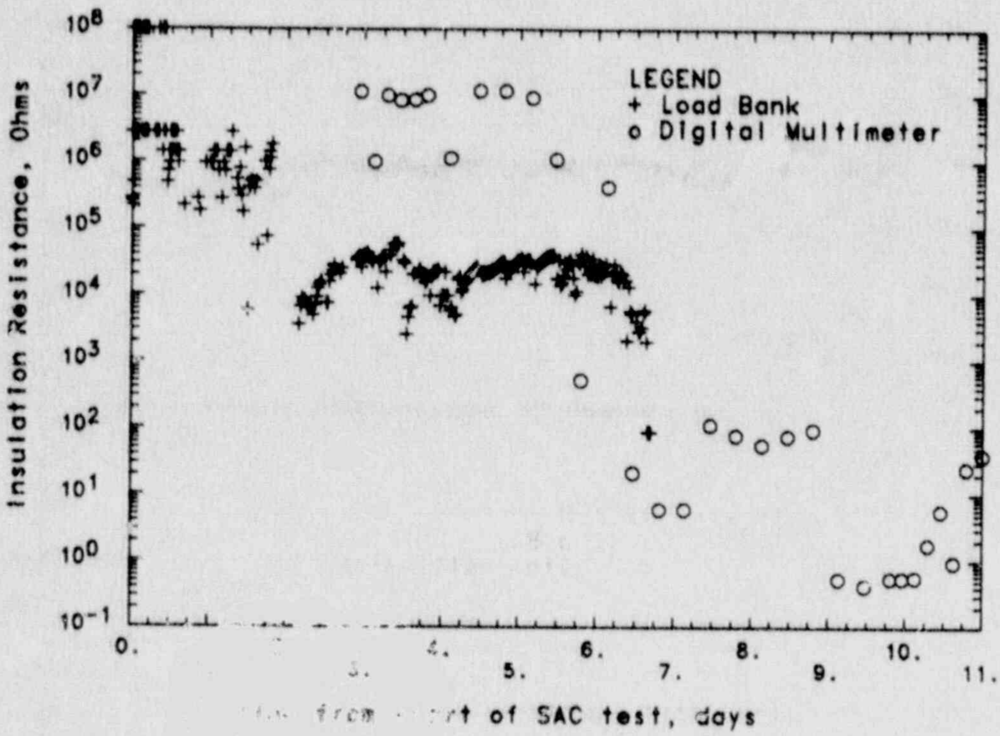


Figure 4-42 Insulation Resistance for Module 6, Positions 2 and 9, Triax Cable

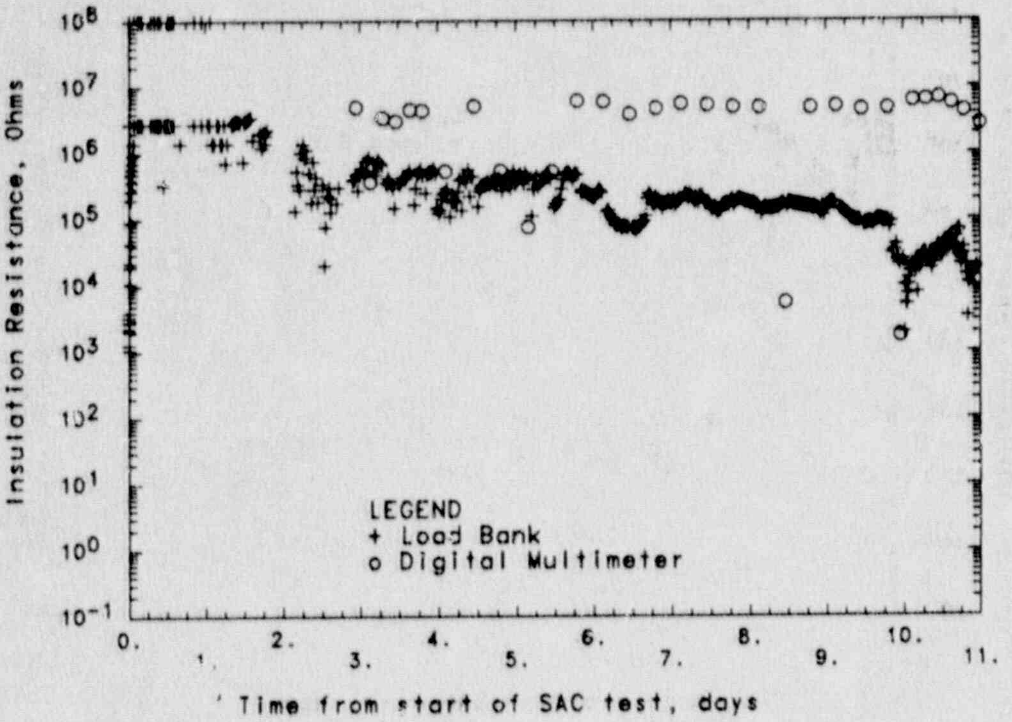


Figure 4-43 Insulation Resistance for Module 2, Positions 3 and 10, #2/0 Cable

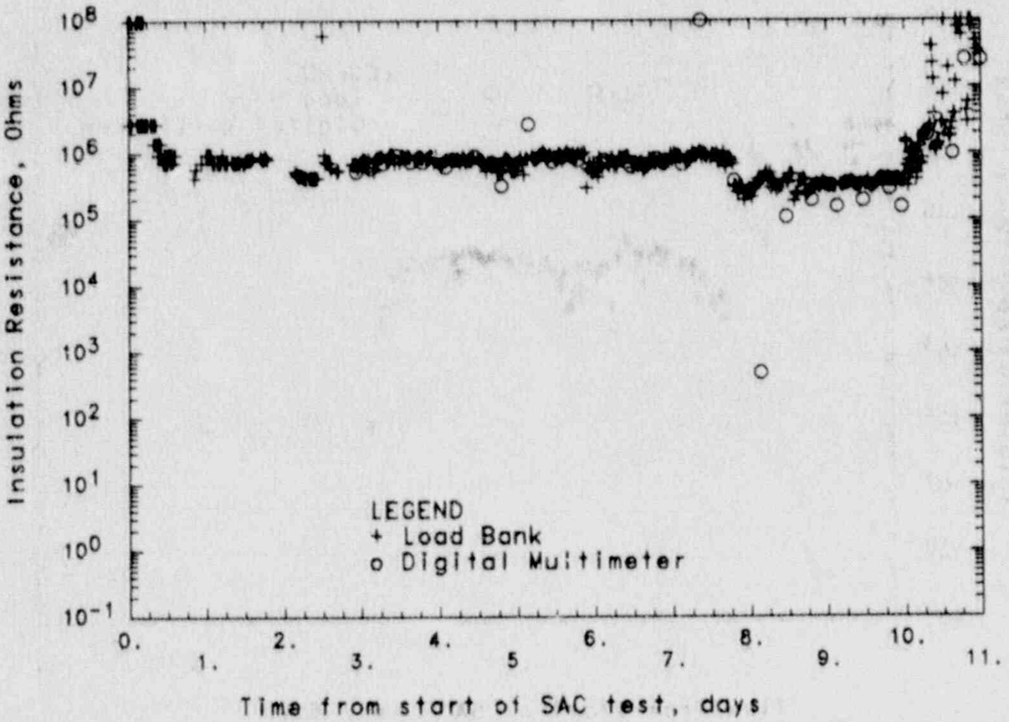


Figure 4-44 Insulation Resistance for Module 45, Position 1, 1000 mcm

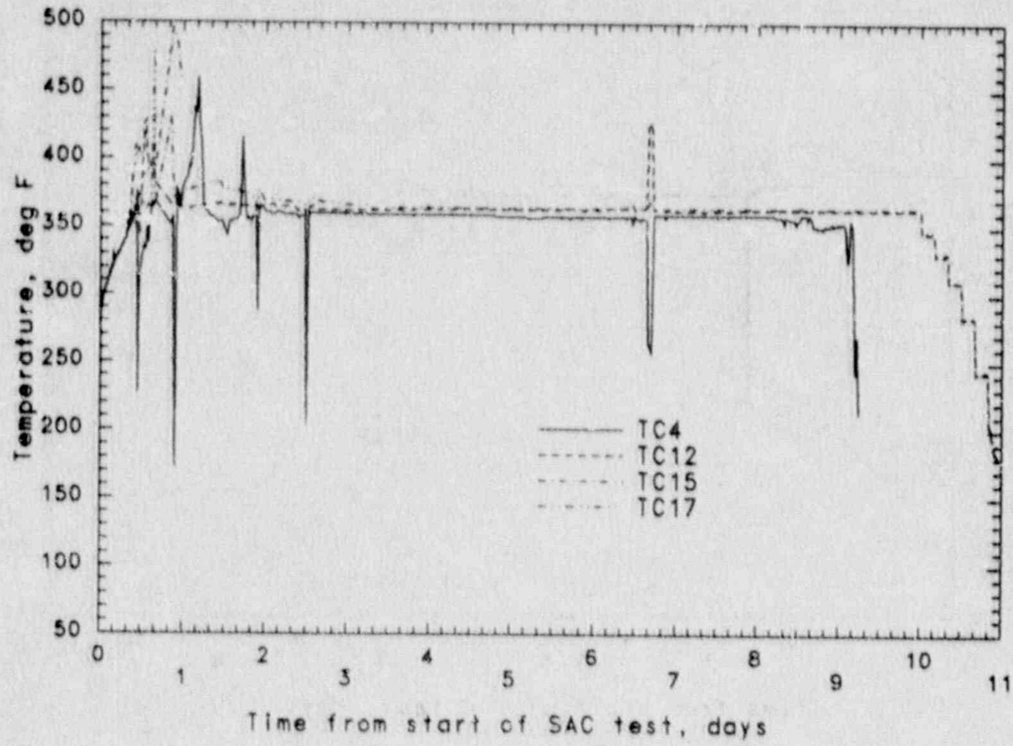


Figure 4-45 SAC Test Data from Thermocouples on Top Inside of Junction Box

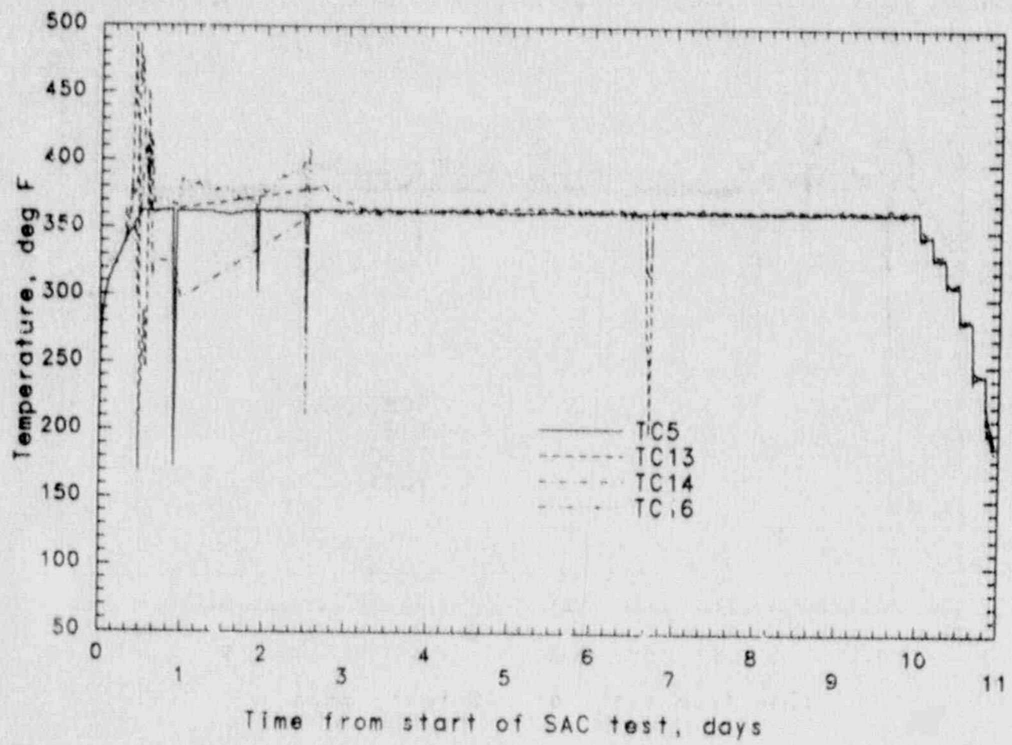


Figure 4-46 SAC Test Data from Thermocouples on Bottom Inside of Junction Box

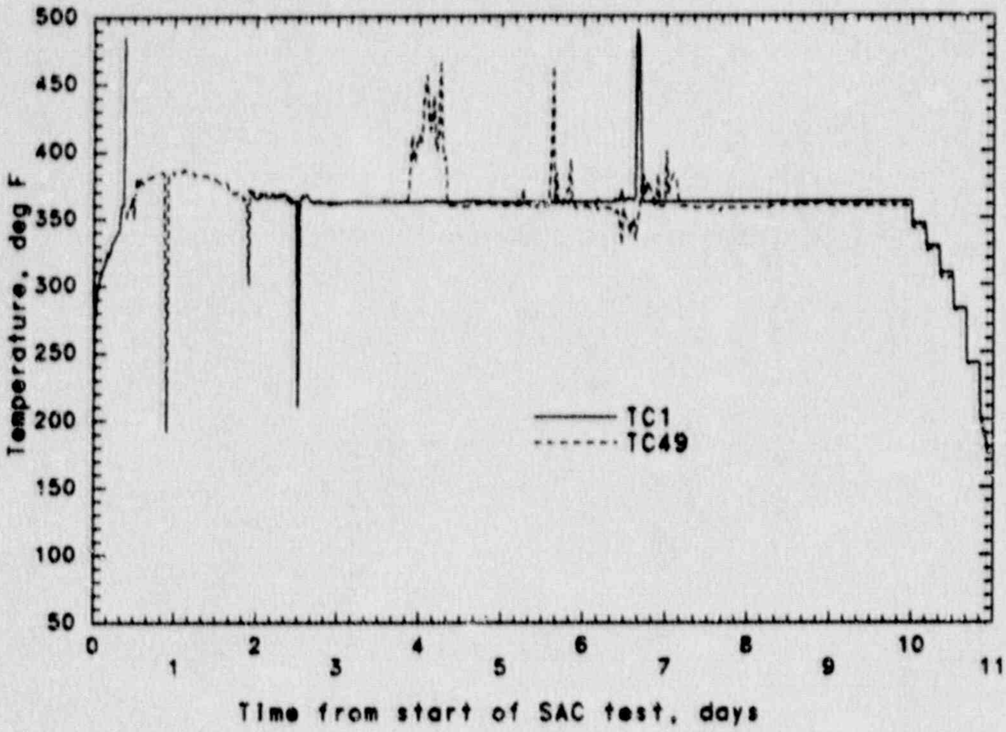


Figure 4-47 SAC Test Data from Thermocouples at Center Inside of Junction Box (In Steam)

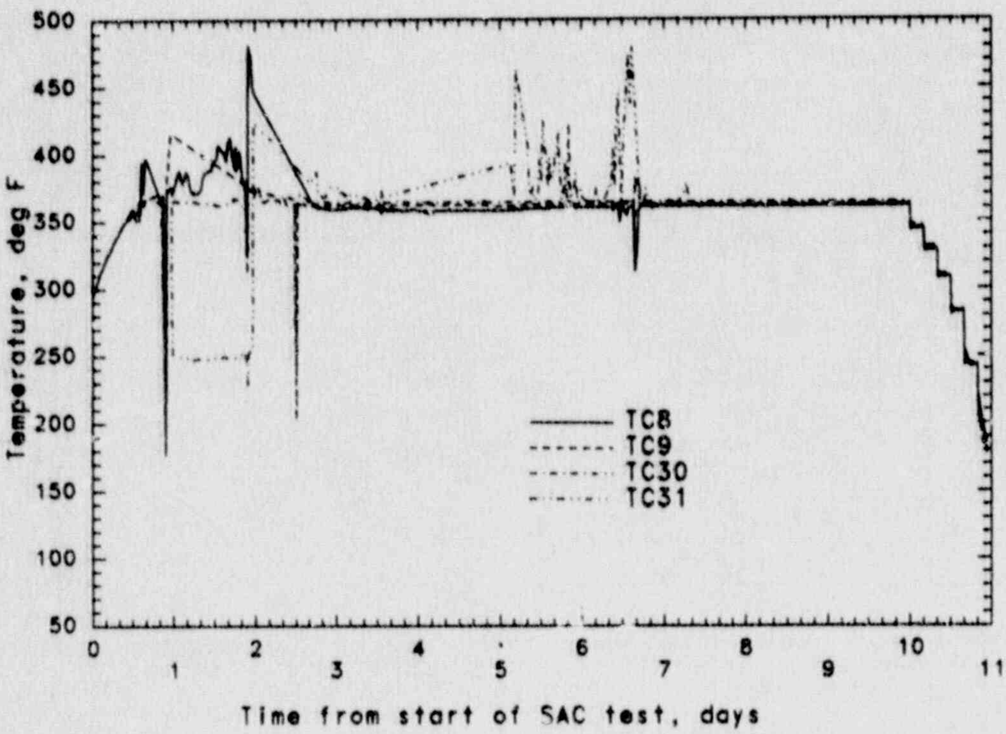


Figure 4-48 SAC Test Data from Thermocouples on Top Outside of Junction Box

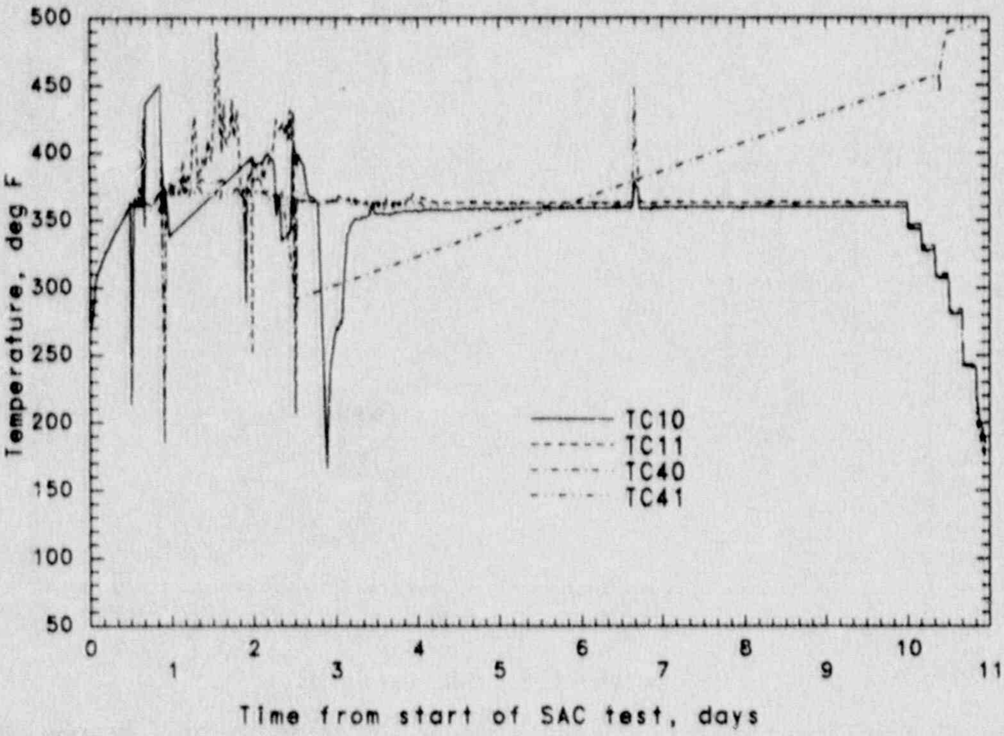


Figure 4-49 SAC Test Data from Thermocouples on Bottom Outside of Junction Box

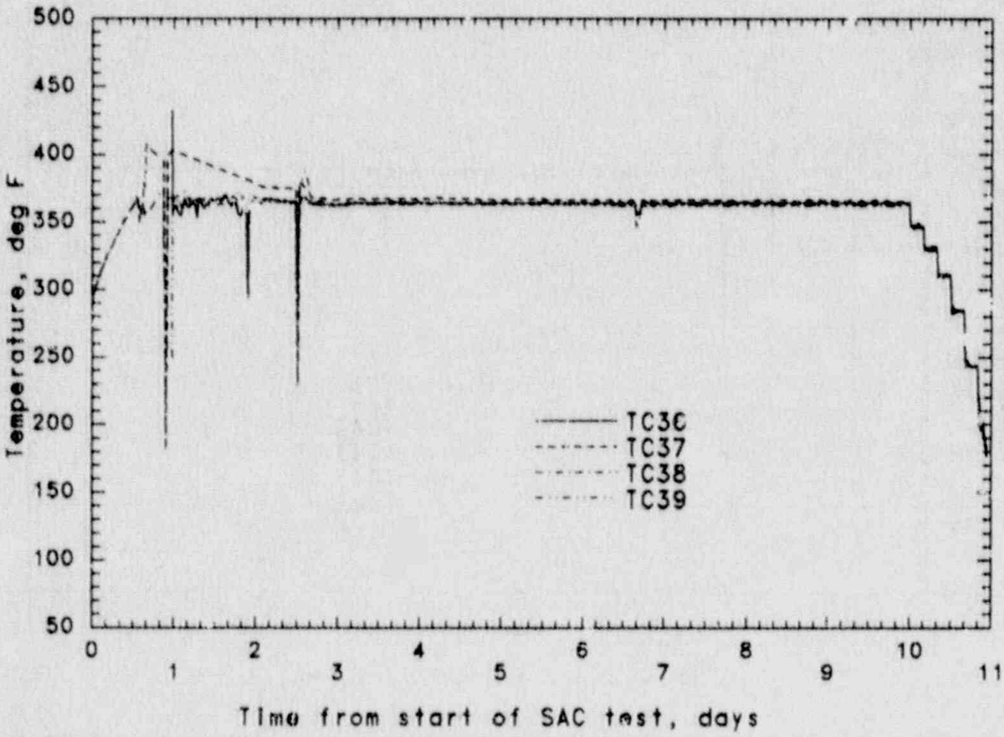


Figure 4-50 SAC Test Data from Thermocouples on North Side Outside of Junction Box

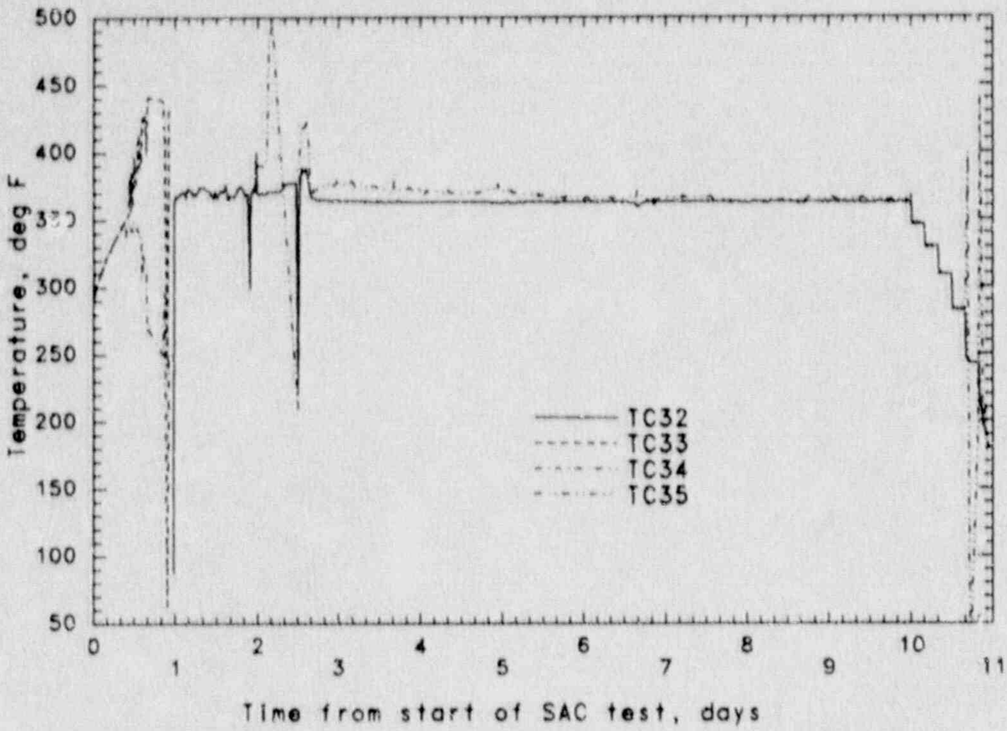


Figure 4-51 SAC Test Data from Thermocouples on South Side Outside of Junction Box

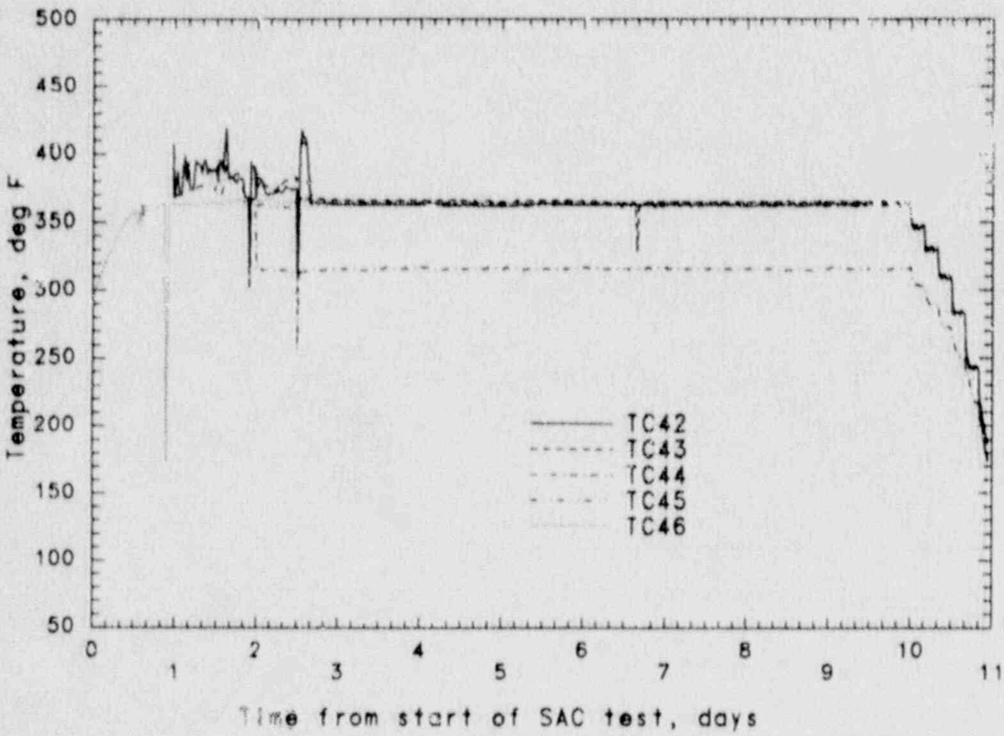


Figure 4-52 SAC Test Data from Thermocouples on West Side Outside of Junction Box

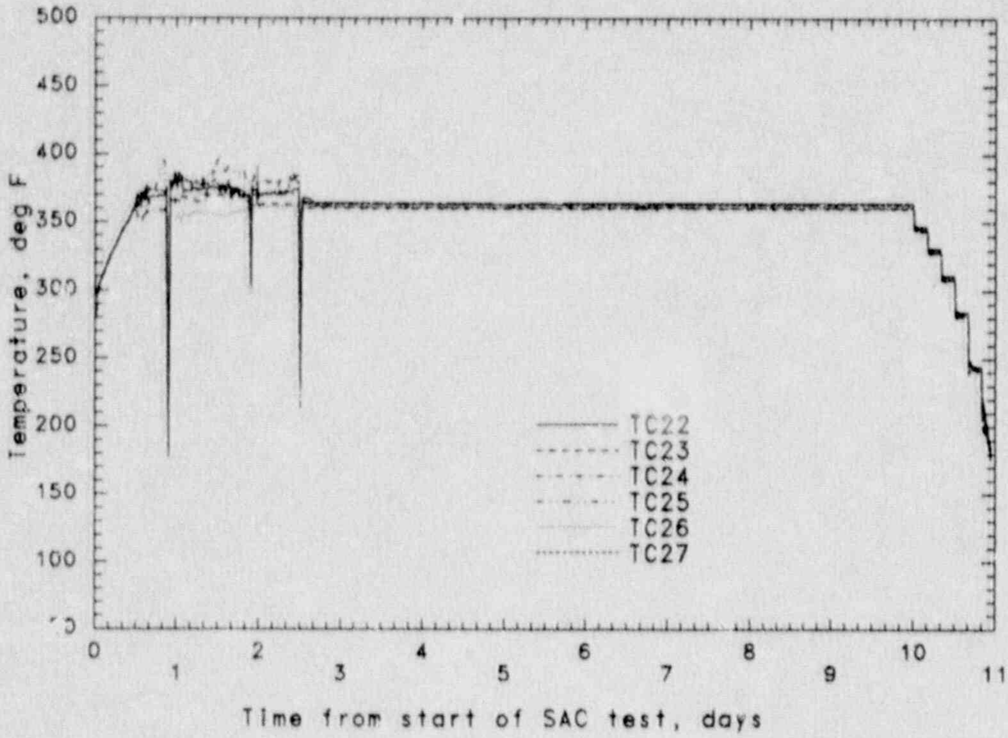


Figure 4-53 SAC Test Data from Thermocouples Near Mounting Plate

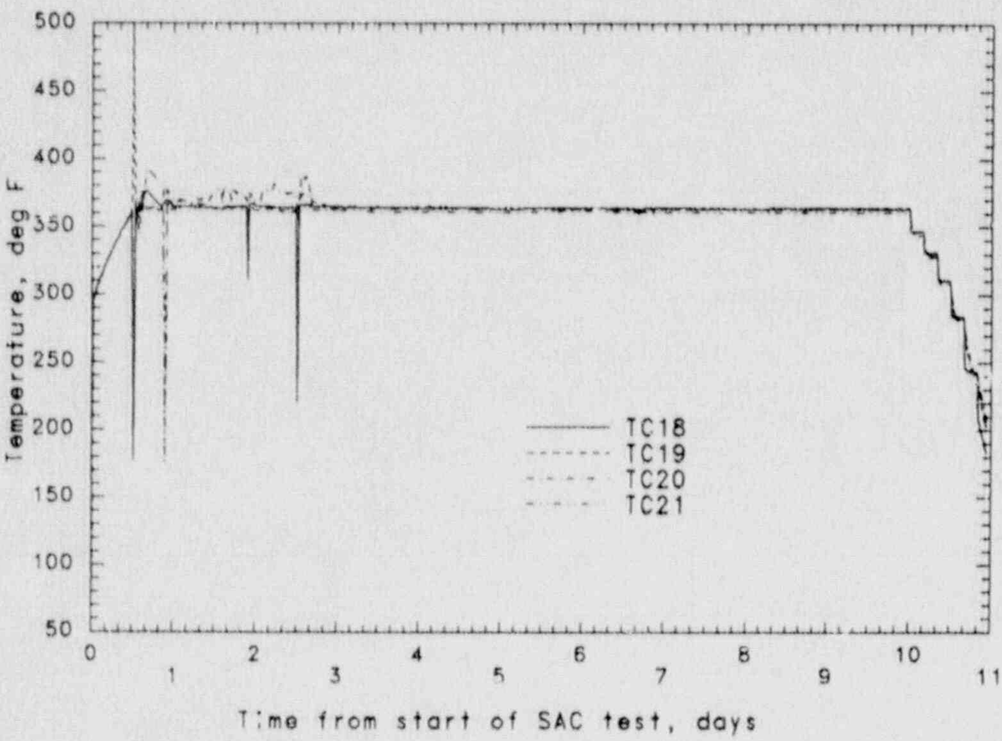


Figure 4-54 SAC Test Data from Thermocouples on Header Plate

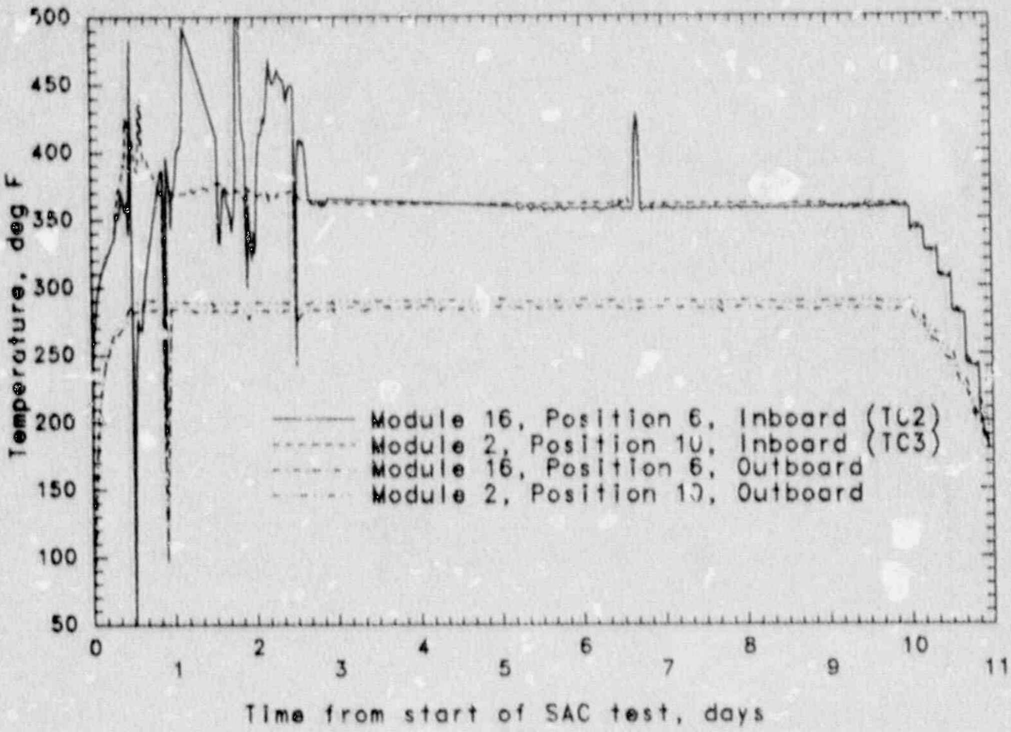


Figure 4-55 SAC Test Data from Thermocouples on Module Connectors

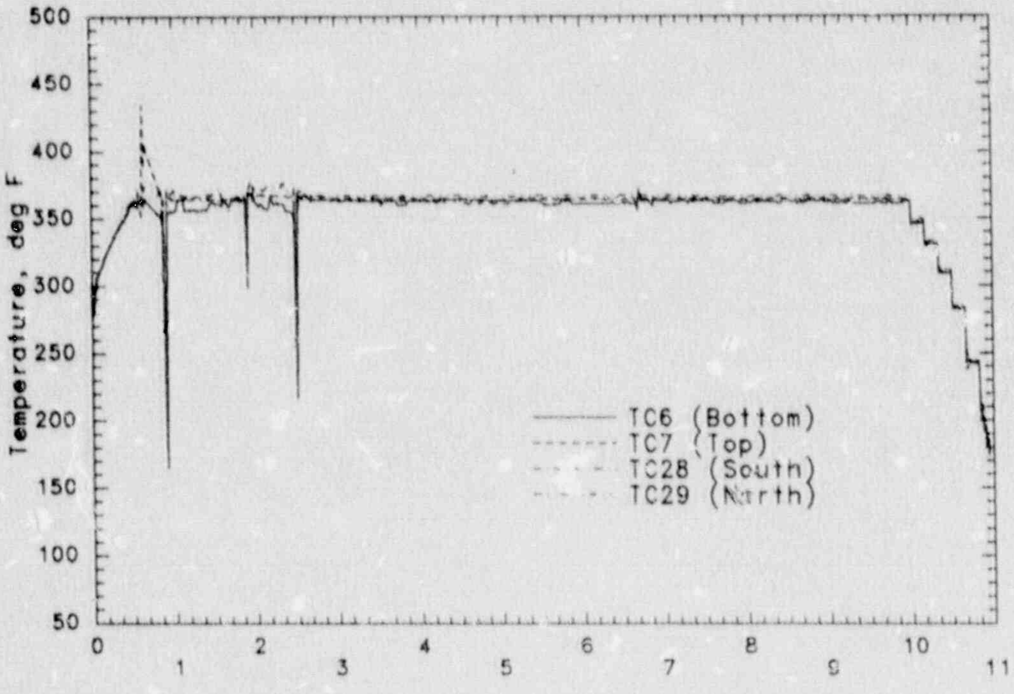


Figure 4-56 SAC Test Data from Thermocouples on Weldneck Flange

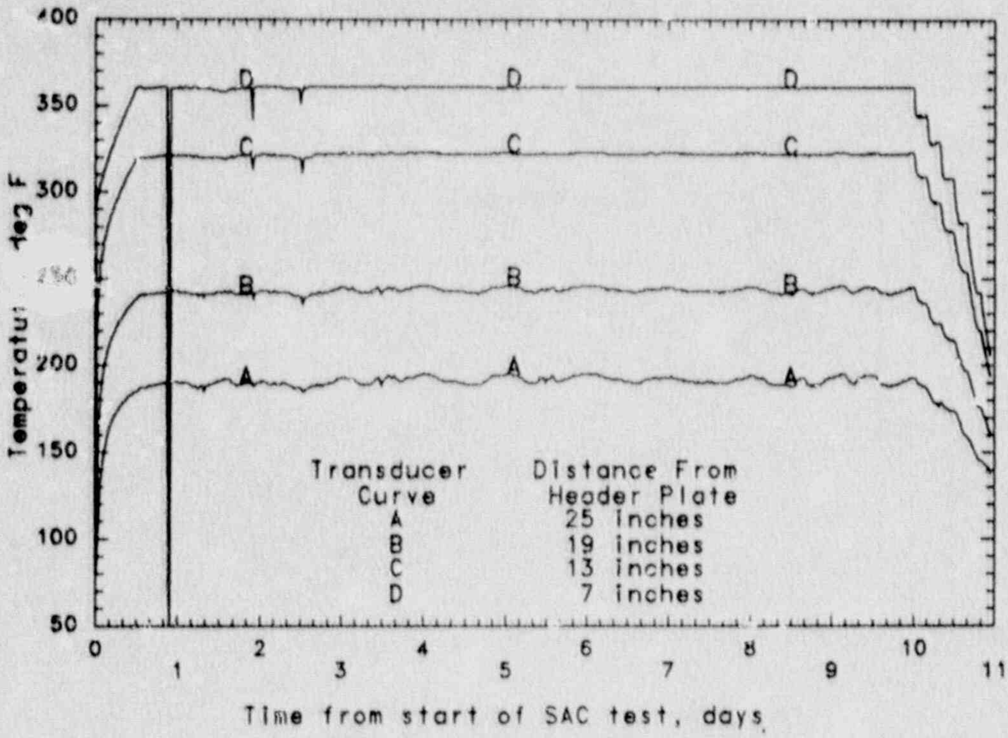


Figure 4-57 SAC Test Data from Thermocouples on Nozzle at Position 1

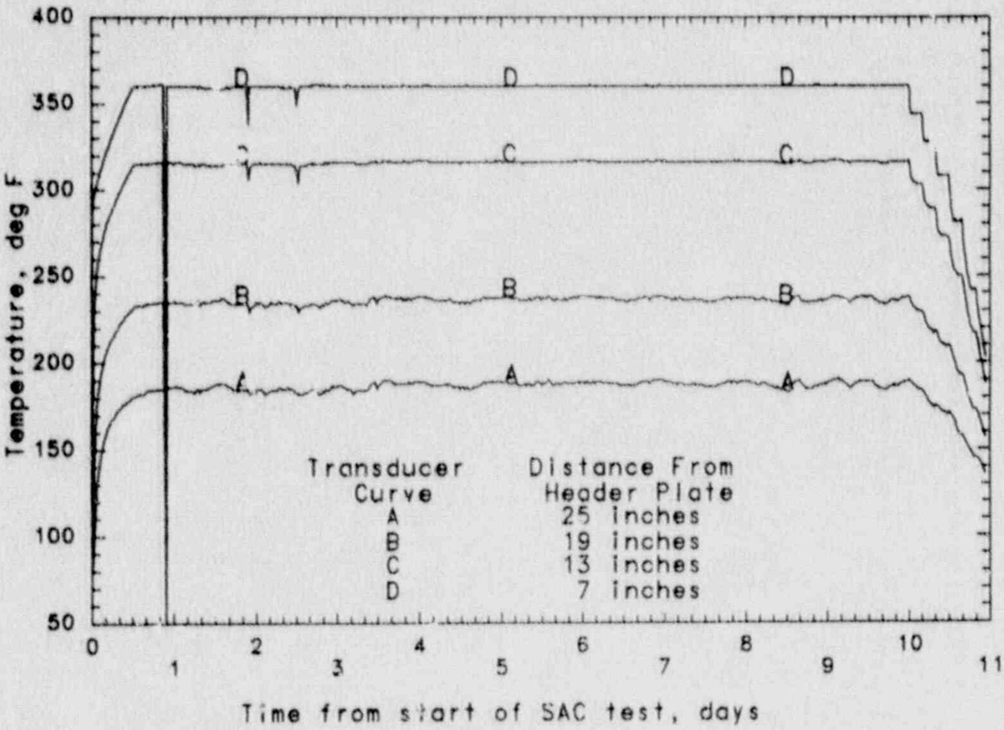


Figure 4-58 SAC Test Data from Thermocouples on Nozzle at Position 2

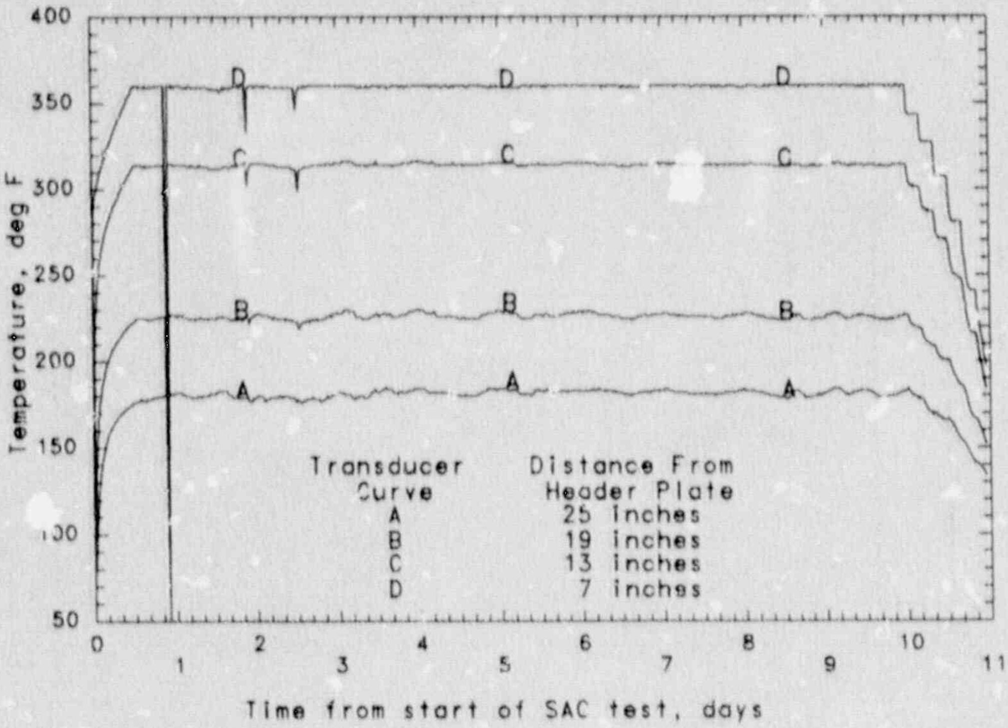


Figure 4-59 SAC Test Data from Thermocouples on Nozzle at Position 3

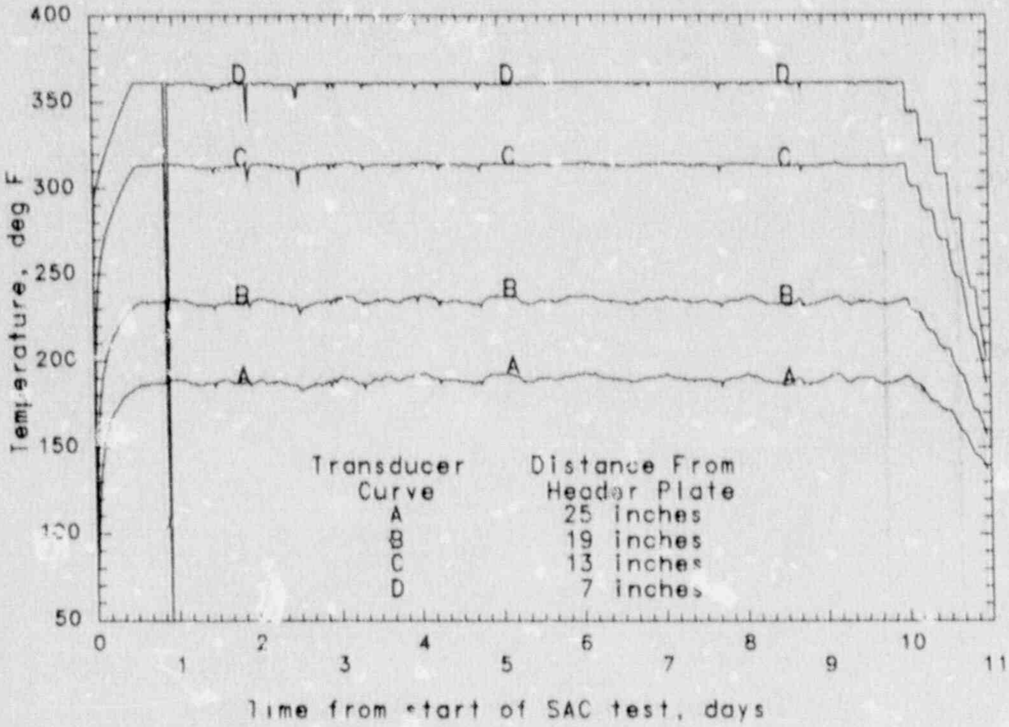


Figure 4-60 SAC Test Data from Thermocouples on Nozzle at Position 4

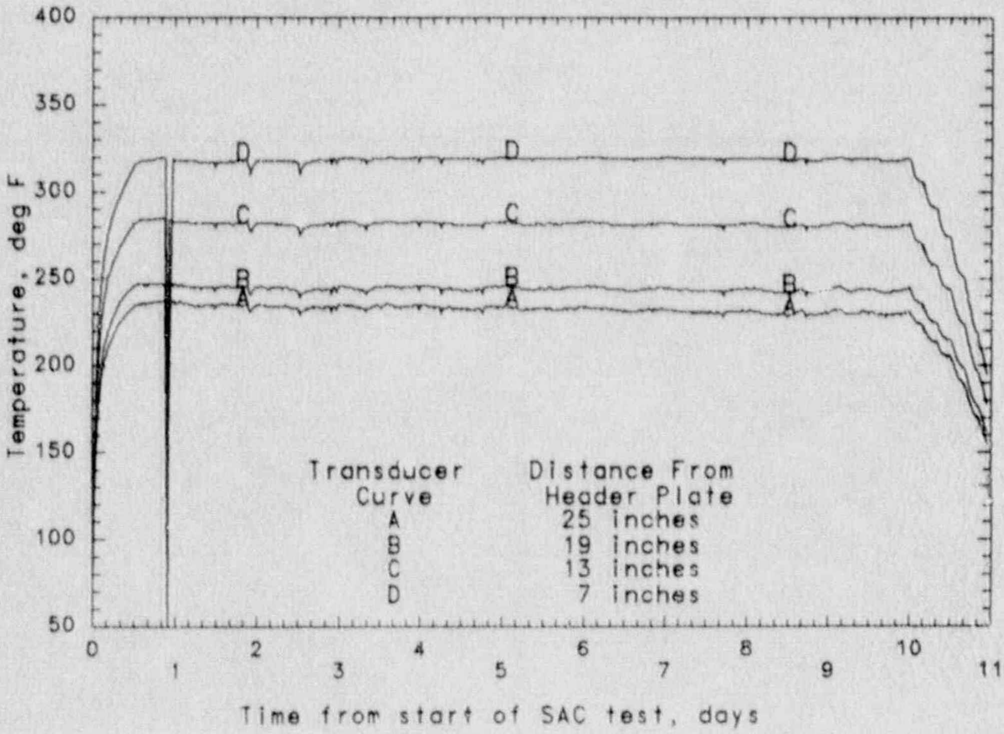


Figure 4-61 SAC Test Data from Thermocouples Along Nozzle Centerline (in Air)

Figure 4-62 Post-SAC Test : Damage to Triax Jacket and Thermocouples

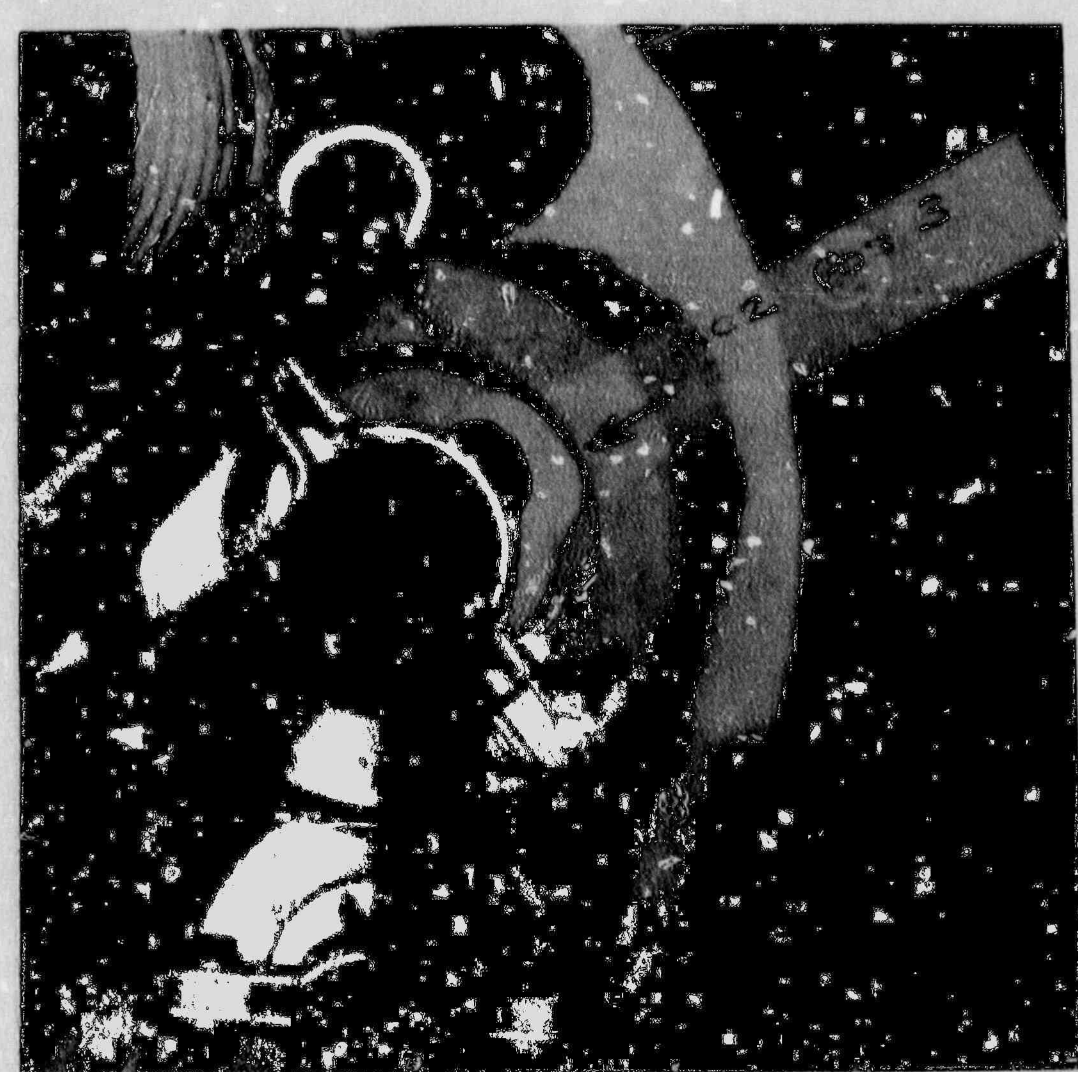


Figure 4-63 Post-SAC Test : Material Extruding from M02 Connector

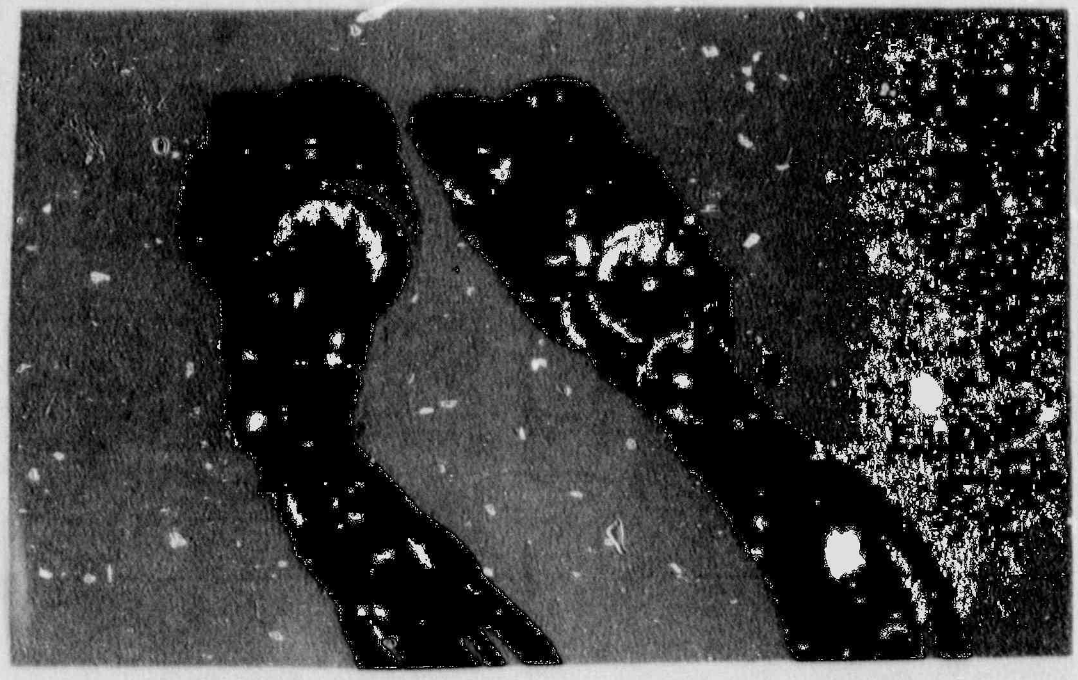


Figure 4-64 Post-SAC Test : M16 Connectors with Extruded Material

Figure 4-65 Post-SAC Test : Signs of Moisture Intrusion on M16 Connectors

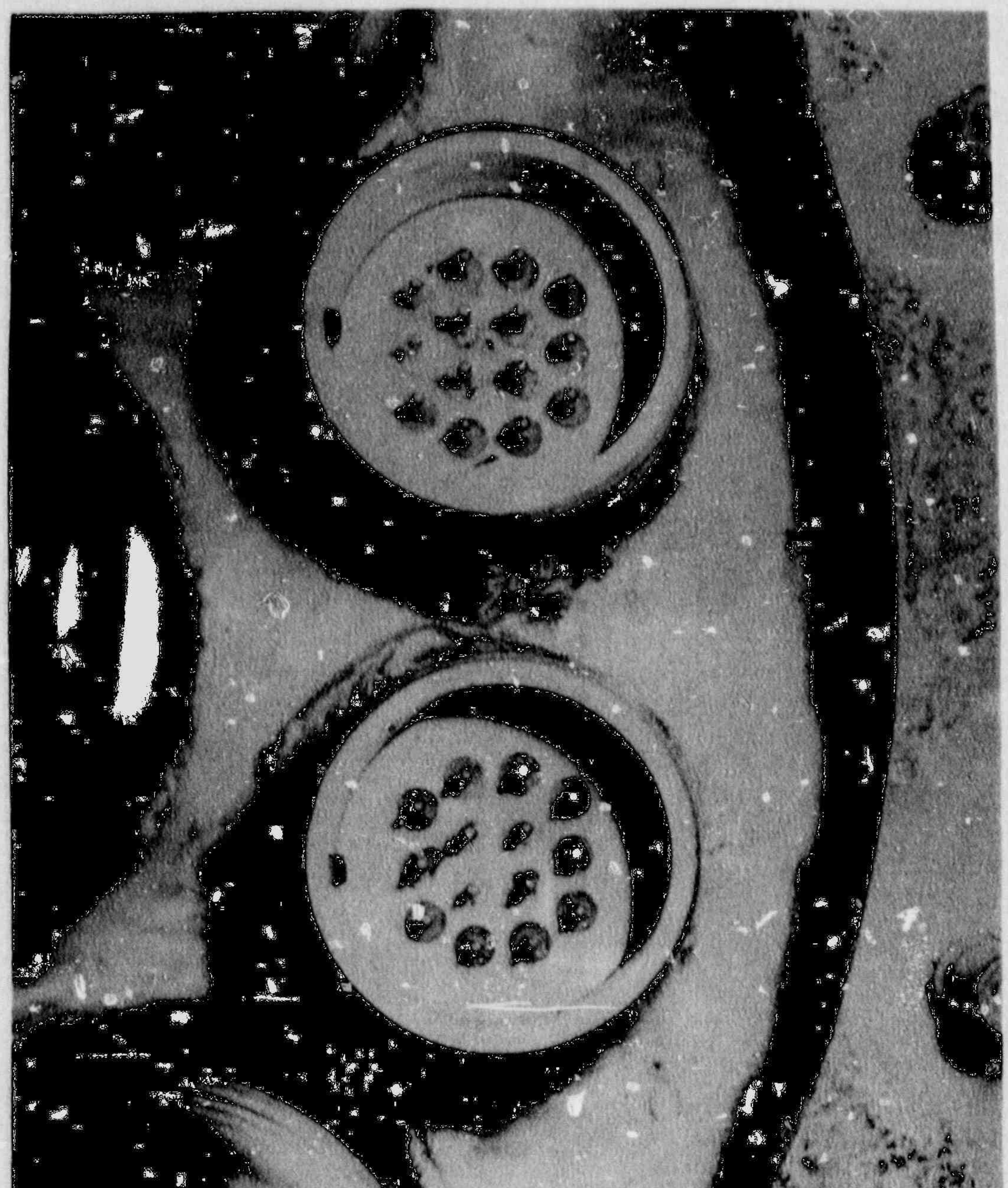


Figure 4-66 Post-SAC Test : Contaminants Around Pins of M16 Modules

Figure 4-67 Post-SAC Test : Contaminants Around Pins of M19 Module

Westinghouse
EPA

1

IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6″

1

IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

1

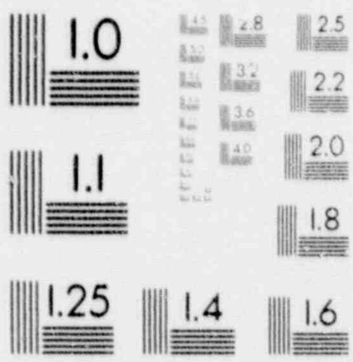
IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6″

1

IMAGE EVALUATION TEST TARGET (MT-3)



150mm

6"

5.0 WESTINGHOUSE EPA[9]

5.1 Design and Certification

The design of the Westinghouse EPA tested in this program was similar to that used in BWR Mark III plants such as Phibbs Bend and Stride nuclear power plants. The EPA was a Low Voltage Penetration Assembly with three modules, which represented a typical cable mix for power, control, and instrumentation functions. The qualification standards were IEEE 317-1976 and IEEE 323-1974.

The EPA, shown schematically in Figure 5-1, consisted of five major components: a header plate, three electrical penetration modules, a standard 12 in. weldneck flange, the nozzle (fabricated from 12 in. Sch 80 pipe), and a junction box on the inside end. The weldneck flange, which is not shown in Figure 5-1, was used to connect the nozzle and header plate rather than a field weld. The nozzle and weldneck flange used in the test on the Westinghouse EPA were the same ones used in the test of the D. G. O'Brien EPA.

The header plate was attached to the weldneck flange with twelve 7/8 in. SAE Grade 8 nuts and bolts, which were torqued in six equal increments to a final value of 300 ft-lbs. Two silicone O-rings were used to maintain a seal between the header plate and the weldneck flange, which were located on the inside containment end of the EPA. The annular area between the two O-rings was pressurized to 15 psig with nitrogen gas and the pressure was monitored to check leak integrity.

A junction box with overall dimensions of 22 x 22 x 24 in. deep was installed on the inside containment end of the penetration assembly. The junction box was bolted to the header plate using eight 1/2 in. hex head bolts, which were torqued to a final value of 40 to 50 ft-lbs. As is normally the case (to facilitate cable installation and to allow direct access to connectors), the junction box was removable and an access cover was provided. The access cover made it much easier to inspect the cables and modules during the various stages of the test sequence. The junction box was not designed to be leak-tight.

The EPA nozzle and its connection to the slip-on flange and mounting plate, Figure 5-2, approximated the heat sink for the EPAs that were designed for use in the Stride and Phibbs nuclear power plants. The nozzle was not insulated in any manner for the test. A typical EPA arrangement for the Stride design is shown in Figure 5-3. The test setup models only the inner header plate and about 1/3 the total nozzle length of the arrangement in Stride. However, this was sufficient to give a representative test of the primary EPA seals and the electrical performance of the cables. Also, note that the slip-on flange was attached to the nozzle approximately 8-1/2 in. from the interface of the header plate and the weldneck flange, whereas in Stride the containment wall was to intersect the nozzle about 10-1/2 in. from this interface. The same nozzle was used for the D. G. O'Brien EPA and the Westinghouse EPA tests in order to reduce costs, and thus the distance between the interface and the slip-on flange represents a compromise for these two designs.

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9. Mention of specific products and/or manufacturers in this document implies neither endorsement or preference nor disapproval by the U.S. Government, any of its agencies, or Sandia Corp., of the use of a specific product for any purpose.

There were three modules included in the Westinghouse EPA: a Type 813, serial number 852200; a type 801, serial number 852201; and a Type 814, serial number 852202. Each module was inserted into a socket in the header plate and held in place with clamps, as shown in Figure 5-4. Two sets of silicone O-rings (total of four) were used to maintain a seal between each module and the header plate. Insertion of a module automatically connected it to the leakage monitoring system for the header-module seal. The wires were sealed in the modules through a proprietary system that uses different epoxy compounds to seal the wires and support the conductors.

The EPA was prewired by Westinghouse using nuclear qualified cable. A net series circuit was created for each wire size by looping the outboard and inboard ends with cables 1 foot in length. Two cables of each wire size, both 25 feet in length, exited the test chamber through a cable seal system developed by Sandia to prevent neck-down problems and degradation due to high temperatures. The cables used in each module are listed in Table 5-1. The #16 AWG ITT Suprenant type KX cables in Modules 1 and 2 were joined together to form a net series circuit. With this one exception, all other loops were completed within a single module, resulting in a total of five cable loops and eight circuits (three of the loops were made up of cables with two conductors).

Table 5-1
Cables Used in the Westinghouse EPA

Module	Wire Manufacturer	Wires per Module	Insulation	Wire Size	Number of Conductors
1/801	Okonite	16	Okonite/Okolon	#2 AWG	1
1/801	ITT Suprenant	1	XLPE/Hypalon	#16 AWG	2 Type KX
2/813	Raychem Flamtrol	50	XLPE	#14 AWG	1
2/813	ITT Suprenant	1	XLPE/Hypalon	#16 AWG	2 Type KX
3/814	Rockbestos	10	XLPE/XLPE	#16 AWG	2
3/814	ITT Suprenant	10	XLPE/Hypalon	#16 AWG	2 Type EX

5.2 Test Preparations and Procedures

Test Overview

The primary purpose of this test was to generate engineering data to evaluate the leak behavior of the EPA under severe accident conditions. As a secondary effort, the electrical degradation of the EPA cables was observed by monitoring the insulation resistance (IR). The test profile for the Westinghouse EPA was representative of the severe accident conditions (SAC) in a boiling water reactor

(BWR) Mark III containment with steam at 75 psia and 400°F. Prior to the SAC test, the EPA was irradiated and thermally aged.

Since this was not considered a qualification or a verification test, there was no pass/fail criteria. The effects of chemical sprays, seismic loading, fault currents, preload pressure cycling, thermal cycling, and operating the cables at rated current and voltage were not addressed. The EPA was not subject to the normal LOCA qualification test profile prior to the SAC test. It must be emphasized that the SAC test is much more severe than the LOCA test.

The significant dates in the test sequence (in 1985) were:

Initial Inspection and Baseline Measurements	July 17-31
Assembly and Instrumentation	September 16-20
Radiation--200 Mrad dose (air)	September 26 - October 4
Inspection and IR measurement	November 4-15
Thermal Aging--300°F for 100 hours	November 18-22
Inspection and IR measurement	November 25-27
Air Leak Test at 60-100°F and 70-80 psia	November 27
Severe Accident Test (steam)	December 2-12
Staircase Rampdown	December 12
Air Leak Test at 60-100°F and 70-80 psia	December 13
Inspection and IR measurement	December 13-16

<u>Test Equipment</u>

The SAC loads were applied in an environmental chamber, which was modified to accept the EPA fixture as shown in Figure 5-2. The boiler in conjunction with an accumulator was capable of delivering 245 lbm/sec of steam at 200 psig and 388°F.

Pressure gages connected to lines to the O-ring aperture seal and the modules were monitored to detect leakage into the gap between the two O-rings on the header plate and into the modules, respectively. However, these systems monitor leak-integrity of components of the EPA; failure of these components does not necessarily indicate a loss of containment integrity. Therefore, a system to measure the total leakage to outside of the containment boundary was developed.[10] Leakage past the EPA must flow into the chamber formed by the EPA nozzle where it would then be piped through condensing equipment. The measurement technique relies on measuring condensate over a known period of time. This system proved accurate and reliable for the range of approximately 1 scc/sec to 10,000 scc/sec. Since leakage past the EPA was not detected during the steam (SAC) test, details of this measurement system are not included in this report.

Twenty-two thermocouples were installed inside the nozzle before radiation aging, including 16 intrinsic thermocouples. As indicated in Figure 5-5, the intrinsic

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10. This system has been documented in a draft report available in the NRC PDR by J. W. Grossman, F. V. Thome, and G. M. Dibisceglie, "Flow Measurement Techniques for Evaluating Leak Behavior Through Electrical Penetration Assemblies Under Severe Accident Conditions," Sandia National Laboratories, Albuquerque, NM, February 1987.

thermocouples were installed along the length of the nozzle at positions approximately 7, 13, 19, and 25 in. from the sealing surface of the weldneck flange. At each axial position, four intrinsic thermocouples were placed 90° apart on the inside surface of the nozzle. In addition, four type K thermocouples were located along the axial centerline of the nozzle approximately 7, 13, 19, and 25 in. from the weldneck flange in order to measure the air temperature. Two thermocouples were attached to the module at position 3; one near the header plate and the other at the inside end.

Before thermal aging, an additional 52 type K thermocouples were installed on the inside and outside of the junction box, on the header plate, the weldneck flange, and on the modules as shown in Figure 5-6.

Each circuit, also referred to as a current loop, was matched with a separate electrical power supply and a monitoring circuit, which are collectively referred to as the load bank. There were 8 current loops from the five cable loops since three of the loops had cables with two conductors. By observing the voltage drop in the monitoring circuit, the insulation resistance and continuity of each cable circuit could be determined, as described later in this section. A direct current of 1/2 amp from the 28 volt power supply was maintained on all cables throughout thermal aging (but not radiation aging) and during the severe accident condition test. A wiring schematic for the load bank is shown in Figure 5-7. The output from the monitoring circuit was recorded on an automatic datalogger.

In addition, insulation resistance was measured at 50 to 500 VDC several times per day with a Hippotronics Megohmmeter to back up and check the continuously recorded data. A Digital Multimeter was used to measure the conductor resistance and also to measure the insulation resistance if the insulation resistance measured with the Hippotronics Megohmmeter was less than 0.1 MΩ at 50 VDC.

Initial Inspection

The Westinghouse EPA was received at Sandia in July 1985; inspection and baseline measurements were made from July 17 through July 31. Nothing unusual was found. Insulation resistance measurements were made with the Hippotronics Megohm meter and are tabulated in Tables 5-2 through 5-5 under the heading "Before Irradiation".

The header-module seal volume was pressurized to 30 psig with nitrogen gas and a leak test was performed. Using Equation A-1 (in Appendix A), the leak rate was found to be $1x10^{-6}$ scc/sec).

The header plate and weldneck flange surfaces were inspected for nicks and scratches (none were found) and then cleaned with acetone and alcohol. The O-rings supplied by Westinghouse were lubricated and installed in the appropriate grooves and the header plate was bolted to the weldneck flange. The aperture seal area was pressurized to 15 psig with bottle nitrogen and the leak rate for the O-ring aperture seal was determined to be ($2x10^{-4}$ scc/sec).

Table 5-2
Insulation Resistance Measurements for Westinghouse EPA

ITT Suprenant Type KX--#16 AWG, XLPE/Hypalon

		Red Conductor to Ground*		Yellow Conductor to Ground		Red to Yellow Conductor	
Before Irradiation		1.3E+11	H500	1.4E+11	H500	3.9E+11	H500
After Irradiation		7.0E+11	H500	6.0E+11	H500	3.2E+11	H500
Before Thermal Aging		1.8E+11	H500	1.9E+11	H500	3.5E+11	H500
Begin Thermal Aging		6.0E+08	H500	4.4E+08	H500	5.5E+08	H500
End Thermal Aging		1.5E+08	H500	1.4E+08	H500	1.4E+08	H500
After Thermal Aging		1.1E+11	H500	1.4E+11	H500	6.8E+11	H500
SAC Test							
Date	Hours						
Initial Reading		7.5E+12	H500	8.5E+12	H500	3.0E+12	H500
12/2	6	1.3E+08	H500	2.0E+08	H500	1.9E+08	H500
12/2	12	6.0E+06	H500	6.0E+06	H500	5.8E+06	H500
12/3	18	1.4E+06	H500	1.8E+06	H500	1.4E+06	H500
12/3	24	1.4E+06	H500	1.7E+06	H500	1.4E+06	H500
12/3	32	1.1E+06	H100	1.8E+06	H500	1.7E+06	H100
12/4	40	2.2E+06	H050	2.0E+06	H500	1.9E+06	H500
12/4	48	2.4E+06	H050	2.3E+06	H500	6.6E+05	H100
12/4	52	3.2E+05	H100	2.3E+06	H500	2.8E+05	H100
12/5	64	1.7E+04	DMM	2.6E+06	H500	2.7E+06	H500
12/5	76	4.5E+04	DMM	4.8E+06	DMM	3.0E+06	H500
12/6	88	5.5E+03	DMM	3.0E+06	H500	3.0E+06	H500
12/6	100	3.8E+02	DMM	2.9E+06	H500	3.0E+06	H500
12/7	112			2.9E+06	H500		
12/7	124			2.8E+06	H500		
12/8	136			2.9E+06	H500		
12/8	148			3.1E+06	H500		
12/9	160	1.8E+01	DMM	5.5E+01	DMM	8.7E+01	DMM
12/9	172	1.7E+01	DMM	6.2E+02	DMM	3.3E+02	DMM
12/10	185	2.7E+01	DMM	4.8E+02	DMM	4.3E+02	DMM
12/10	196	4.3E+01	DMM	1.2E+03	DMM	3.2E+06	DMM
12/11	208	4.7E+01	DMM	5.9E+04	DMM	9.8E+03	DMM
12/11	220	5.7E+01	DMM	5.3E+04	DMM	9.5E+04	DMM
12/12	232	6.7E+01	DMM	1.6E+05	DMM	1.5E+05	DMM
12/12	239	1.9E+01	DMM	1.4E+03	DMM	5.3E+02	DMM
12/12	243	6.0E+00	DMM	5.4E+02	DMM	3.5E+02	DMM
12/12	247	9.9E+00	DMM	1.2E+01	DMM	4.6E+00	DMM
12/13	268	9.8E+03	DMM	1.0E+04	DMM	1.2E+01	DMM

* The insulation resistance measurement techniques is indicated as follows: H500--Hippotronics Megohm meter at 500 V; H100--Hippotronics Megohm meter at 100 V; H050 Hippotronics Megohm meter at 50 V; DMM--Digital Multimeter.

Table 5-3
Insulation Resistance Measurements for Westinghouse EPA

ITT Suprenant Type EX--#16 AWG, XLPE/Hypalon

		Red Conductor <u>to Ground</u>		Purple Conductor <u>to Ground</u>		Red to Purple <u>Conductor</u>	
Before Irradiation		1.4E+11	H500	1.8E+11	H500	4.5E+11	H500
After Irradiation		3.5E+11	H500	3.0E+11	H500	1.9E+11	H500
Before Thermal Aging		4.1E+11	H500	5.8E+11	H500	4.1E+11	H500
Begin Thermal Aging		9.2E+07	H500	1.0E+08	H500	9.0E+07	H500
End Thermal Aging		4.2E+07	H500	4.8E+07	H500	3.6E+07	H500
After Thermal Aging		7.1E+10	H500	1.3E+11	H500	3.9E+11	H500
SAC Test							
<u>Date</u>	**<u>Hours</u>**						
Initial Reading		1.8E+12	H500	1.9E+12	H500	1.7E+12	H500
12/2	**6**	3.2E+07	H500	5.2E+07	H500	5.1E+07	H500
12/2	**12**	3.2E+06	H500	4.5E+06	H500	3.1E+06	H500
12/3	**18**	1.5E+03	DMM	1.5E+06	H500	2.0E+06	DMM
12/3	**24**	8.5E+05	DMM	1.2E+06	H500	1.2E+06	H500
12/3	**32**	9.0E+05	H100	1.2E+06	H500	1.3E+06	H500
12/4	**40**	1.0E+06	H500	1.2E+06	H500	1.3E+06	H500
12/4	**48**	1.1E+06	H500	1.3E+06	H500	1.1E+06	H500
12/4	**52**	1.2E+06	H100	1.3E+06	H500	1.1E+06	H100
12/5	**64**	1.1E+06	H100	1.3E+06	H500	1.4E+06	H500
12/5	**76**	1.2E+06	H500	1.5E+06	H500	1.3E+06	H500
12/6	**88**	1.3E+05	H050	1.4E+06	H500	1.5E+06	H500
12/6	**100**	3.0E+04	DMM	1.3E+06	H500	1.4E+06	H500
12/7	**112**	2.6E+04	DMM	4.5E+06	H100	8.2E+05	DMM
12/7	**124**	4.2E+06	DMM	8.3E+05	H100	1.0E+06	DMM
12/8	**136**			9.5E+05	H100		
12/8	**148**			1.5E+04	DMM		
12/9	**160**	1.7E+04	DMM	1.8E+04	DMM	4.3E+04	DMM
12/9	**172**	5.7E+03	DMM	1.7E+04	DMM	1.6E+04	DMM
12/10	**185**	9.2E+03	DMM	1.9E+04	DMM	1.8E+04	DMM
12/10	**196**	1.2E+04	DMM	3.0E+04	DMM	1.8E+04	DMM
12/11	**208**	1.8E+04	DMM	1.9E+04	DMM	2.3E+04	DMM
12/11	**220**	5.4E+03	DMM	1.9E+04	DMM	1.7E+04	DMM
12/12	**232**	3.6E+06	DMM	4.9E+06	DMM	1.6E+05	DMM
12/12	**239**	2.8E+03	DMM	5.5E+04	DMM	9.0E+04	DMM
12/12	**243**	3.1E+06	DMM	3.1E+06	DMM	1.6E+04	DMM
12/12	**247**	8.5E+02	DMM	8.8E+02	DMM	1.9E+01	DMM
12/13	**268**	8.0E+06	DMM	8.0E+06	DMM	1.7E+01	DMM

Table 5-4
Insulation Resistance Measurements for Westinghouse EPA

	Rockbestos #16 AWG, 2 conductor, XLPE/XLPE					
	Black Conductor to Ground		White Conductor to Ground		Black to White	
Before Irradiation	3.9E+11	H500	5.0E+11	H500	2.0E+12	H500
After Irradiation	3.5E+11	H500	4.2E+11	H500	8.0E+11	H500
Before Thermal Aging	1.7E+11	H500	9.0E+12	H500	1.8E+12	H500
Begin Thermal Aging	2.8E+09	H500	3.0E+09	H500	5.7E+08	H500
End Thermal Aging	1.1E+09	H500	1.2E+09	H500	3.8E+08	H500
After Thermal Aging	2.5E+12	H500	3.0E+12	H500	5.0E+12	H500

SAC Test

Date	Hours	Black Conductor to Ground		White Conductor to Ground		Black to White	
Initial Reading		3.5E+12	H500	5.0E+12	H500	1.0E+13	H500
12/2	6	6.0E+07	H500	9.1E+07	H500	3.8E+07	H500
12/2	12	8.0E+06	H500	5.0E+06	H500	4.0E+06	H500
12/3	18	3.4E+06	H500	2.9E+06	H500	1.0E+06	H500
12/3	24	2.9E+06	H500	2.5E+06	H500	1.6E+04	DMM
12/3	32	2.1E+06	H500	2.2E+06	H500	1.9E+04	DMM
12/4	40	1.2E+06	H500	1.4E+06	H500	1.2E+06	DMM
12/4	48	1.8E+06	H500	2.0E+06	H500	6.5E+05	H100
12/4	52	8.0E+05	H100	1.9E+06	H500	7.3E+05	H100
12/5	64	1.4E+06	H500	1.9E+06	H500	9.5E+05	H100
12/5	76	1.1E+06	H500	1.9E+06	H500	4.8E+05	DMM
12/6	88	9.2E+05	H100	9.2E+05	H100	9.0E+05	H100
12/6	100	7.9E+05	H100	1.2E+06	H100	8.0E+05	H100
12/7	112	3.4E+06	H100	5.9E+06	H100	2.2E+06	H100
12/7	124	6.0E+05	H100	1.0E+06	H100	3.8E+05	H100
12/8	136	5.8E+05	H100	1.1E+06	H100	7.2E+05	H100
12/8	148	6.1E+05	H100	1.1E+06	H500	5.8E+05	H100
12/9	160	5.5E+05	H100	7.9E+05	H100	6.7E+05	H100
12/9	172	5.4E+05	H100	7.2E+05	H100	6.3E+05	H100
12/10	185	5.2E+05	H100	1.0E+06	H500	7.0E+05	H100
12/10	196	5.3E+05	H100	1.0E+06	H100	7.1E+05	H100
12/11	208	5.3E+05	H100	1.0E+06	H100	6.9E+05	H100
12/11	220	4.9E+05	H100	5.1E+05	H100	4.9E+05	H100
12/12	232	4.6E+05	H100	4.6E+05	H100	3.5E+04	DMM
12/12	239	4.5E+05	H100	4.7E+05	H100	5.0E+04	DMM
12/12	243	1.0E+06	H500	1.0E+06	H500	2.2E+06	H500
12/12	247	1.4E+07	H500	1.4E+07	H500	1.1E+04	DMM
12/13	268	2.1E+12	H500	2.5E+12	H500	8.0E+06	H500

Table 5-5
Insulation Resistance Measurements for Westinghouse EPA

		Raychem #14 AWG XLPE Conductor to Ground		Okonite #2 AWG Okonite/Okolon Conductor to Ground	
Before Irradiation		1.5E+11	H500	1.7E+11	H500
After Irradiation		1.8E+11	H500	5.2E+10	H500
Before Thermal Aging		7.8E+09	H500	2.3E+11	H500
Begin Thermal Aging		2.1E+09	H500	8.0E+08	H500
End Thermal Aging		5.2E+08	H500	3.9E+08	H500
After Thermal Aging		1.5E+12	H500	5.9E+11	H500
SAC Test					
<u>Date</u>	**<u>Hours</u>**				
Initial Reading		2.5E+11	H500	2.5E+11	H500
12/2	**6**	2.9E+07	H500	1.5E+07	H500
12/2	**12**			2.7E+06	H500
12/3	**18**	2.4E+06	H500	1.2E+06	H500
12/3	**24**	2.4E+06	H500	4.2E+05	H100
12/3	**32**	2.5E+06	H500	5.5E+05	H100
12/4	**40**	2.3E+06	H500	3.9E+06	H050
12/4	**48**	2.0E+06	H100		
12/4	**52**	2.1E+06	H500	3.0E+05	H100
12/5	**64**	1.8E+06	H500	2.1E+05	H100
12/5	**76**	1.7E+06	H500	2.0E+05	DMM
12/6	**88**	1.5E+06	H500	1.2E+05	H050
12/6	**100**	1.3E+06	H500	1.0E+05	H050
12/7	**112**	1.0E+06	H500	7.2E+04	DMM
12/7	**124**	8.0E+05	H100	5.2E+04	DMM
12/8	**136**	6.9E+05	H100	2.9E+06	DMM
12/8	**148**	6.0E+05	H100	4.2E+04	DMM
12/9	**160**	4.9E+05	H100	9.9E+04	DMM
12/9	**172**	4.3E+05	H100	2.8E+04	DMM
12/10	**185**	3.8E+05	H100	3.3E+05	DMM
12/10	**196**	3.5E+05	H100		
12/11	**208**	3.2E+05	H100	1.0E+04	DMM
12/11	**220**	3.0E+05	H100	1.4E+04	DMM
12/12	**232**	2.7E+05	H100	4.3E+06	DMM
12/12	**239**	3.0E+05	H100	2.7E+04	DMM
12/12	**243**	9.0E+05	H100	1.8E+05	DMM
12/12	**247**	6.9E+06	H500	5.7E+05	DMM
12/13	**268**	2.2E+09	H500	6.2E+09	H500

Radiation Aging

The EPA was exposed to a total dose of 200 Mrad using a cobalt source as measured at the outside of the header plate. The dose rate ranged from about 0.5 to 1.0 Mrad/hr over the entire EPA and inside connector. The total exposure time was 248 hours. During the irradiation period, the cobalt was lowered 3 times for a total of 14 hours so that the irradiation would be completed during normal working hours. No unintentional cobalt lowering took place during this period. Figure 5-8 illustrates the location of the EPA relative to the cobalt array. The 1/4 in. thick liner was used for flux mapping and also helps to reduce the radiation gradients. A continuous air flow between the barrel and the EPA nozzle was maintained to keep the temperature below 120°F. The thermocouples that were monitored during irradiation included gages at locations 1D, 3D, and 5B on the nozzle and on module 3 at the header and the inside end. The thermocouple readings during the irradiation never exceeded 106°F.

The O-ring aperture seal pressure was also monitored during radiation aging. This was important in order to verify that the pressure was sufficient to maintain adequate force on the seals, which holds them in their "normal" position. The aperture seal pressure varied between 13.1 and 16 psig during irradiation. Several pressure drop tests were conducted during irradiation and the calculated leak rates were always less than $3x10^{-4}$ scc/sec.

Insulation resistance measurements and pressure drop tests were performed after irradiation. The insulation resistance data is given in Tables 5-2 through 5-5; there were no unusual readings. Pressure drop tests were performed after irradiation; the O-ring aperture seal leak rate was $6x10^{-6}$ scc/sec and the module leak rate was $1x10^{-6}$ scc/sec.

The torque on the header plate bolts was also checked after irradiation. Four of the twelve bolts had dropped to 200-250 ft-lbs; these bolts were retorqued to the specified value of 300 ft-lbs.

Thermal Aging

The EPA nozzle was mounted into the test chamber mounting plate in preparation for thermal aging. Figure 5-9 shows the condition of the modules and cables after irradiation and before thermal aging. Thermal aging and the SAC test were conducted in the same chamber in order to minimize handling between these two phases of the test. The junction box was mounted to the header plate for the first time. Since it was important to maintain a uniform temperature during thermal aging, a large number of thermocouples (52) were installed both inside and outside the junction box and on the EPA nozzle as shown in Figure 5-6.

In order to install the EPA in the test chamber, the leakage monitoring systems for the modules and the O-ring aperture seal were depressurized and the line was cut. The pressure lines were fed through the mounting plate on the test chamber and reconnected. Both systems were pressure drop tested; the leak rate for the O-ring aperture seal was $6x10^{-6}$ scc/sec and that for the modules was $1x10^{-6}$ scc/sec.

Insulation resistance measurements were taken and are listed in Tables 5-2 through 5-5 under the heading "Before Thermal Aging". In general the cable insulation resistances at this time were equal to or higher than their baseline values, with only the Raychem cable insulation resistance being lower than its baseline value.

On November 18, the heaters and blowers were turned on and the controller was set to 300°F. The average value of all thermocouples inside the junction box, which is plotted in Figure 5-10, was used to control the aging temperature. For the purposes of this test, the exposure time for thermal aging was counted from the time at which the average temperature reached 292°F. The average temperature reached 298°F six hours later and stayed at 300°F ± 2°F for the remaining 94 hours of the total 100 hour exposure period. The maximum and minimum temperatures inside the junction box were ±12°F from the average, and the maximum fluctuation at any one specific location was ±2°F. This indicates that uniformity in the heating and resultant temperatures was achieved.

In the D. G. O'Brien EPA test, there was evidence that the temperature inside the junction box during the SAC test was raised by 20 to 30°F due to electrical heating from the cables. However, in this test, the temperatures did not change when the load bank was disconnected to make insulation resistance measurements with the Hippotronics Megohm meter. Although there was no evidence of electrical heating in this test, improvements that were made in the steam circulation system during the SAC test on the D. G. O'Brien EPA (see Section 4-3) probably would have made electrical heating much more difficult to detect if it was occurring.

The pressures in the monitoring spaces for the module seals and for the aperture seal during thermal aging are plotted in Figure 5-11. The module pressure increased during thermal aging more than would be expected due to the temperature rise alone, which could be explained by outgassing of the epoxy seal. After thermal equilibrium was achieved, the leak rate from the modules was nearly constant at $1.5x10^{-4}$ scc/sec, while that from the aperture seal was about $1x10^{-5}$ scc/sec. The aperture seal pressure did not increase during heat-up, which indicates that either i) the leak rate was significantly higher during heat-up or ii) the assumption that the temperature of the internal volume of the monitoring gas is equal to the average header plate temperature (see Appendix A) is inaccurate. A higher leak rate during heat-up could result from differential thermal expansion of the inside and outside silicone O-rings.

Insulation resistance measurements were made with the Hippotronics Megohmmeter several times during thermal aging. However, since there was little change in the reading during thermal aging, only the values at the beginning and end of thermal aging are recorded in Tables 5-2 through 5-5. At 300°F, most of the cable insulation resistances fell by three to four orders of magnitude compared to their insulation resistances before thermal aging, which is typical. The insulation resistances recorded after thermal aging (when the EPA had cooled to ambient temperature) show a significant if not total recovery. The cables were energized and data from the load bank was recorded during thermal aging, but since insulation resistances of all the cables remained at or above 50 MΩ (which is the maximum accurate range for insulation resistances obtained from the load bank) the data is of little significance and hence not reported.

The thermocouple data taken during thermal aging are plotted in Figures 5-12 through 5-24. The following observations can be made:

- There was some stratification of the temperature inside the junction box from top to bottom (compare Figures 5-12 and 5-13). However, the deviation in temperature at any one location was small.

- Although there is some non-uniformity in the air temperature of the chamber (Figures 5-14 through 5-16), the temperature of the EPA components inside the chamber (the header plate, modules, and weldneck flange is quite uniform (compare Figures 5-17 through 5-19).

- Outside of the test chamber, there is a significant axial temperature gradient in the EPA nozzle (Figures 5-20 through 5-23). However, the air temperature inside the nozzle is much more uniform (Figure 5-24).

Post-Thermal Aging

The torques on the header plate bolts were not checked after thermal aging since to do so would have required removal of the junction box, which would have disrupted the thermocouples and cables. Although the torque on four of the bolts had dropped after irradiation, the torque on all the bolts remained above 200 ft-lbs. Furthermore, the O-ring aperture seal leak rate was small ($5x10^{-6}$ scc/sec) and had not changed significantly from that measured before thermal aging. Thus, there was no reason to suspect a significant drop in the header plate bolt torque and so the torque was not checked after thermal aging to avoid possible damage to the test apparatus. The module leak rate was the same as that measured prior to thermal aging ($1x10^{-6}$ scc/sec).

In order to simulate the installation of an EPA in which terminal blocks are installed, the jacket and insulation were cut to the wire conductor on some of the cable loops. None of the cable lengths that passed through the test chamber penetrations were cut. The cables for which the jacket and insulation were cut are listed below:

- Raychem
- Rockbestos--white insulator
- Okonite
- ITT Suprenant Type EX--red insulator

The cuts created moisture paths to the module epoxy seal, and thus this resulted in a more severe test of the leak integrity of the EPA. Figure 5-25 shows the condition of the cables after radiation and thermal aging and also shows the cuts made in the cables.

Air Leak Test

Prior to conducting the SAC test, the cable penetrations through the test chamber were filled with epoxy and insulation resistance measurements were made. The insulation resistance data taken at this time is listed in Tables 5-2 through 5-5 in the row labeled SAC Test, Initial Reading.

The test chamber was sealed and pressurized to 75 $\pm$ 5 psia with air at room temperature. No leaks were detected and the pressure in the O-ring aperture and the pressure in the modules did not increase.

5.3 Conduct of the Severe Accident Test

The SAC test was started at 08:00 on December 2, 1985. In the first two hours, pressure and temperature were increased at a steady rate to approximately 250°F and 30 psia using steam at saturation conditions. From this point, the pressure and temperature were raised at a slower rate over the next eight hours to a final pressure and temperature of approximately 75 psia and 400°F using superheated steam. The temperature and pressure were then maintained at this level with only minor deviations for the remaining 9.5 days of the SAC test. The chamber temperature was defined as the average of 19 thermocouples mounted outside the junction box about two inches from the surface (gages 13-32 except 31, which was faulty). The chamber pressure and temperature for the first day of the test are shown in Figure 5-26 along with the BWR Mark III accident profile, which represents the desired test loads.

The steam system functioned nearly flawlessly during the SAC test. The average chamber temperature as well as the actual temperature at any given location varied by less than ±5°F for the last 9.5 days of the test. The maximum and minimum temperatures in the chamber were about 40°F above and below the average chamber temperature, respectively.

The pressure-temperature rampdown consisted of two steps--the first at 300°F and 67 psia and the second at 250°F and 30 psia (both conditions correspond to saturated steam). The original plan had called for steps at 350°F, 50 psia and 300°F, 25 psia, which both correspond to superheated steam. The change was made to reduce the time necessary to stabilize the system, i.e., to reduce the time needed to obtain thermal equilibrium.

5.4 Test Data and Results

Data collected during the SAC test consists of measurements of the O-ring aperture seal pressure, the module seal pressure, leakage through the EPA, insulation resistance and continuity of the cables, and temperature at various locations.

Leakage Measurements

The pressures in the monitoring space for the module seals and aperture seal are plotted in Figure 5-27. The behavior is very similar to that observed during thermal aging. The module pressure increased during heat-up and then slowly decreased after the header plate temperature reached equilibrium, but the increase was significantly more than can be accounted for by the temperature rise alone. Outgassing of the epoxy seems to be the most likely explanation for the pressure increase. Leakage from the chamber past the first epoxy seal (**into** the module monitoring space) must also be considered as a possible explanation for the pressure increase (unlike thermal aging, where the chamber was essentially at ambient temperature and consequently there was no positive differential pressure from the chamber to the module monitoring space). After about three days into the SAC test, the indicated leakage was **out** of the module monitoring space at a rate of approximately $3x10^{-6}$ scc/sec.

There are arguments for and against both explanations. The fact that the module pressure only increased to about 39 psig and did not more closely approach the test pressure of 62 psig seems to argue against a failure of the first epoxy seal. On the other hand, during cool-down, the module pressure dropped to about 5 psig, which is a much greater drop from the pressure at the start of the test (about 15 psig) than can be explained by the slow leak rate out of the module (on the order of 10^{-5} scc/sec) that was observed from initial inspection through the SAC test. It does not seem that a definitive explanation for the pressure increase can be provided. However, it is clear that there was no significant leakage through the modules (and past the EPA) during the SAC test.

The indicated leak rate from the aperture seal monitoring space was quite low throughout the SAC test; for instance from the end of the first day to the end of the sixth day leak rate calculated from the pressure drop was only 8×10^{-6} scc/sec. The aperture seal pressure did not increase during heat-up as expected. As discussed in the section on thermal aging, the explanation is that either the leak rate was significantly higher during heat-up or the assumption that the temperature of the internal volume of the monitoring gas is equal to the average header plate temperature (see Appendix A) is inaccurate. A higher leak rate during heat-up could result from differential thermal expansion of the inside and outside silicone O-rings.

The pressure inside the nozzle was also recorded during the SAC test. There were no significant changes in the nozzle pressure, which again indicates that there was no leakage past the Westinghouse EPA during the SAC test.

Temperature Measurements

Thermocouple data is plotted in Figures 5-28 through 5-40. The observations that can be made are very similar to those made for thermal aging:

- There was some stratification of the temperature inside the junction box from top to bottom (compare Figures 5-28 and 5-29). However, the deviation in temperature at any one location was small. The stratification of air temperatures in the chamber was more pronounced (Figures 5-30 through 5-32).
- The temperatures of the EPA components inside the chamber (the header plate, modules, and weldneck flange, Figures 5-33 through 5-35) corresponded closely with the temperatures inside the junction box.
- Outside of the test chamber, there was a significant axial temperature gradient in the EPA nozzle (Figures 5-36 through 5-39). However, the air temperature inside the nozzle was much more uniform (Figure 5-40). Also, the following anomaly was observed during the SAC test (and not during thermal aging): at both 3 o'clock and 9 o'clock, the temperature of the nozzle 13 in. from the header plate was actually less than that 19 in. from the header plate.

Electrical Performance

Measurements of cable insulation resistances were taken with either the Hippotronics Megohmmeter or the Digital Multimeter periodically throughout the SAC test, from two to four times per day. This data is tabulated in Tables 5-2 through 5-4. The insulation resistance calculated from the load bank are plotted in Figures 5-41 through 5-48.

The degradation in insulation resistance depended on the cable type and not on the EPA module. The first low resistance was in the ITT Suprenant Type KX cable. The insulation resistance to ground of the red cable, Figure 5-41, fell below 1 kΩ at about 4 days into the SAC test. However, the insulation resistance to ground of the yellow cable (Figure 5-42) remained above 0.1 MΩ for about 6 days, and the insulation resistance between the red and yellow cable was greater than 0.2 MΩ for just over 4 days.

The load bank data for the ITT Suprenant Type EX cable show that the insulation resistance to ground for both conductors (Figures 5-43 and 5-44) was greater than 10 kΩ for the first 5 days of the test. Measurements taken with the Megohmmeter and the Digital Multimeter show a sharp drop in the insulation resistance of the red conductor from 3 MΩ to 1.5 kΩ between 12 and 18 hours into the SAC test. Although the insulation resistance of this cable subsequently recovered, it is believed that the insulator may have been damaged by the 500 V potential applied during the Megohmmeter measurement.

Both conductors of the Rockbestos cable (also #16 AWG) had insulation resistances to ground of greater than 1 MΩ for the first four days and of greater than 0.4 MΩ for the duration of the SAC test. However, at 24 hours into the SAC test, the insulation resistance between the black and white cable dropped to 16 kΩ and then recovered to 0.6 MΩ by 48 hours. Water was observed leaking out of the cable end that was attached to the load bank. Near the end of the test, the resistance between conductors again dropped into the 10 to 50 kΩ range.

There was evidence to suggest that the insulators of the thermocouple cables were damaged by the 500 V potential applied by the Megohmmeter. All of the EPA thermocouple cable insulators exhibited this behavior: the resistance fell markedly after a measurement was made with the Megohmmeter. The use of the 50 V to 500 V potential to measure the the insulation resistance of thermocouple cables is a severe tests since in actual service these types of cables would normally be subject to a potential of less than 0.1 V.

The insulation resistance of the Raychem #14 AWG cable, Figure 5-47, gradually degraded throughout the SAC test but remained quite high even at the end of the test. Although the rate of degradation was somewhat higher, similar behavior was recorded for the Okonite #2 AWG cable.

The insulation resistance of all of the cables recovered significantly during cooling.

As described in Section 5.2, the white Rockbestos, the red Suprenant Type EX, the Raychem, and the Okonite conductors were cut at the junction box to simulate field connections. There was no evidence that the electrical or mechanical performance of these conductors was any different than those cables that were not cut. All of the cables (including those that were not cut) cracked during the SAC test and allowed moisture to seep inside the insulator (the jacket) to outside the pressure chamber.

5.5 Posttest Observations

The chamber was allowed to naturally cool overnight from December 12 to 13. Cooling air was turned on at 08:00 hours on December 13. The final insulation resistance measurements were made when the EPA temperature had fallen to 90°F; this data is listed in Tables 5-2 through 5-5 under the row at 268 hours.

The same type of air leak rate test that was conducted before the severe accident test was repeated at this time. The chamber was pressurized to 62 psig with air at room temperature. The pressure in the O-ring aperture and in the modules was 15 psig and was unchanged during the air leak rate test. No leakage through the EPA was detected.

The interior of the test chamber and the junction box were in very good condition, as shown in Figure 5-49. The EPA cables had degraded (hardened?) and there were additional cracks in addition to the intentional cuts made after thermal aging (compare Figures 5-49 and 5-25). The leak rate for the aperture seal was $1x10^{-4}$ scc/sec and that for the modules was $7x10^{-5}$ scc/sec.

5.6 Summary and Conclusions

A Westinghouse EPA typical of those used in the containment building of a BWR Mark III nuclear power plant was tested under severe accident conditions simulated with steam at temperatures and pressure up to 400°F and 75 psia for ten days. The EPA was first irradiated and then thermally aged. The primary objective was to generate engineering data that could be used to evaluate the leak integrity of the EPA. A secondary objective was to investigate the EPAs's electrical performance.

No significant leakage through the Westinghouse EPA was detected at any time during the test sequence, including the the severe accident tests and the air leak tests at ambient temperature before and after the SAC test. Although the pressure in the monitoring space for the EPA modules did increase during the SAC test by an amount greater than that associated with the temperature rise alone, outgassing of the epoxy seals is a more plausible explanation than failure (and leakage) of the module seals. Even if the inside module seals did leak, the outside module seals definitely prevented any leakage past the EPA to "outside containment". Again, the structural and leak integrity of the Westinghouse EPA was maintained during the entire 10 day period of the severe accident test.

Data on the thermal behavior of the EPA was also collected during this test. The data indicated that some temperature stratification can be expected inside the junction boxes of EPA, and that there is a substantial axial temperature gradient along the EPA nozzle outside containment. This suggests that outboard seals may perform better than inboard seals.

The insulation resistances of the EPA conductors were gradually degraded during the SAC test, but electrical continuity was maintained throughout the test. The insulation resistance of all the cables was greater than 1 kΩ for the first four days of the SAC test. The rate of degradation was more dependent on the type of the cable used than on the module design. The insulation resistance of all cables in the Westinghouse EPA recovered significantly during cooling after the SAC test. Although the insulation resistances of the cables in the Westinghouse EPA held up relatively well, conclusions regarding electrical performance based solely on insulation resistance data must be made with caution. A cable's electrical performance also depends on the application, in particular, the voltage, current, and impedance requirements of the equipment or device to which the cable is connected.

The insulators of the thermocouple cables appeared to have been damaged by the high potential applied during measurements made with the Hippotronics

Megohmmeter, which applies a potential between 50 V and 500 V. This was probably an overtest of the thermocouple cables, since in actual service the cables are normally subject to a potential of less than 0.1 V. Therefore, this data should be interpreted with caution.

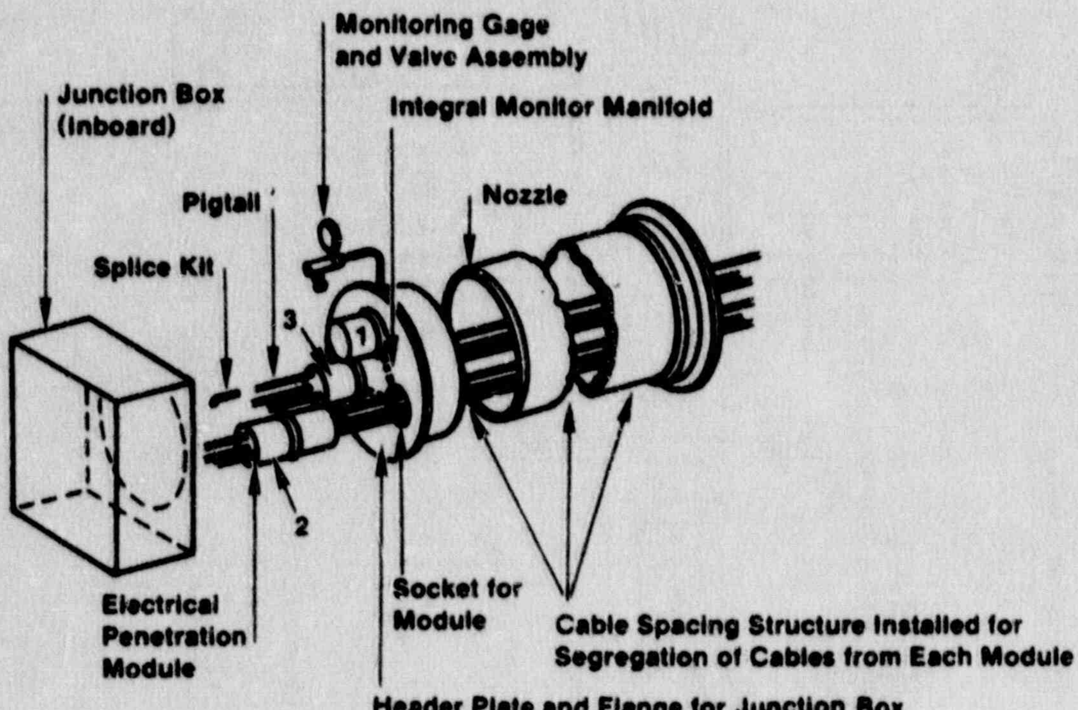

Figure 5-1 Schematic of Westinghouse EPA Modular Concept

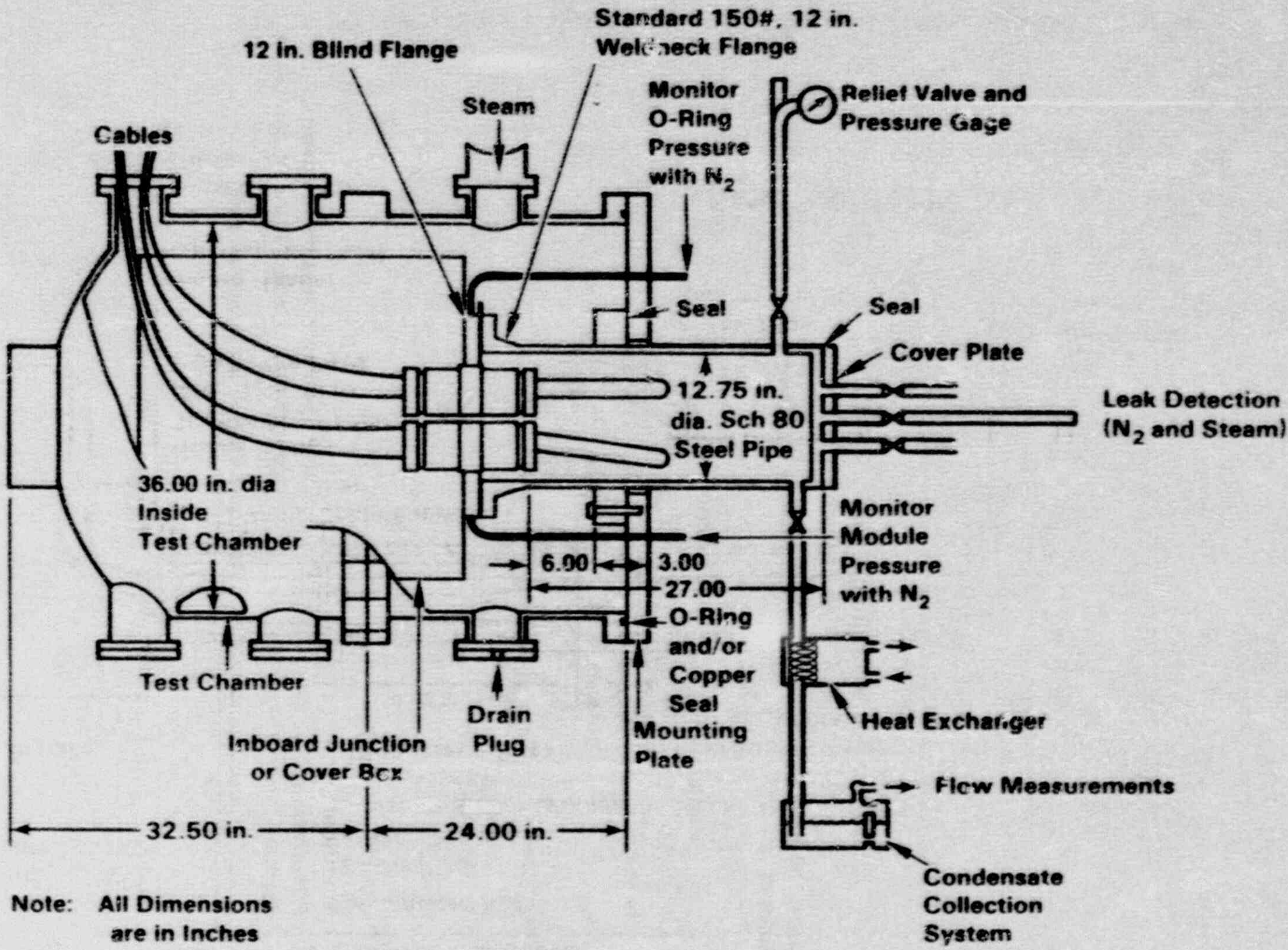

Figure 5-2 Schematic of Westinghouse EPA Test Configuration

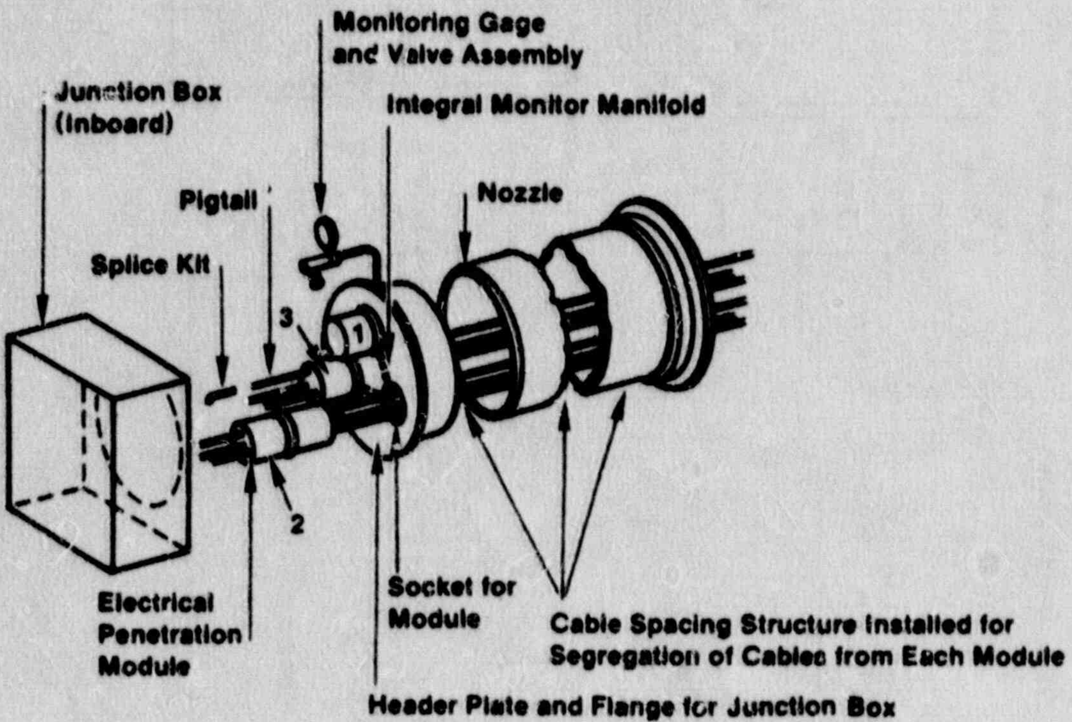

Figure 5-1 Schematic of Westinghouse EPA Modular Concept

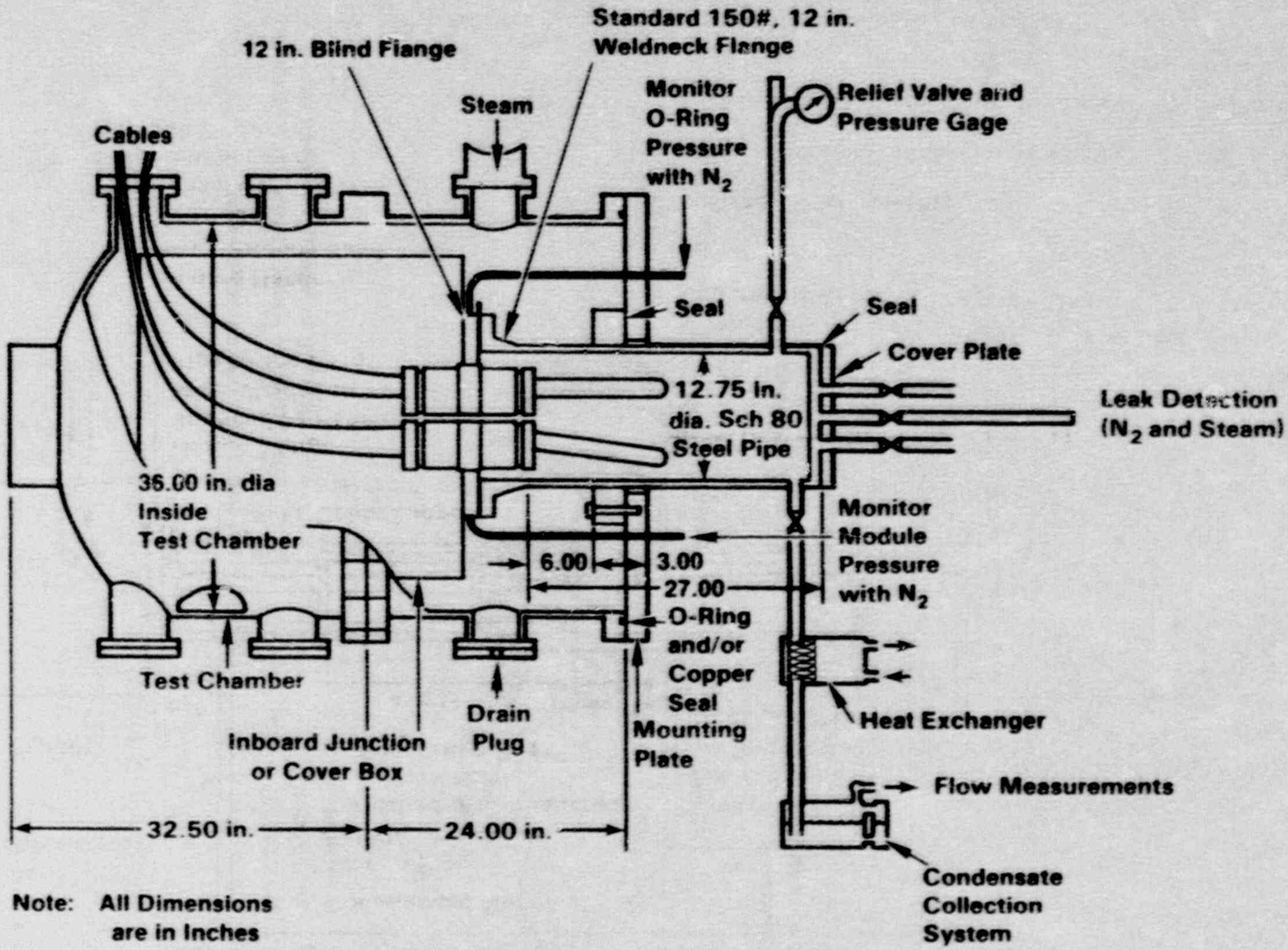

Figure 5-2 Schematic of Westinghouse EPA Test Configuration

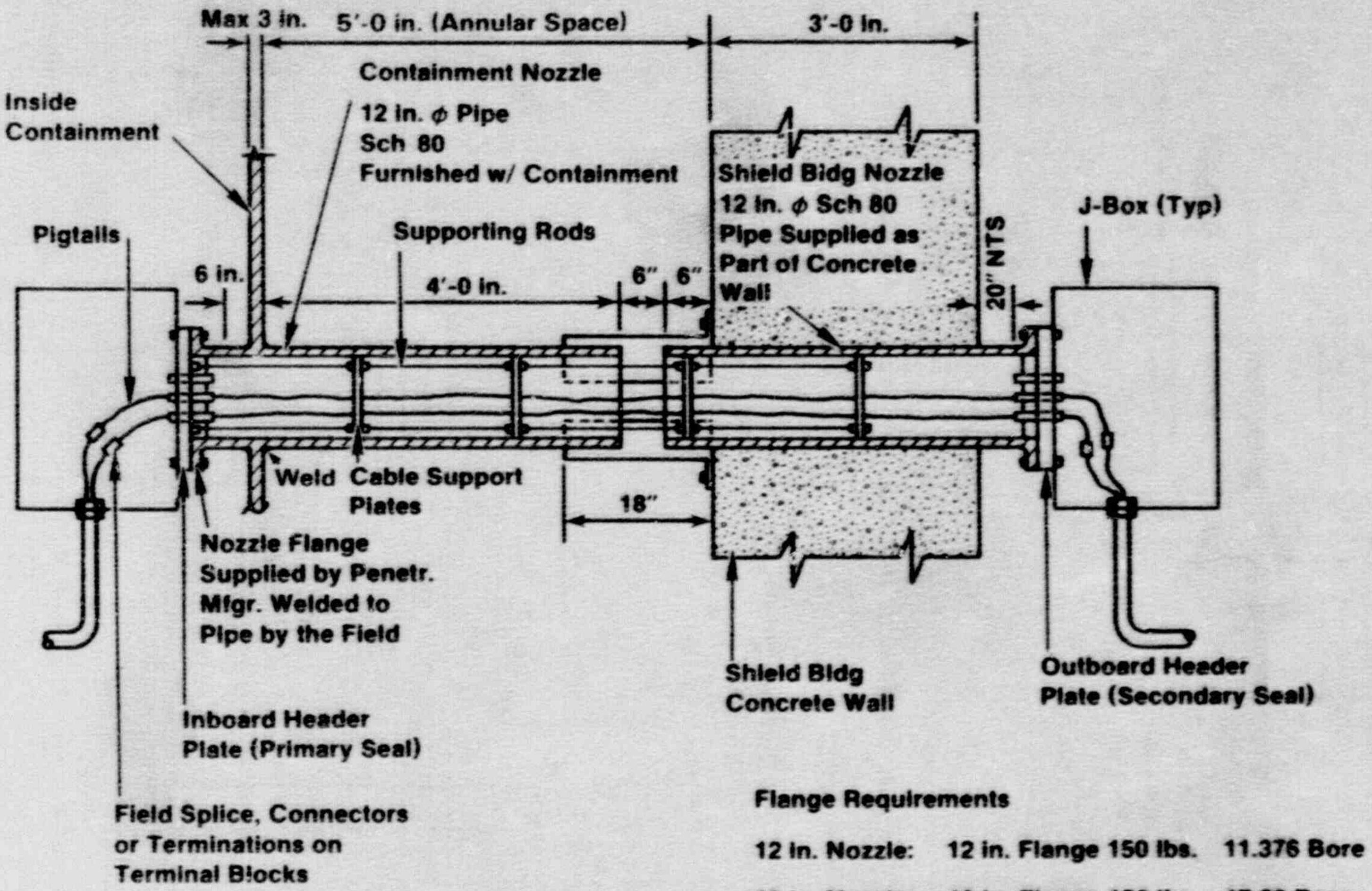

Figure 5-3 EPA Nozzle Design Used in Stride Nuclear Power Plant

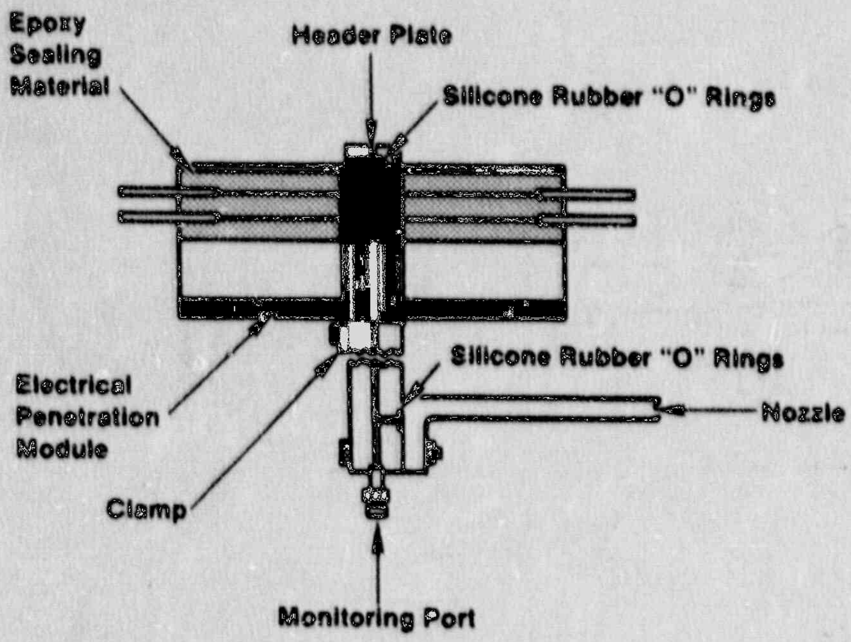

Figure 5-4 Module Insertion and Sealing in Header Plate

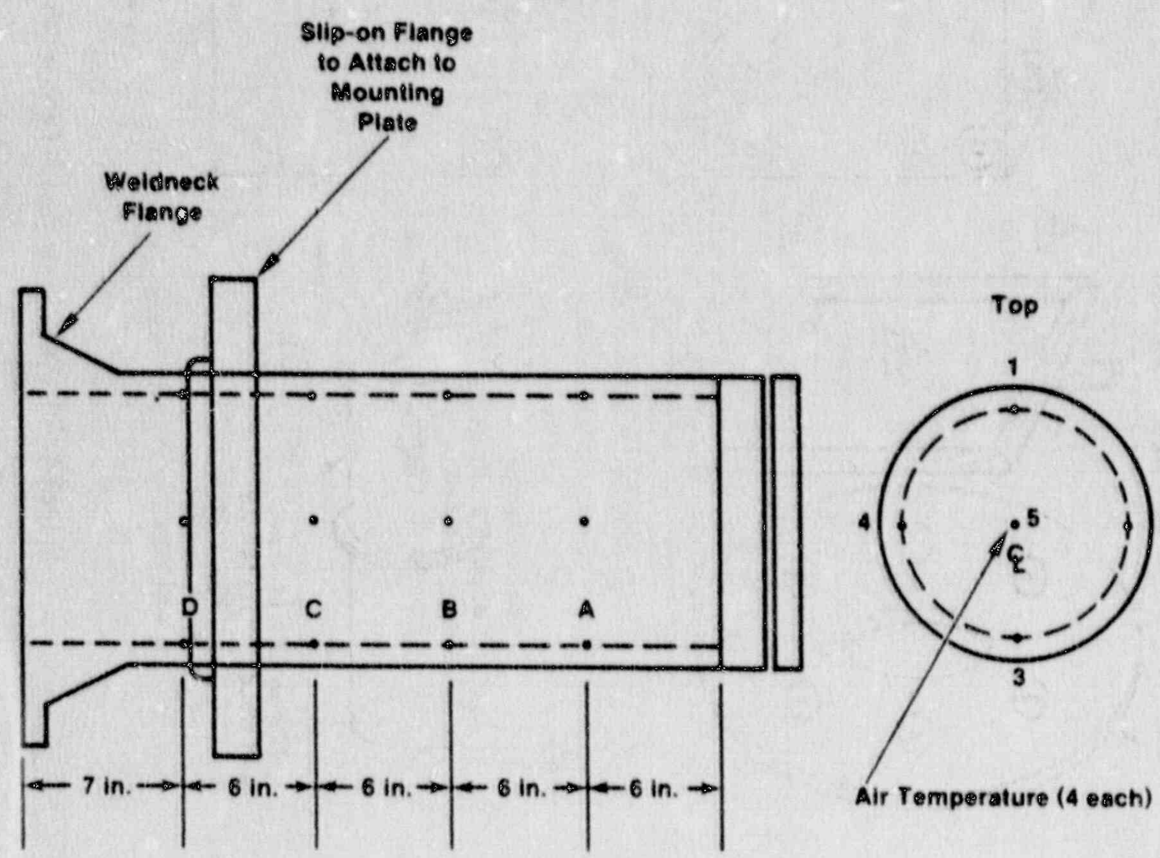

Figure 5-5 Locations of Thermocouples on Nozzle

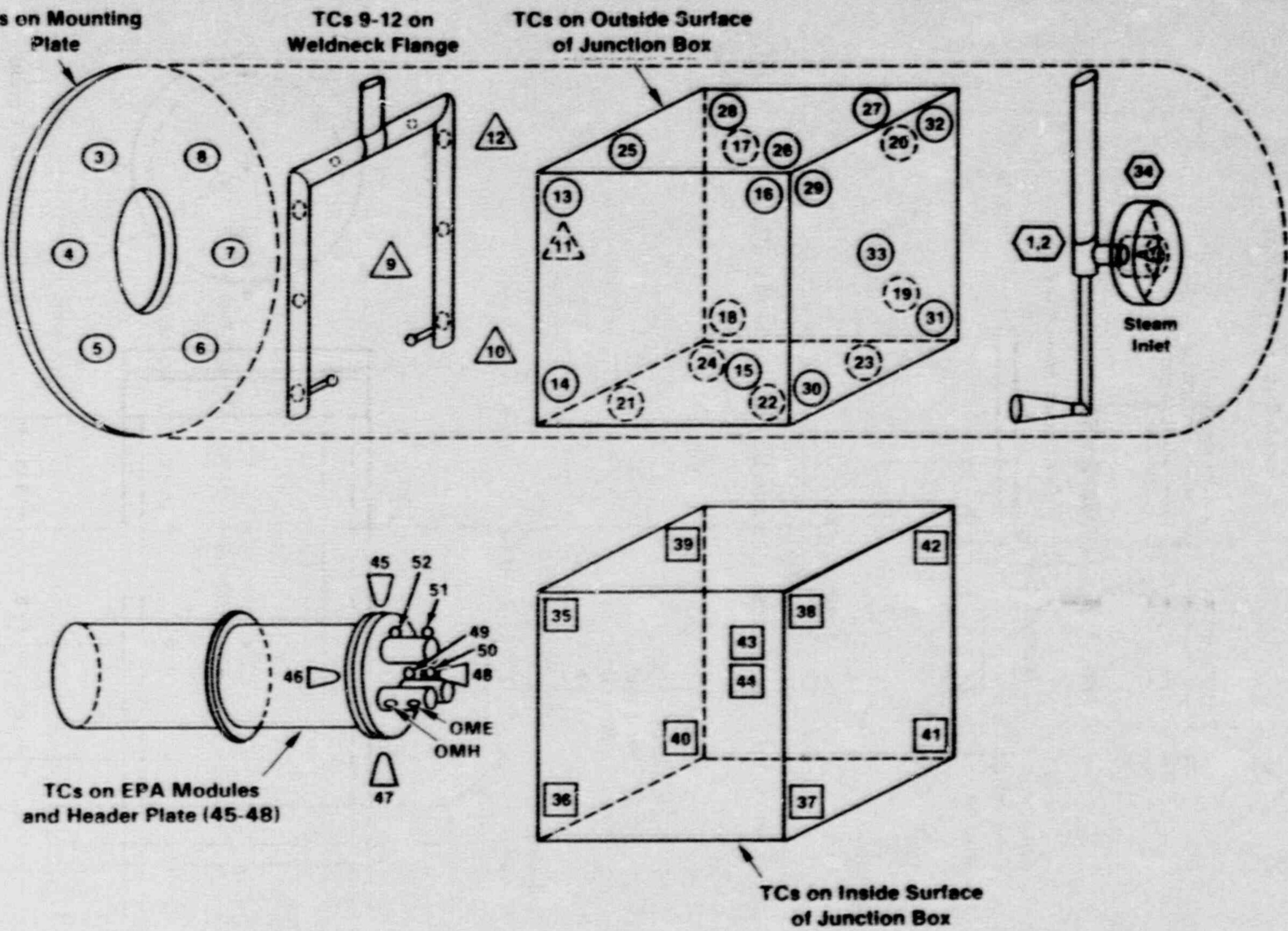

Figure 5-6 Locations of Thermocouples Inside Test Chamber

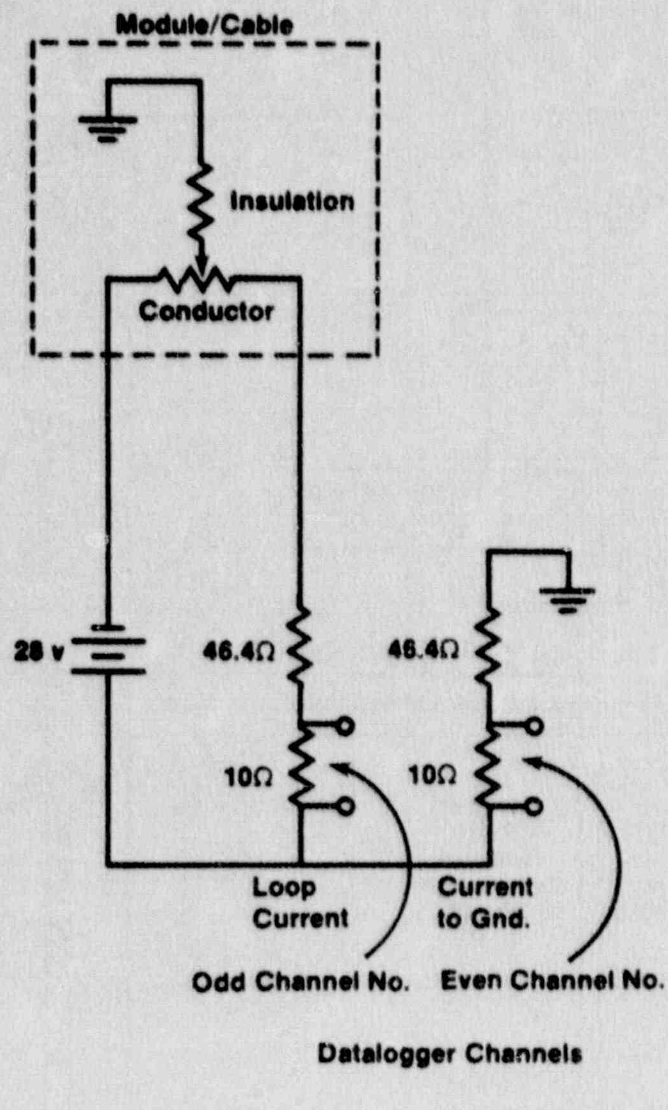

Figure 5-7 Circuit for Monitoring Continuity and Insulation Resistance

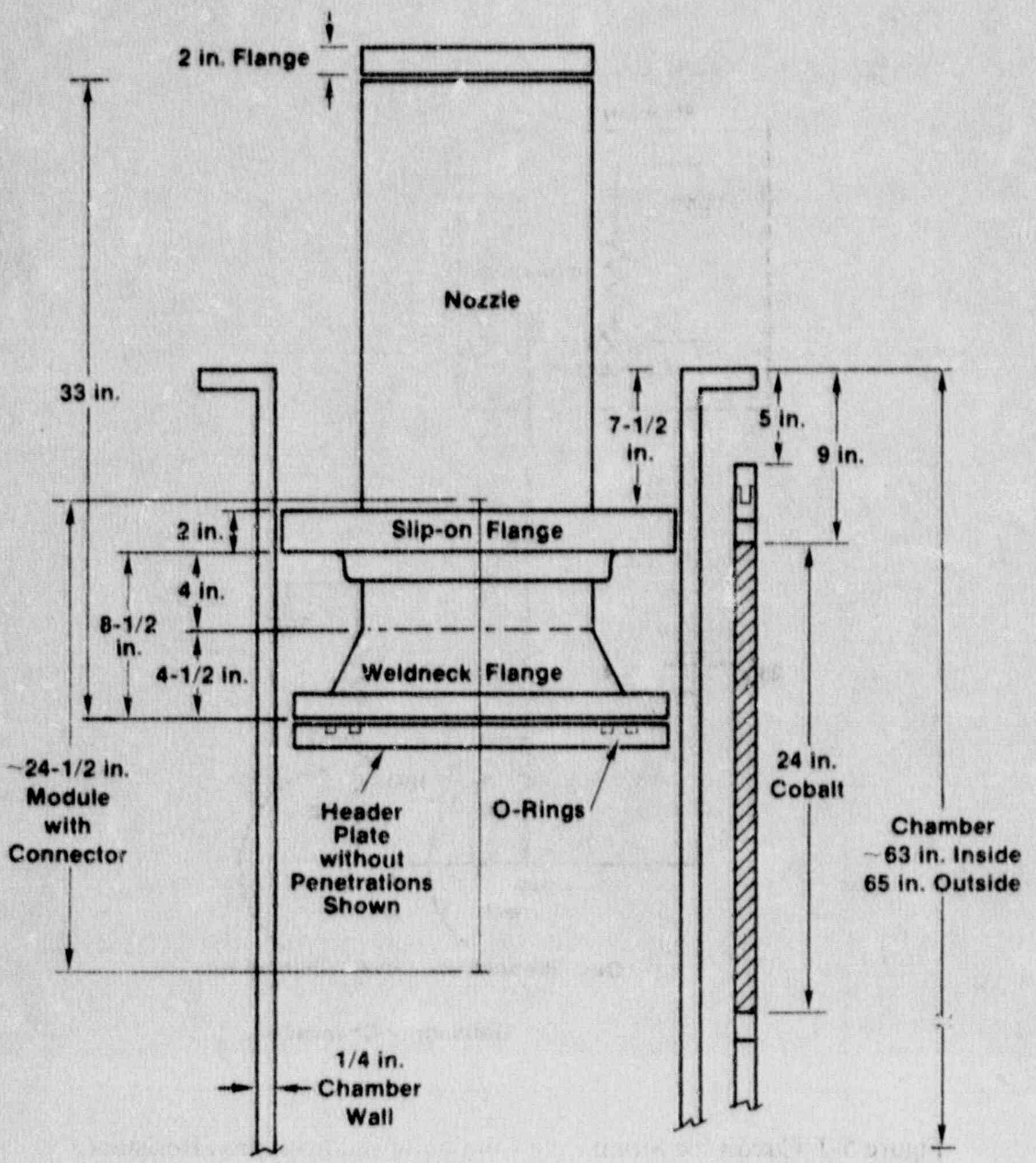

Figure 5-8 Location of EPA Relative to Cobalt Array

Figure 5-9 Condition of Modules and Cables After Irradiation

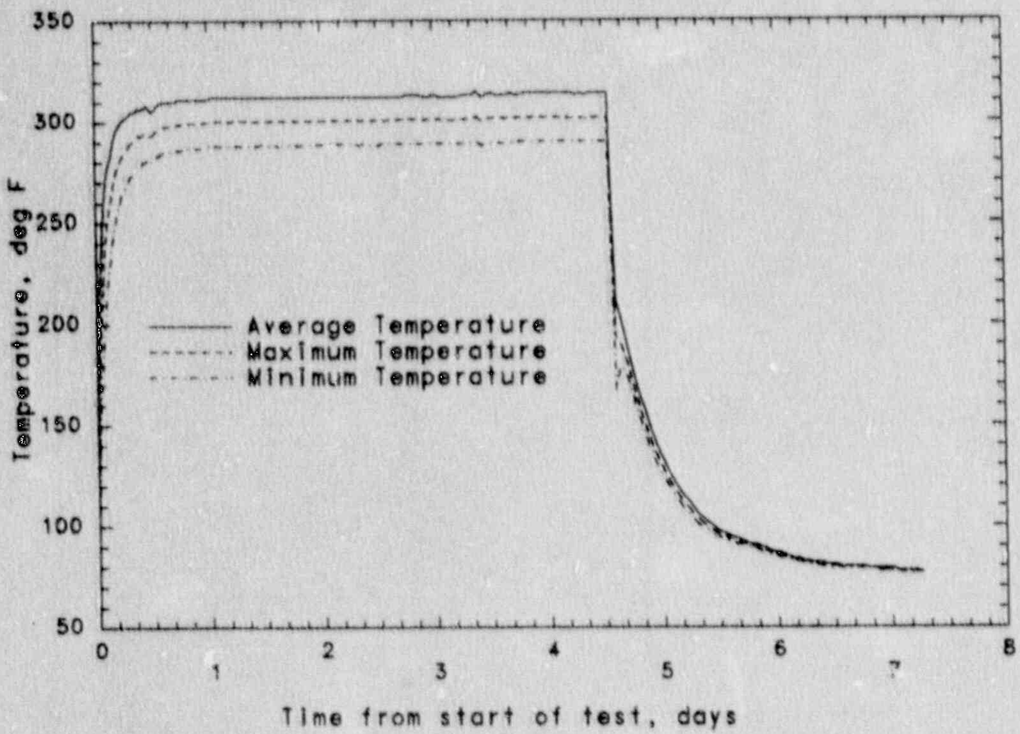

Figure 5-10 Temperature Extremes Inside Junction Box During Thermal Aging

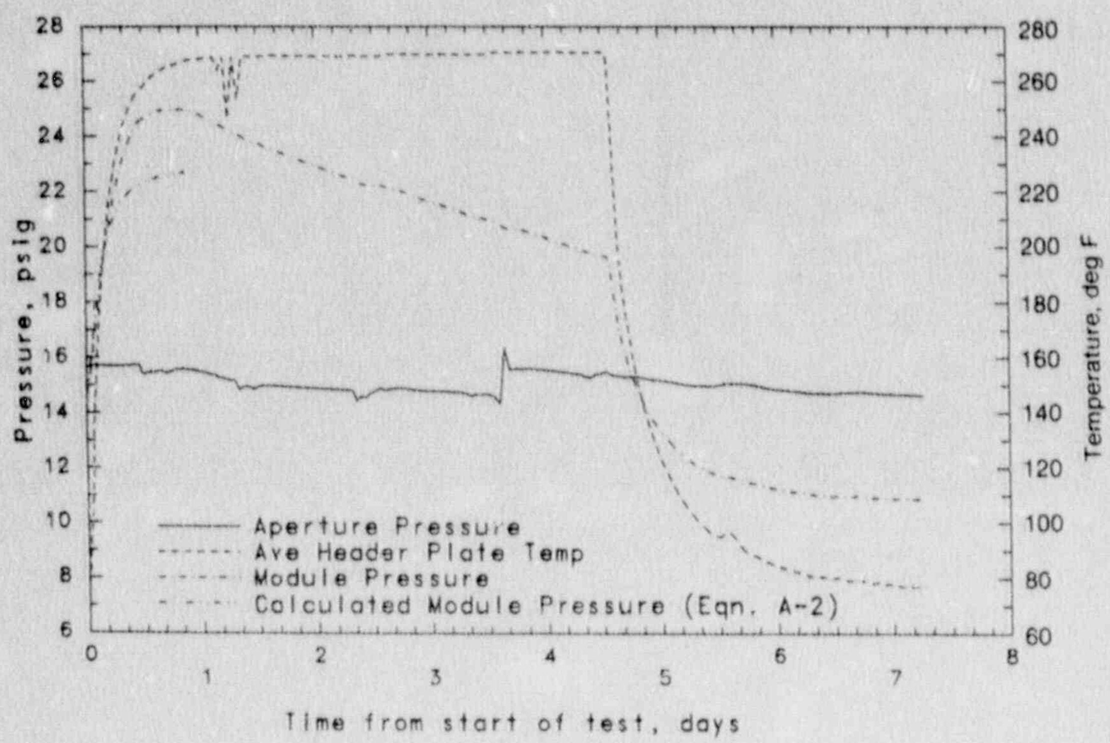

Figure 5-11 Monitoring Space Pressure Histories During Thermal Aging

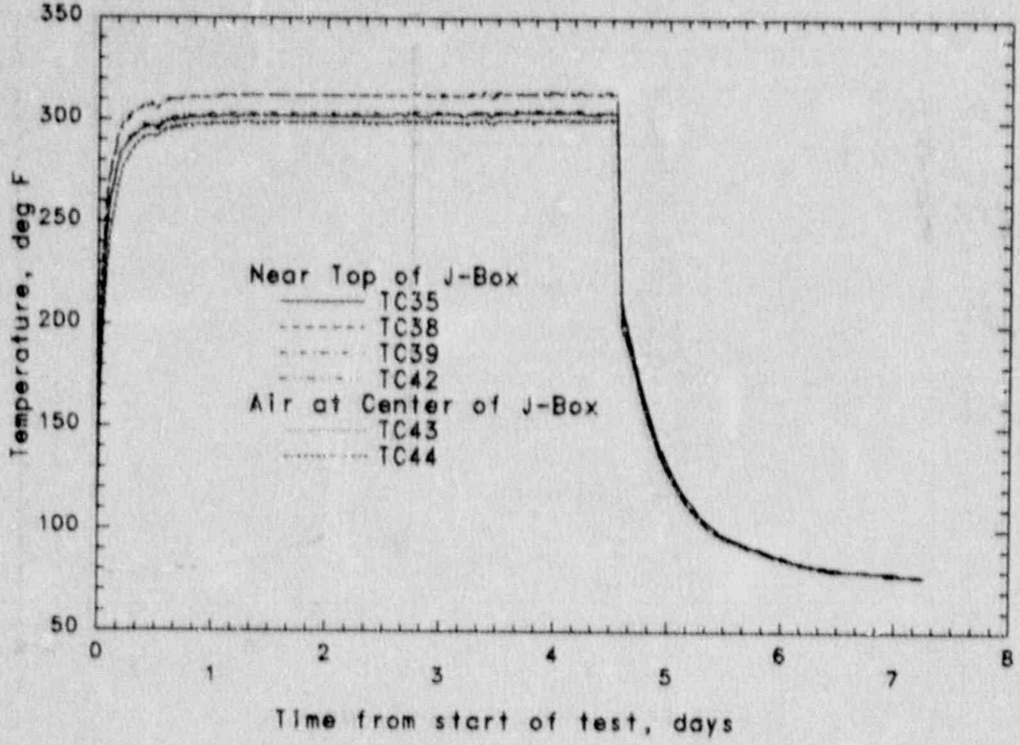

Figure 5-12 Temperature Inside Junction Box (Top) During Thermal Aging

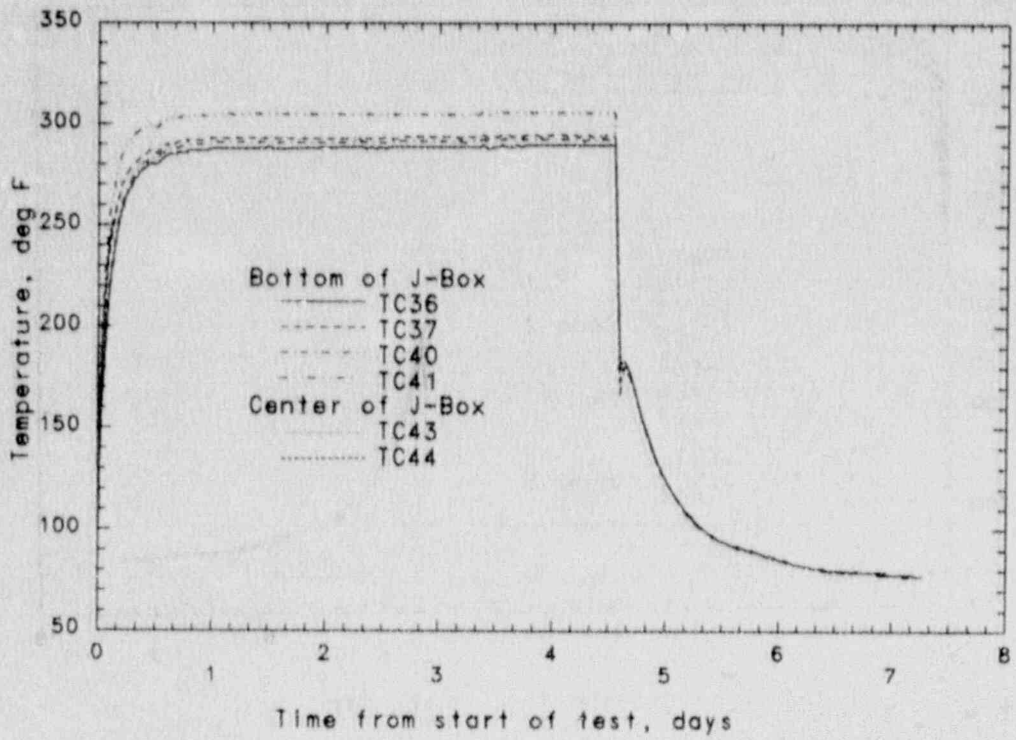

Figure 5-13 Temperature Inside Junction Box (Bottom) During Thermal Aging

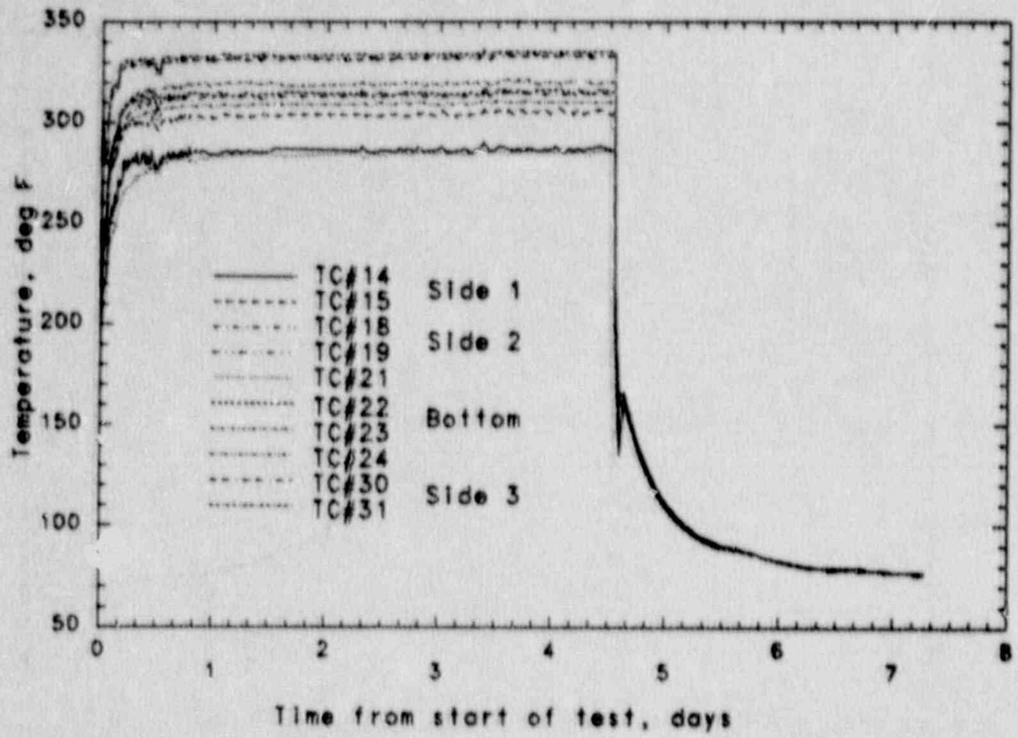

Figure 5-14 Temperature Outside of Junction Box, Near Bottom, During Thermal Aging

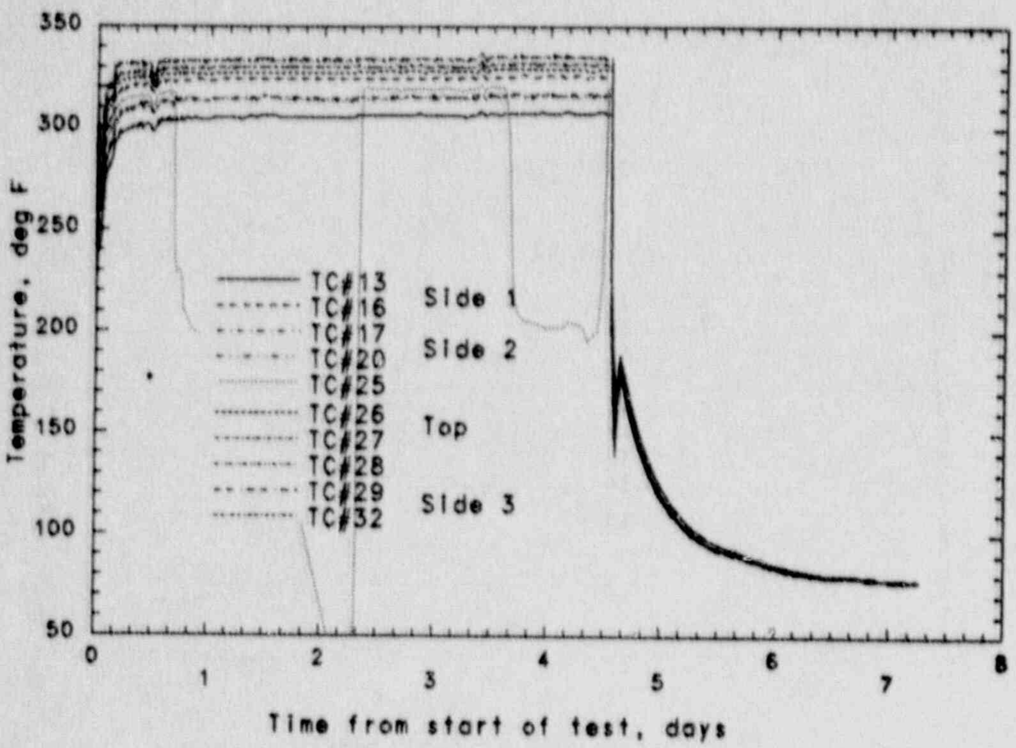

Figure 5-15 Temperature Outside of Junction Box, Near Top, During Thermal Aging

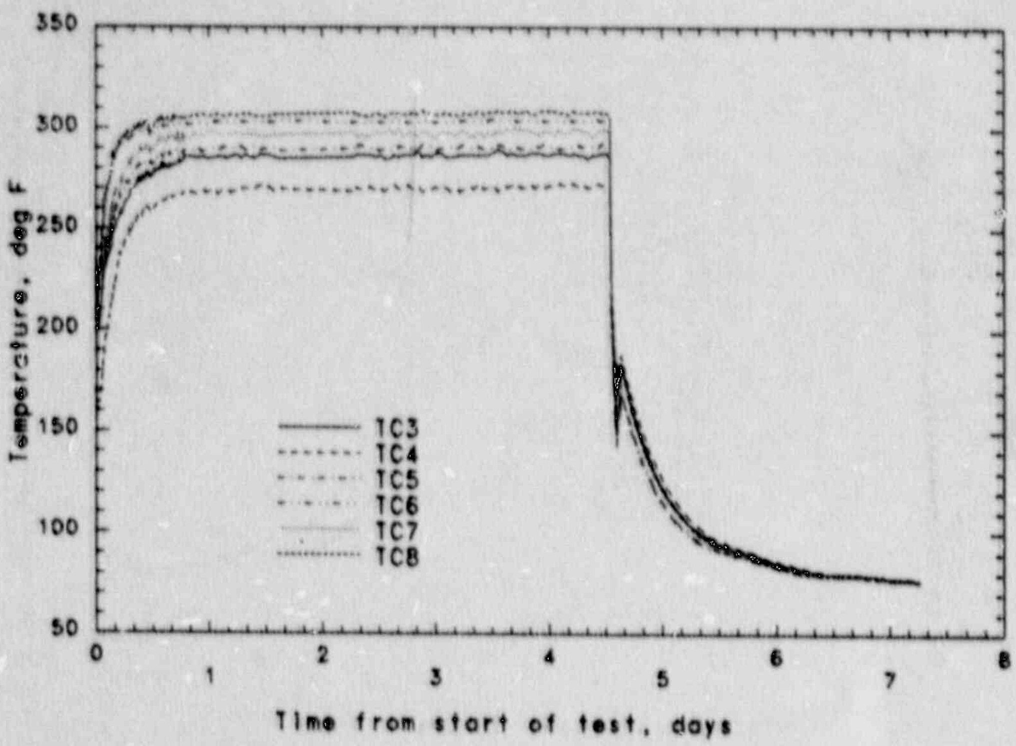

Figure 5-16 Temperature Near Mounting Plate During Thermal Aging

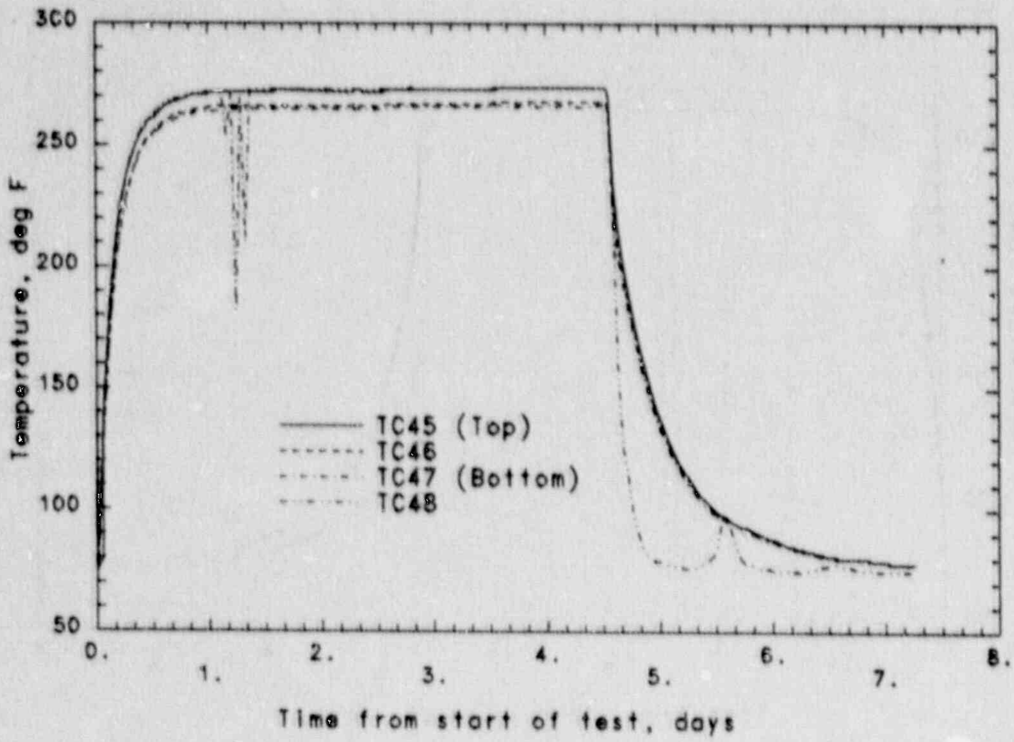

Figure 5-17 Temperature of Header Plate During Thermal Aging

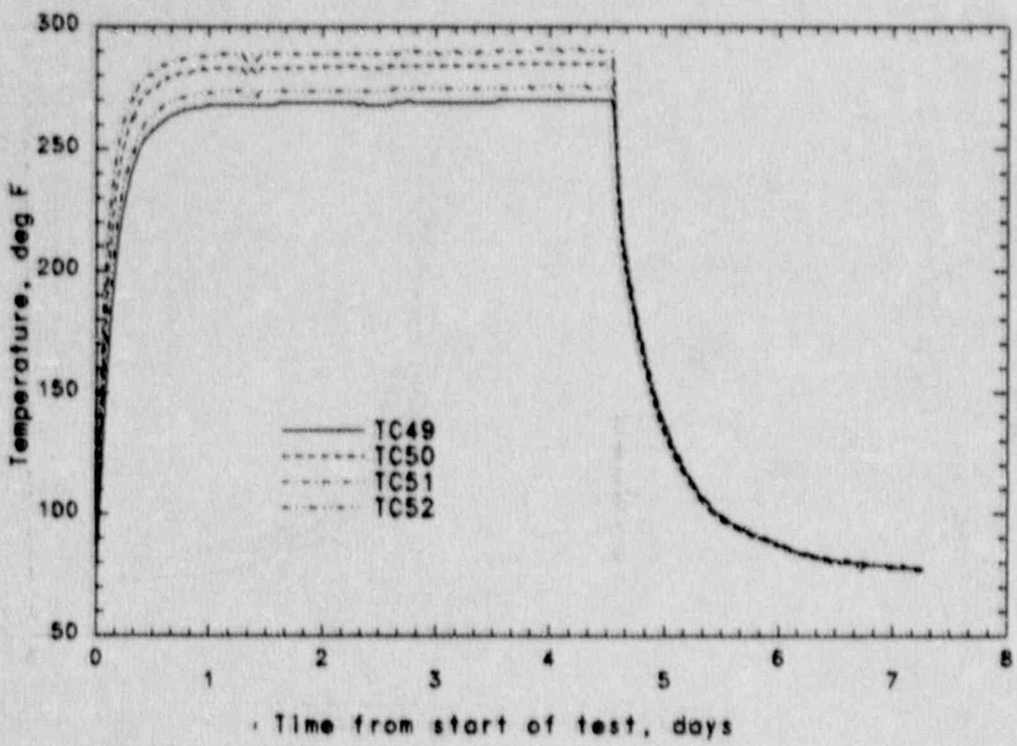

Figure 5-18 Temperature Near Inside Module Seals During Thermal Aging

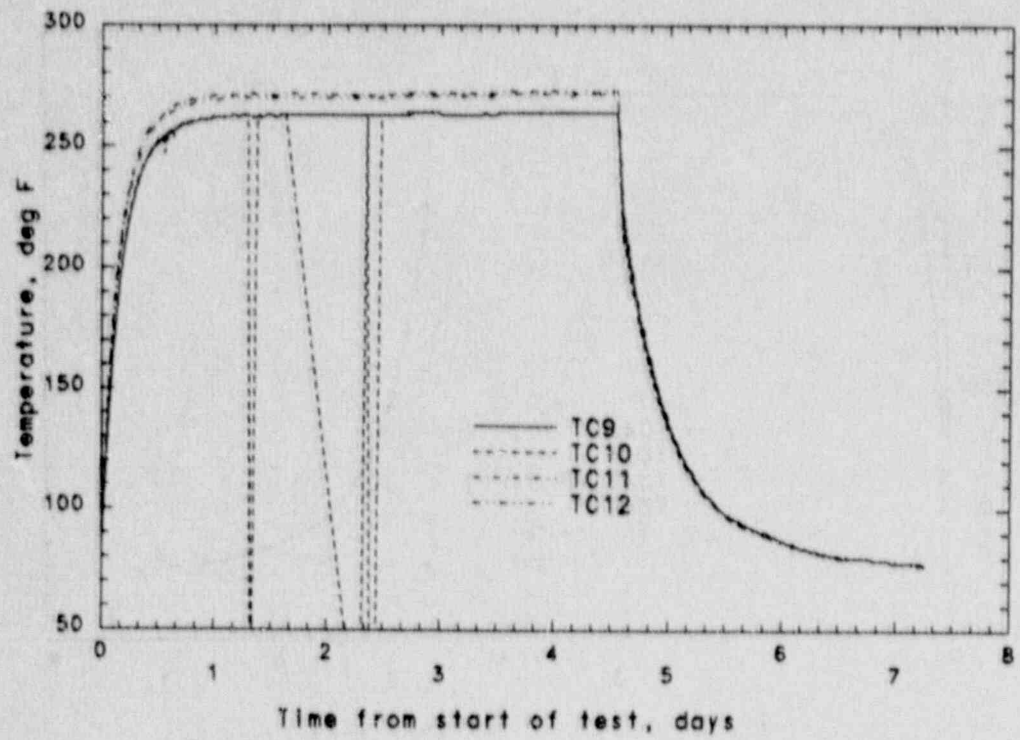

Figure 5-19 Temperature of Weldneck Flange During Thermal Aging

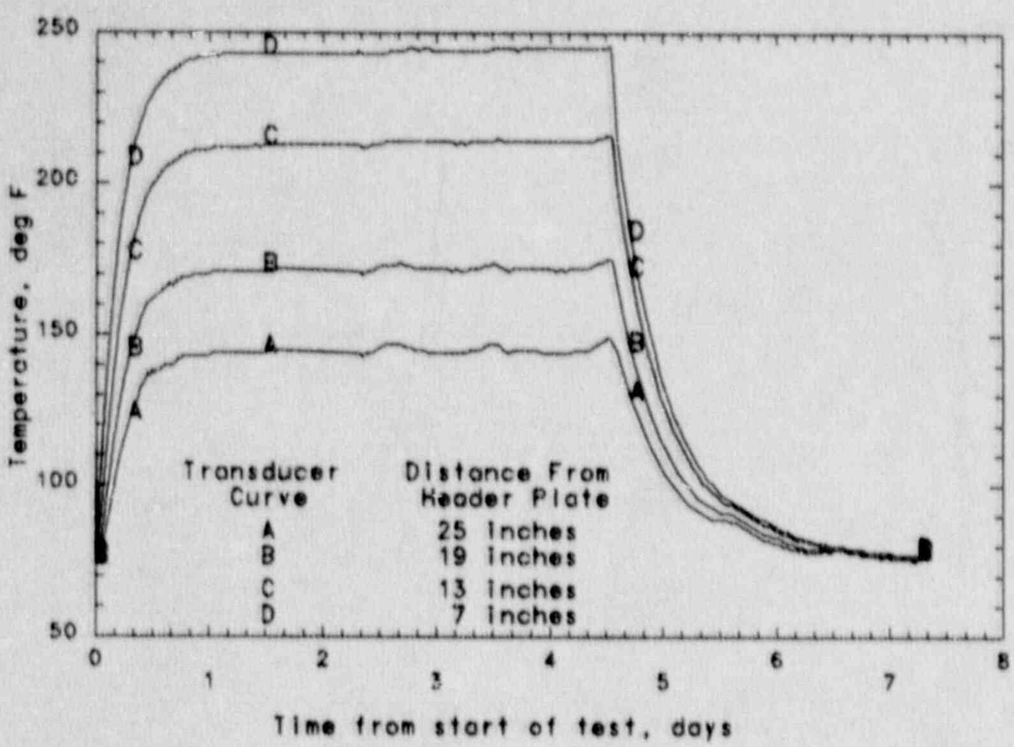

Figure 5-20 Nozzle Temperature at Position 1 During Thermal Aging

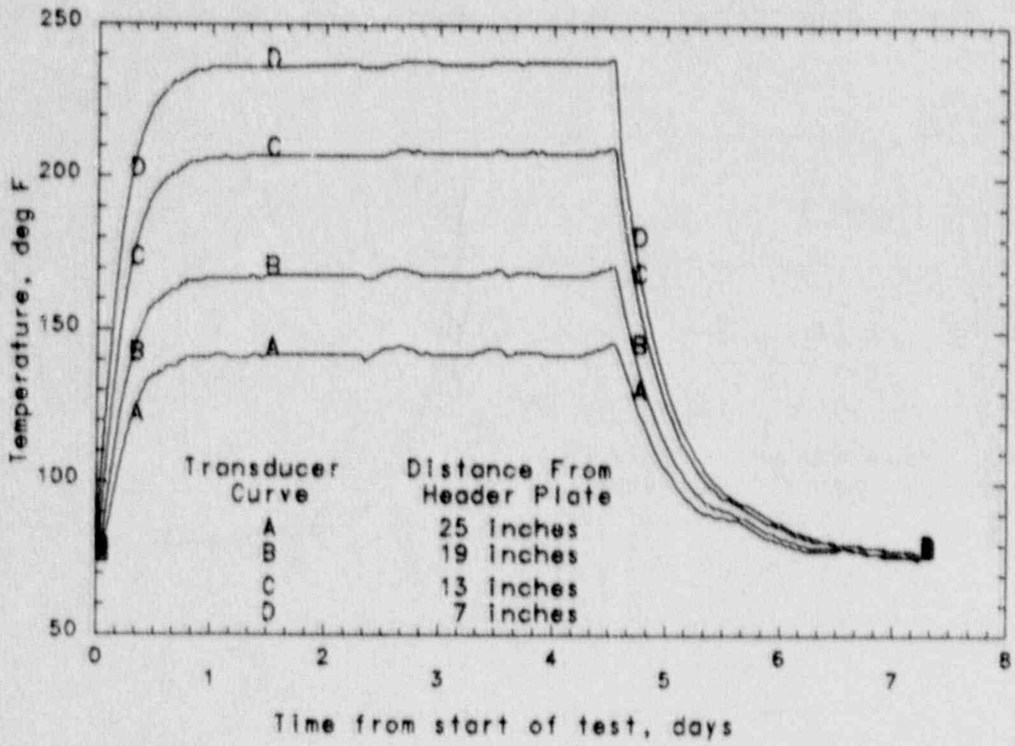

Figure 5-21 Nozzle Temperature at Position 2 During Thermal Aging

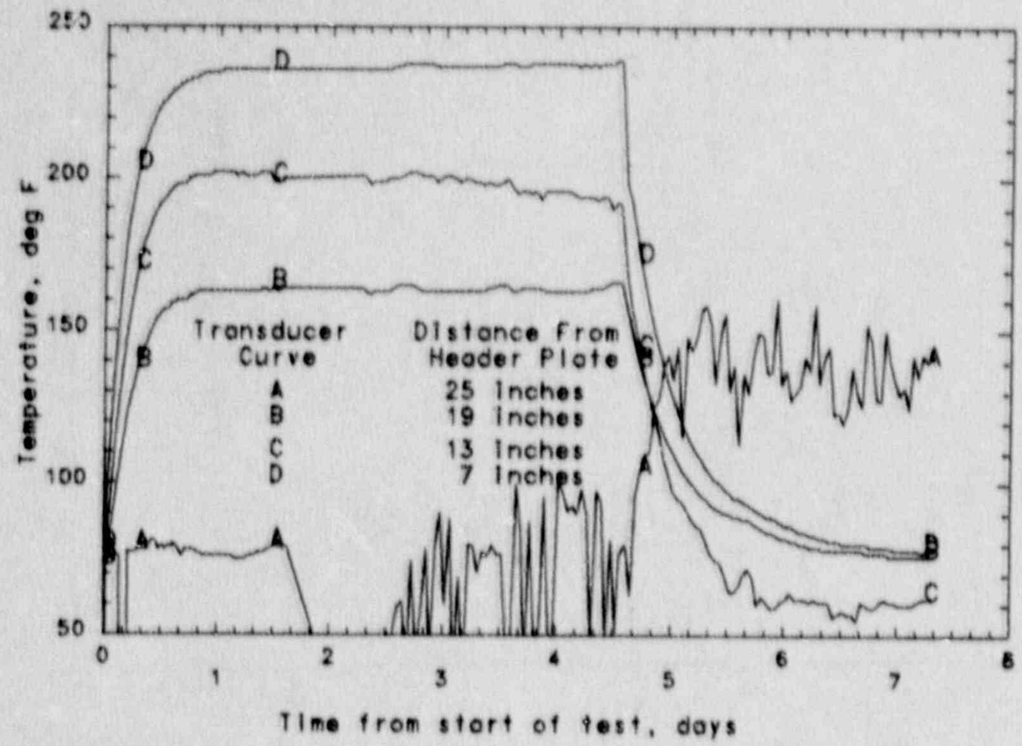

Figure 5-22 Nozzle Temperature at Position 3 During Thermal Aging

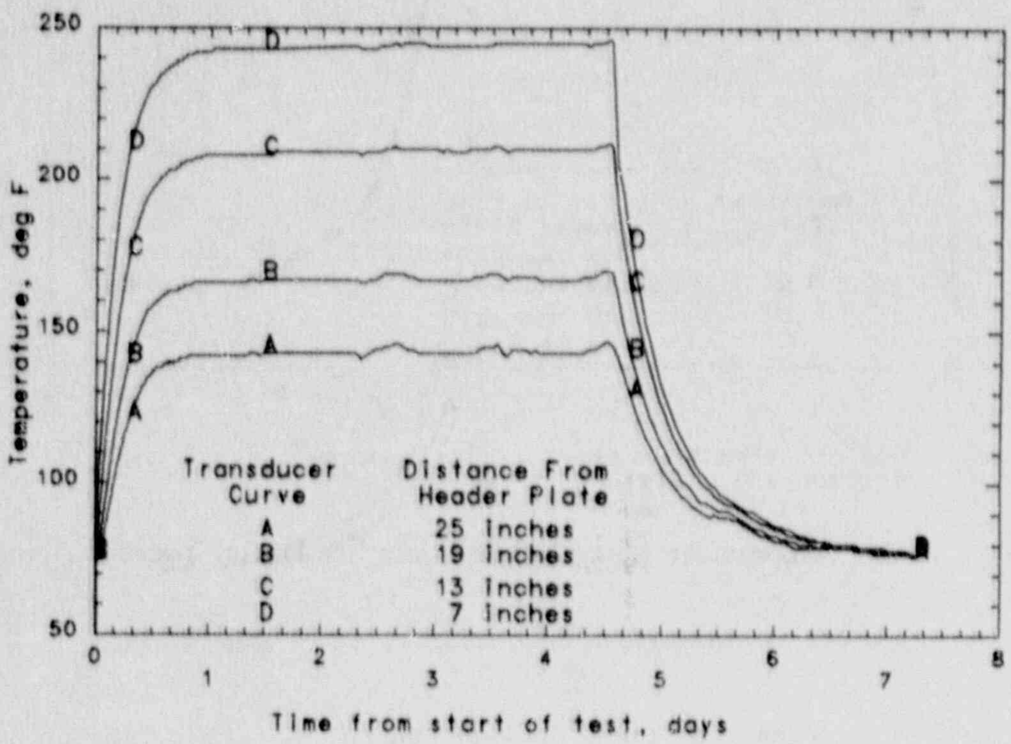

Figure 5-23 Nozzle Temperature at Position 4 During Thermal Aging

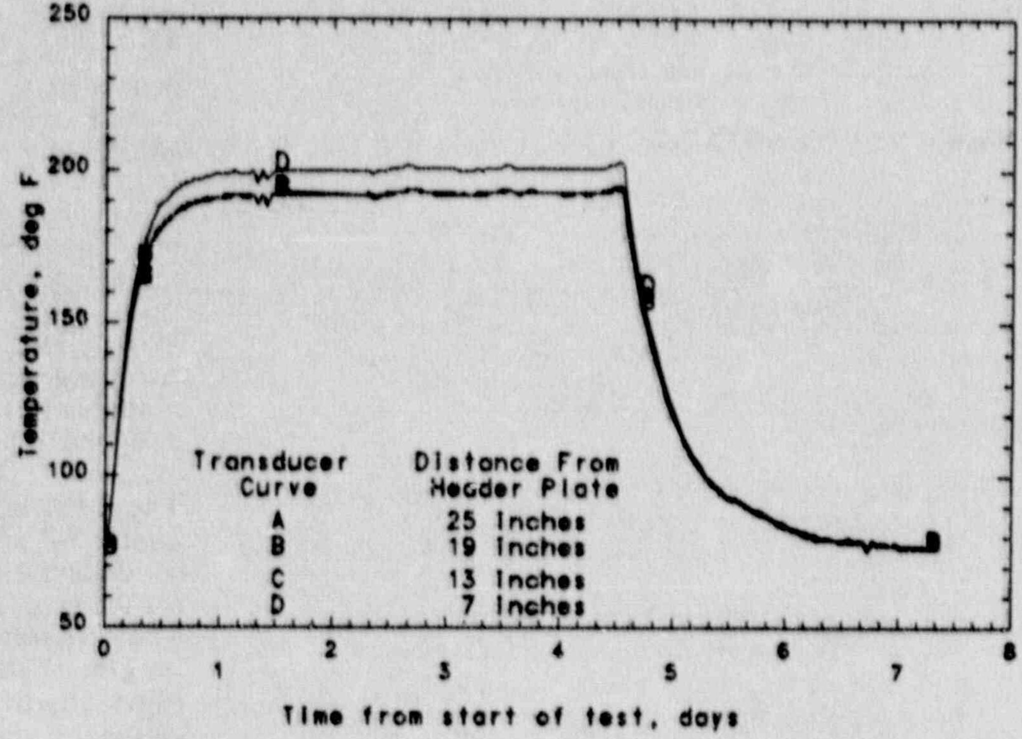

Figure 5-24 Air Temperature Along Nozzle Centerline During Thermal Aging

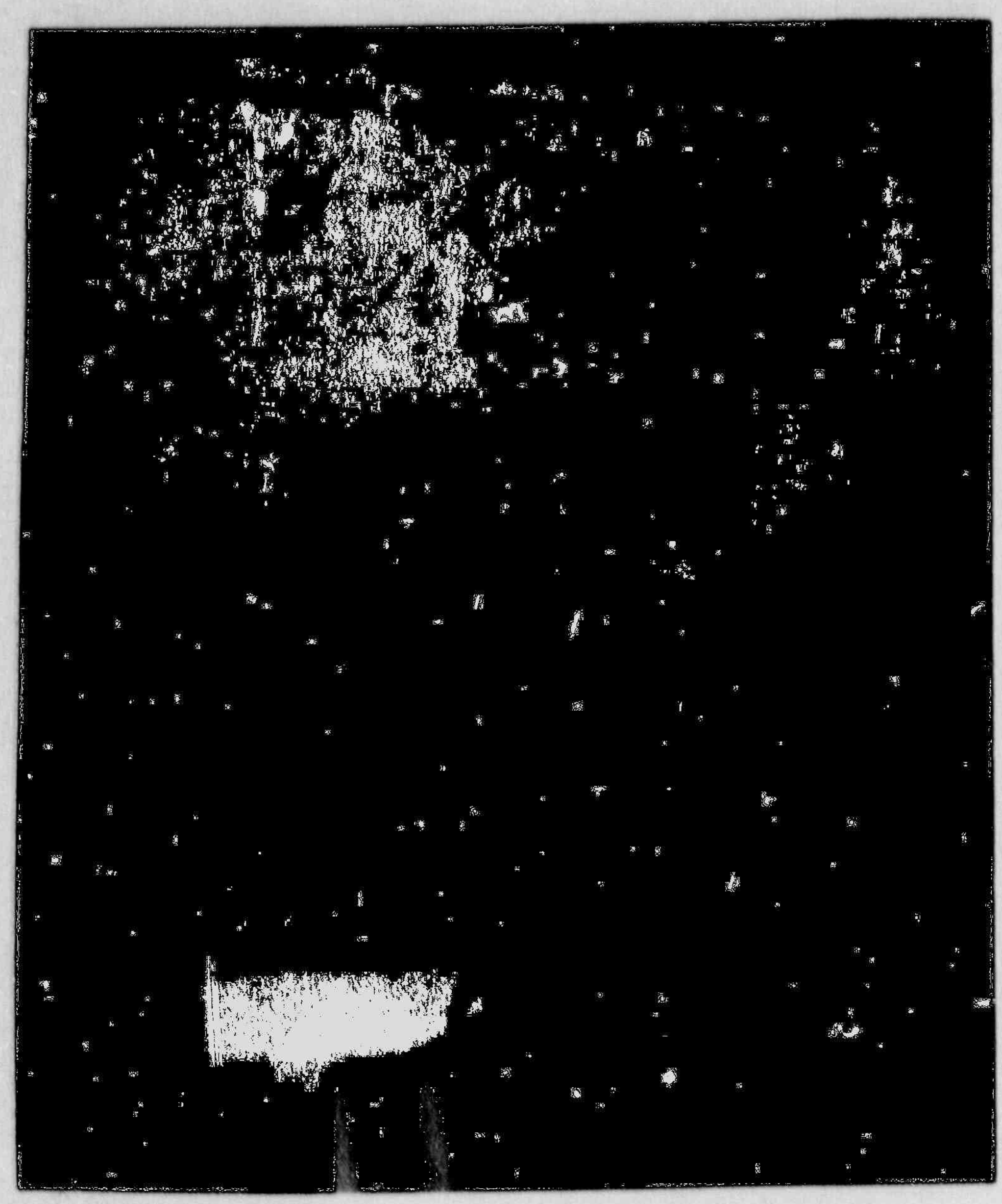

Figure 5-25 Intentional Cuts and Condition of Cables after Thermal Aging

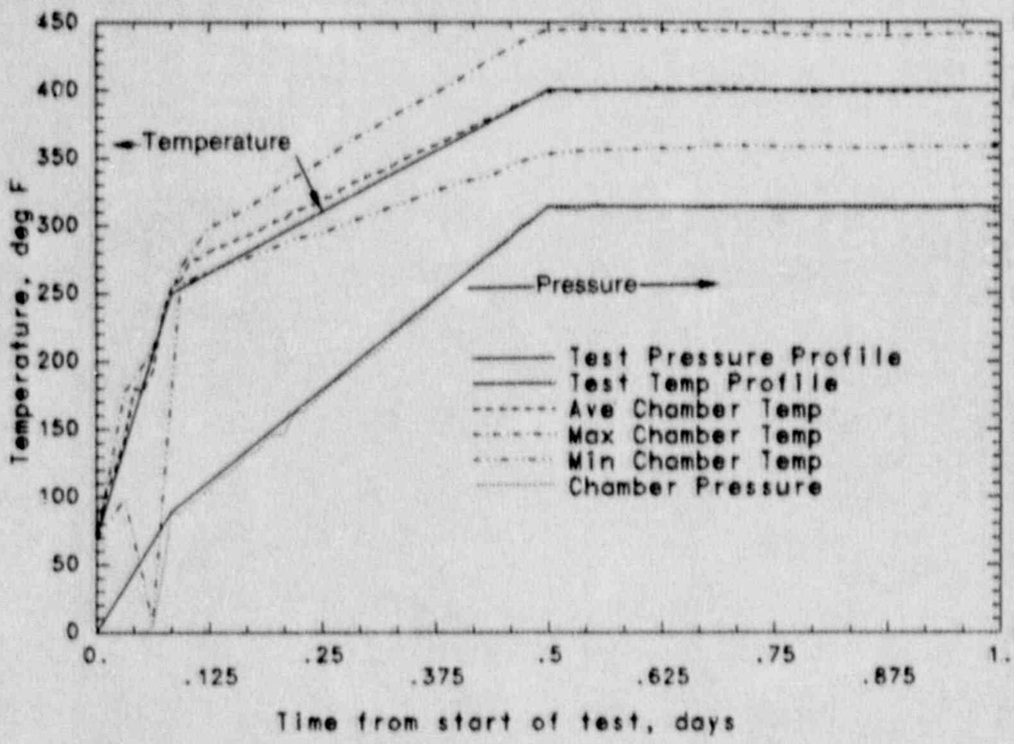

Figure 5-26 SAC Test Pressure and Temperature Profiles

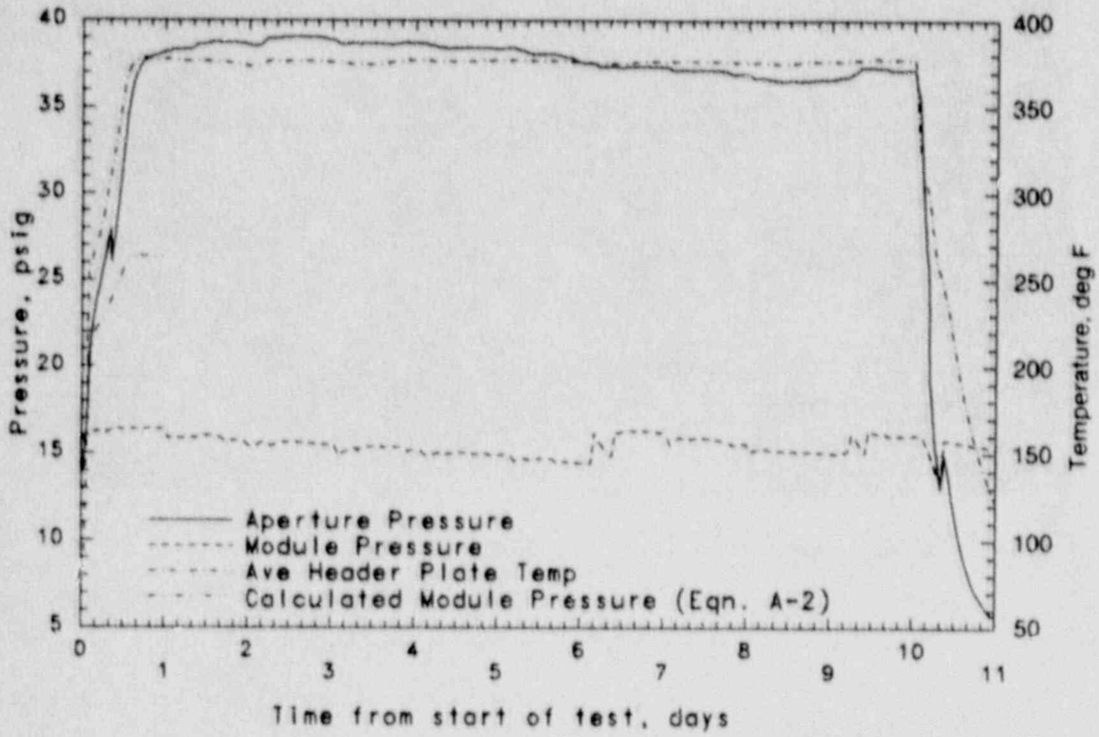

Figure 5-27 Module and Aperture Seal Pressures During the SAC Test

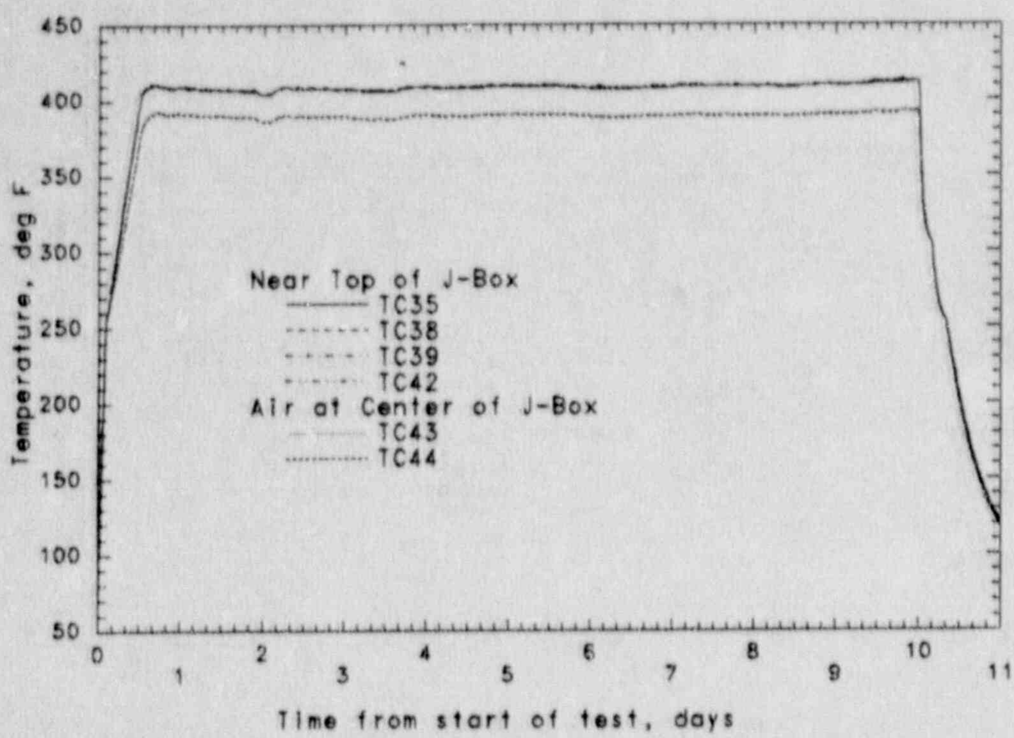

Figure 5-28 Temperature Inside Junction Box, Near Top

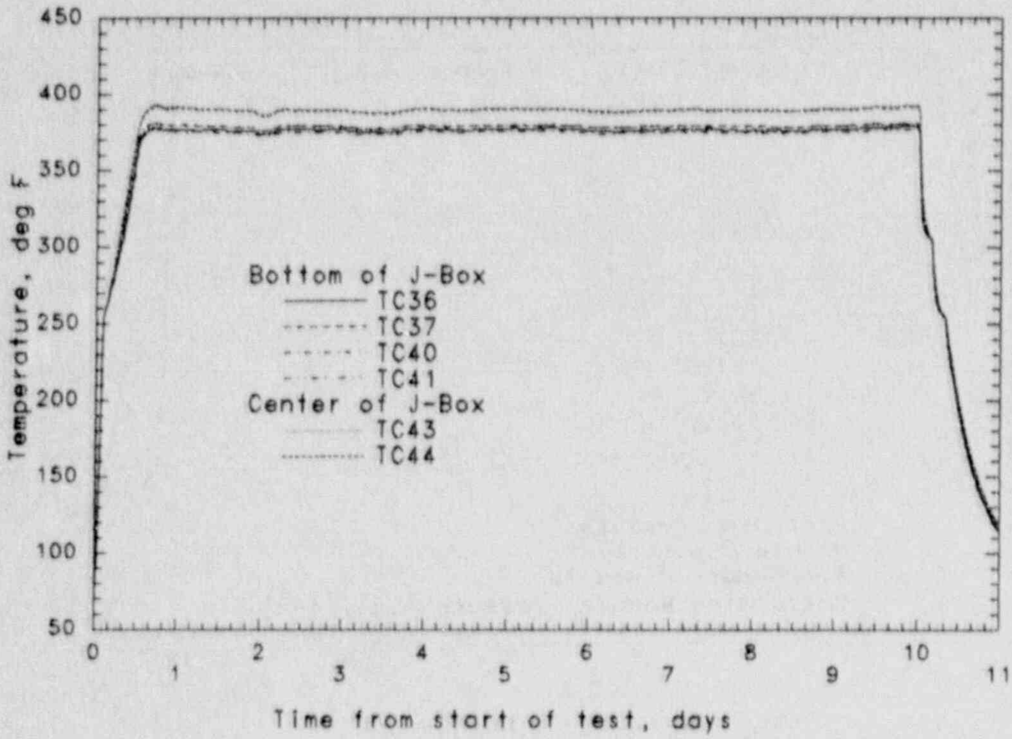

Figure 5-29 Temperature Inside Junction Box, Near Bottom

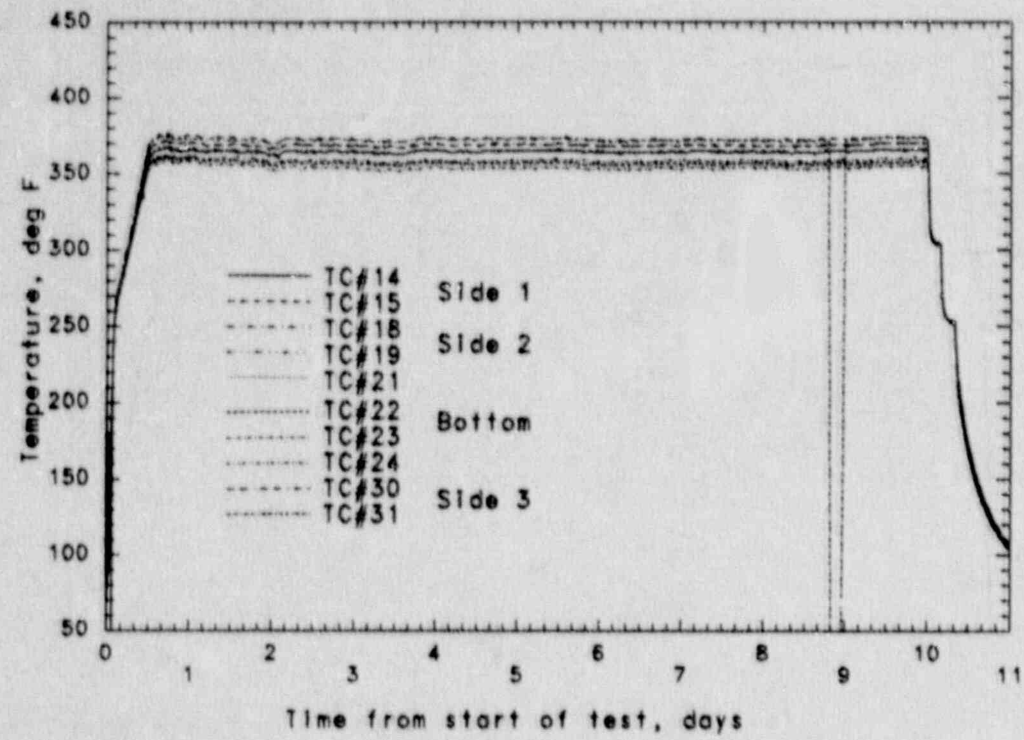

Figure 5-30 Temperature on Bottom Outside of Junction Box

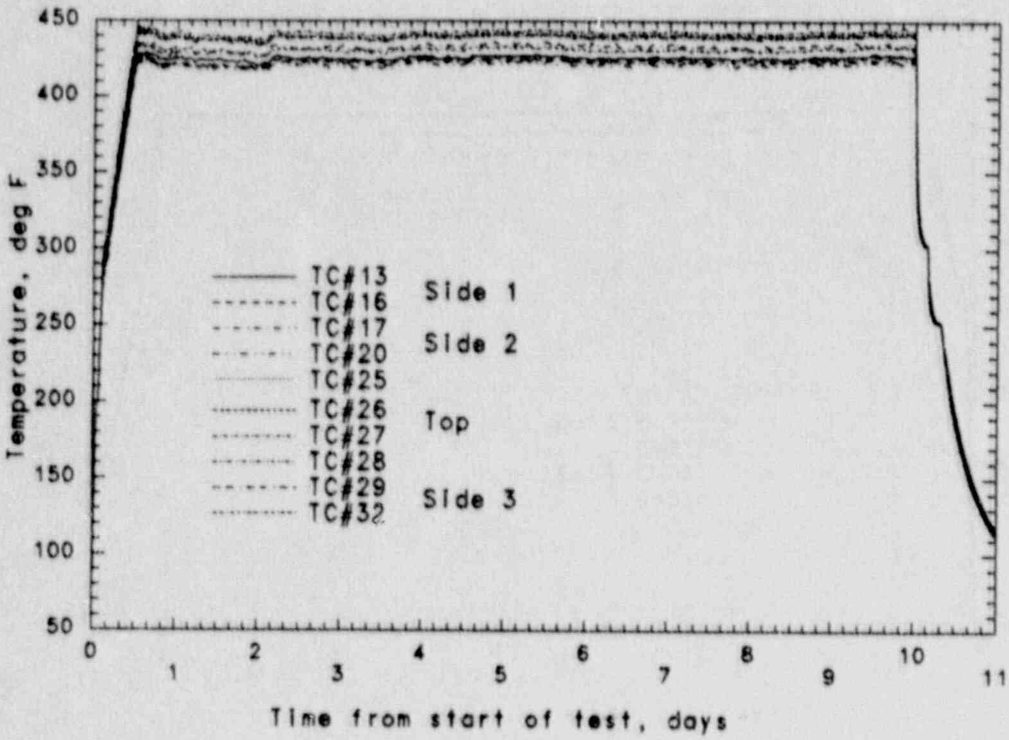

Figure 5-31 Temperature on Top Outside of Junction Box

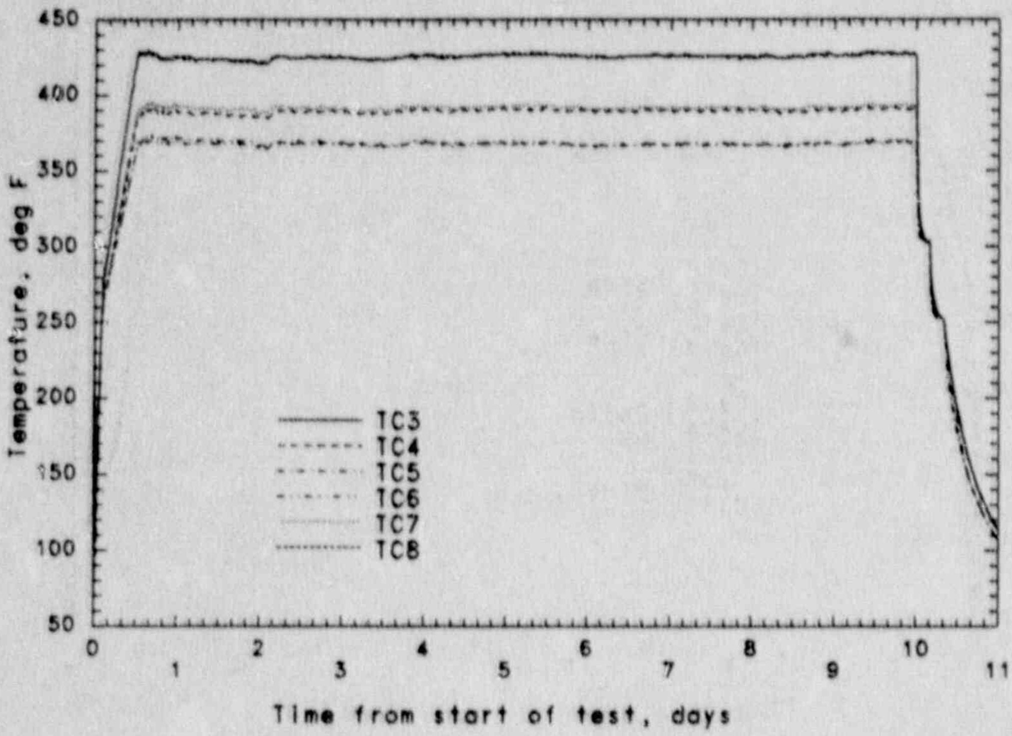

Figure 5-32 Temperature Near Mounting Plate

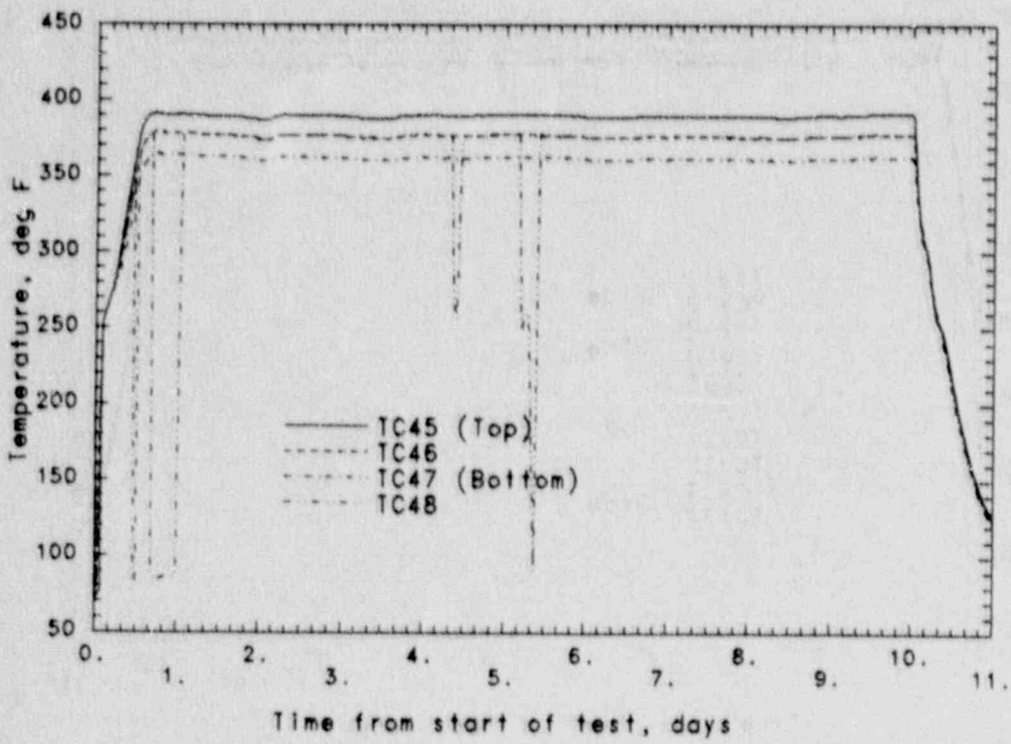

Figure 5-33 Temperature of Header Plate

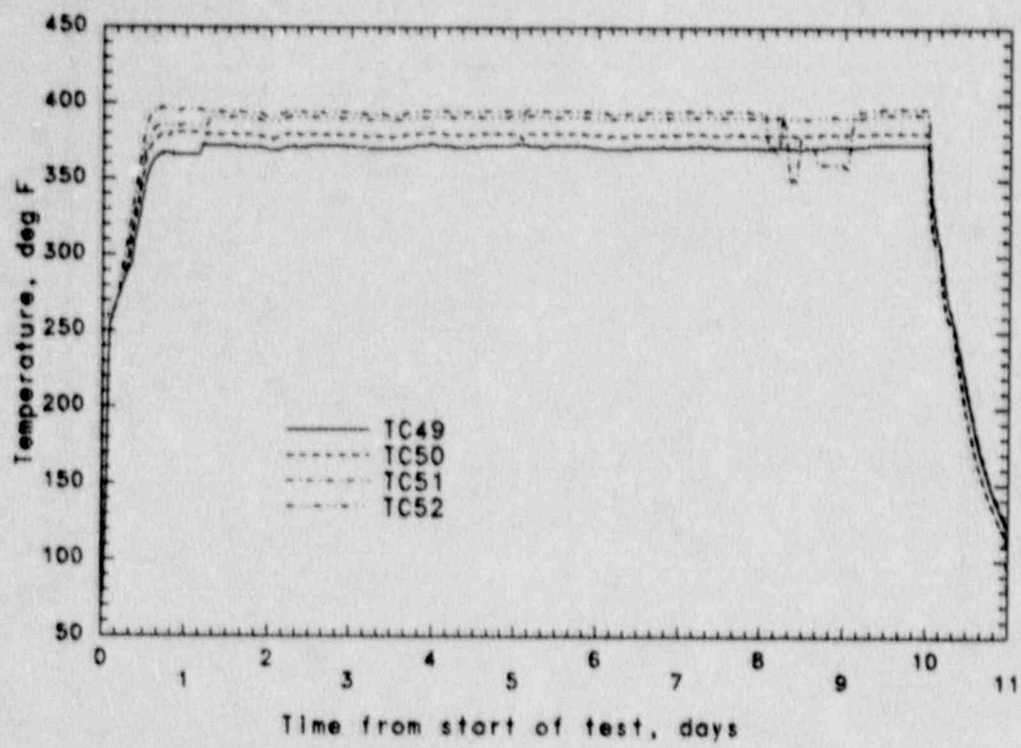

Figure 5-34 Temperature Near Inside Module Seals

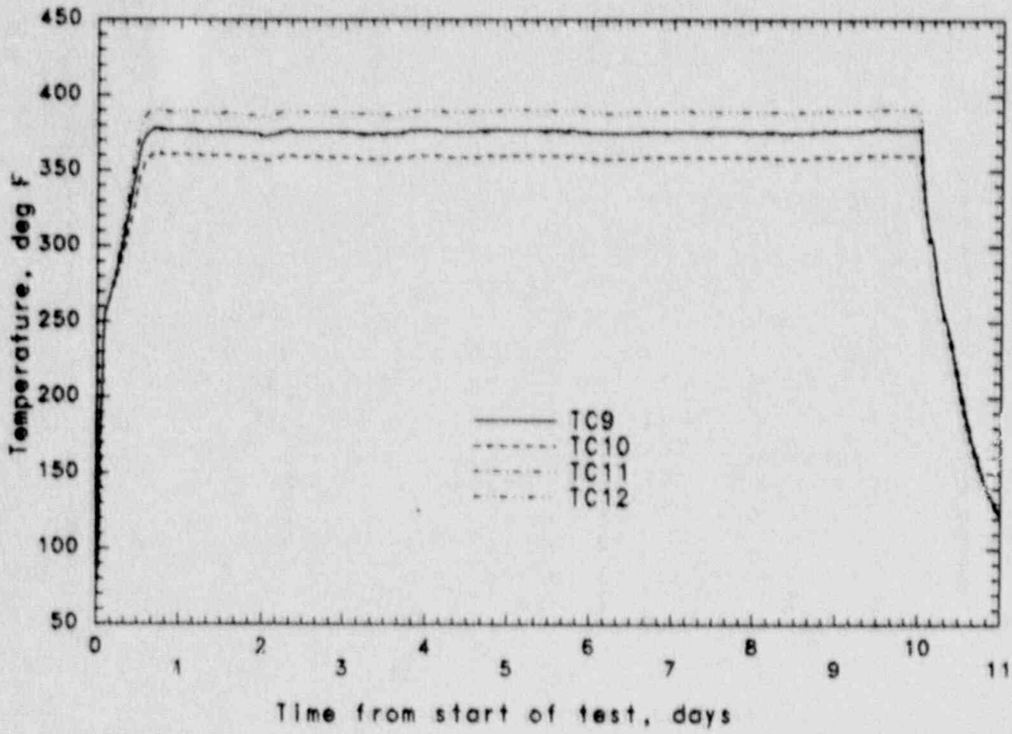

Figure 5-35 Temperature of Weldneck Flange

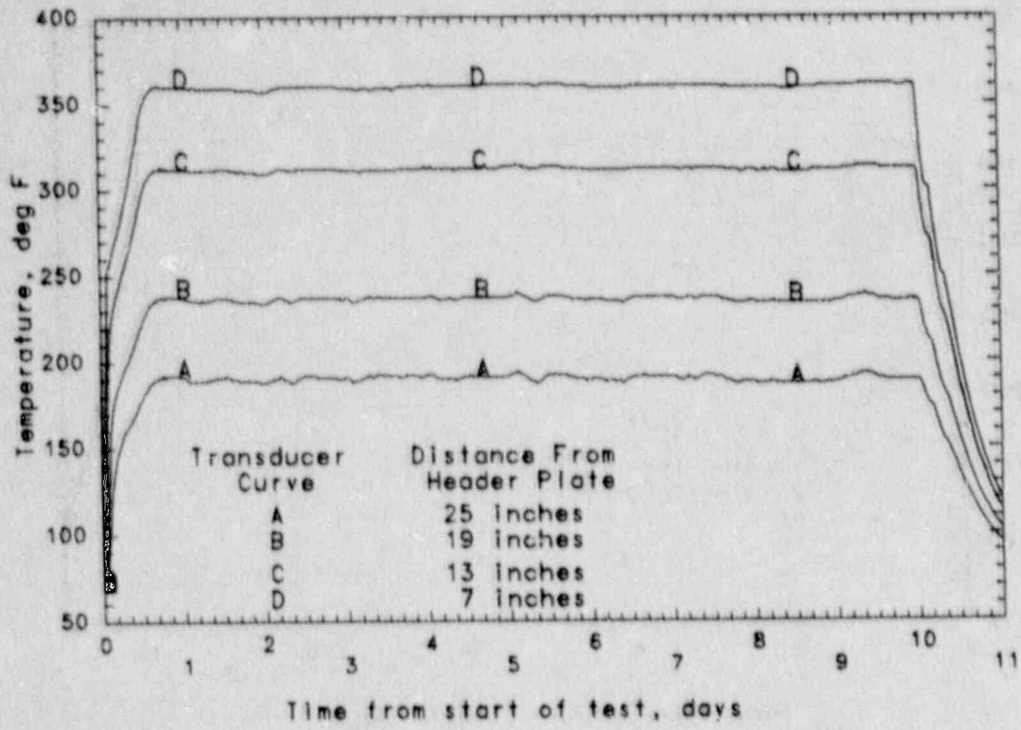

Figure 5-36 Nozzle Temperature at Position 1

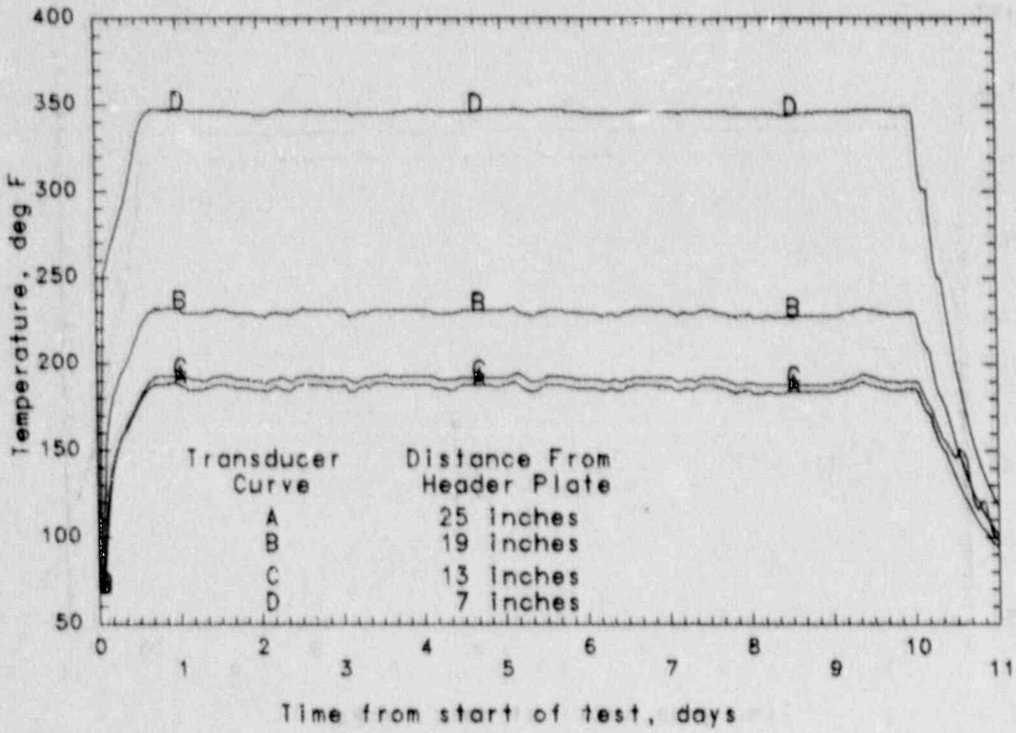

Figure 5-37 Nozzle Temperature at Position 2

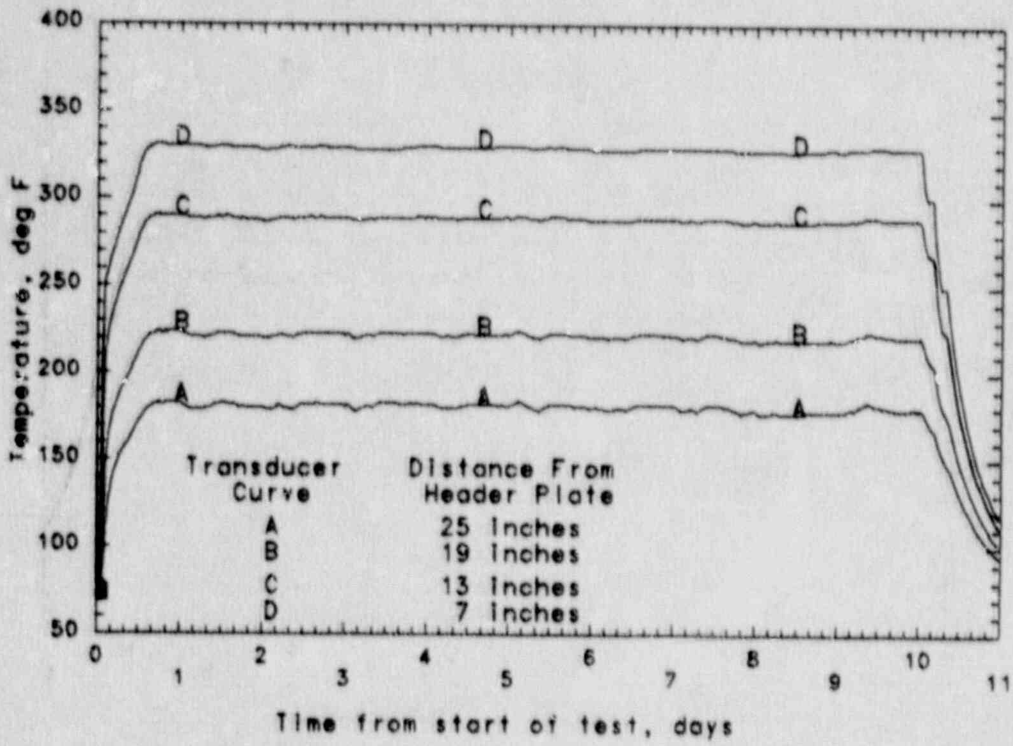

Figure 5-38 Nozzle Temperature at Position 3

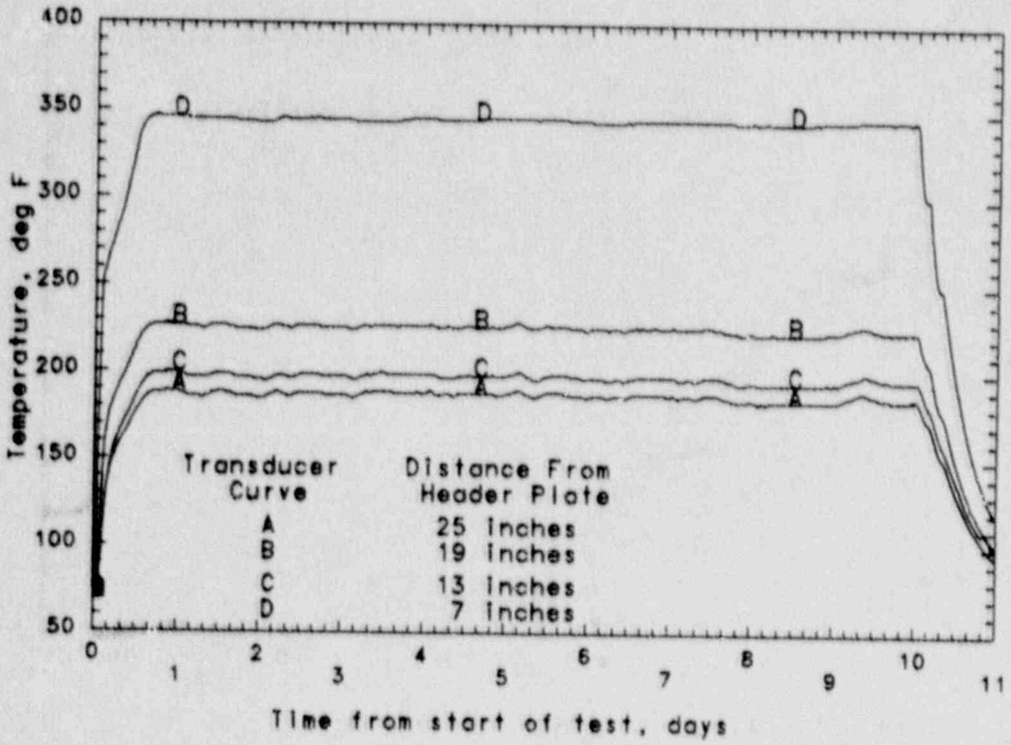

Figure 5-39 Nozzle Temperature at Position 4

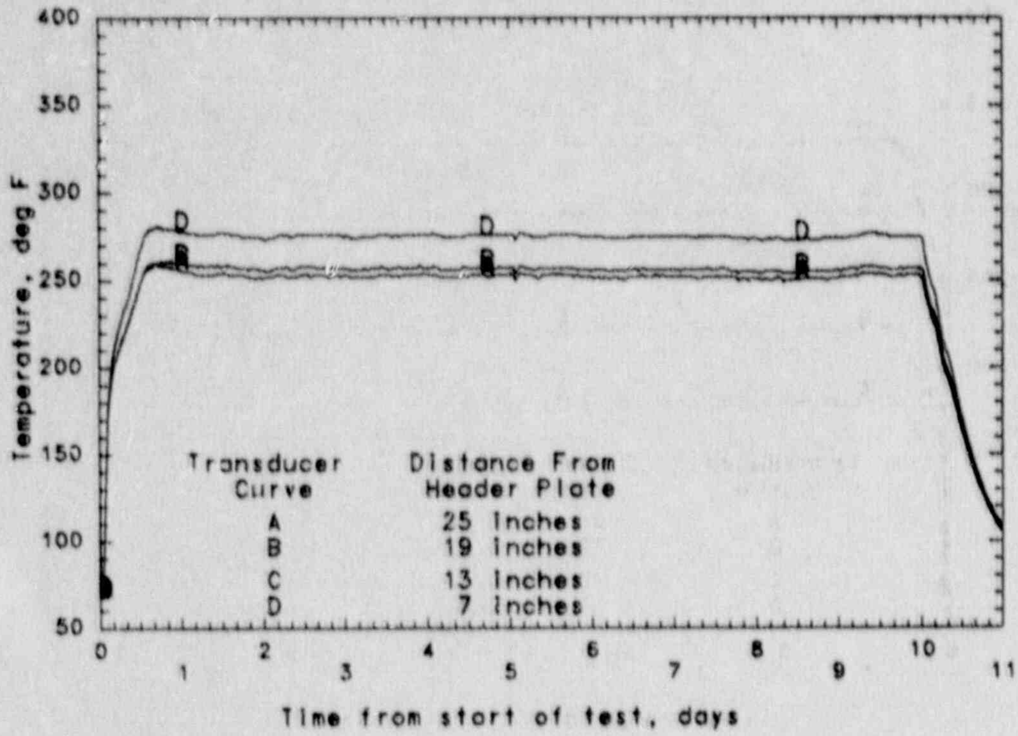

Figure 5-40 Air Temperature Along Nozzle Centerline

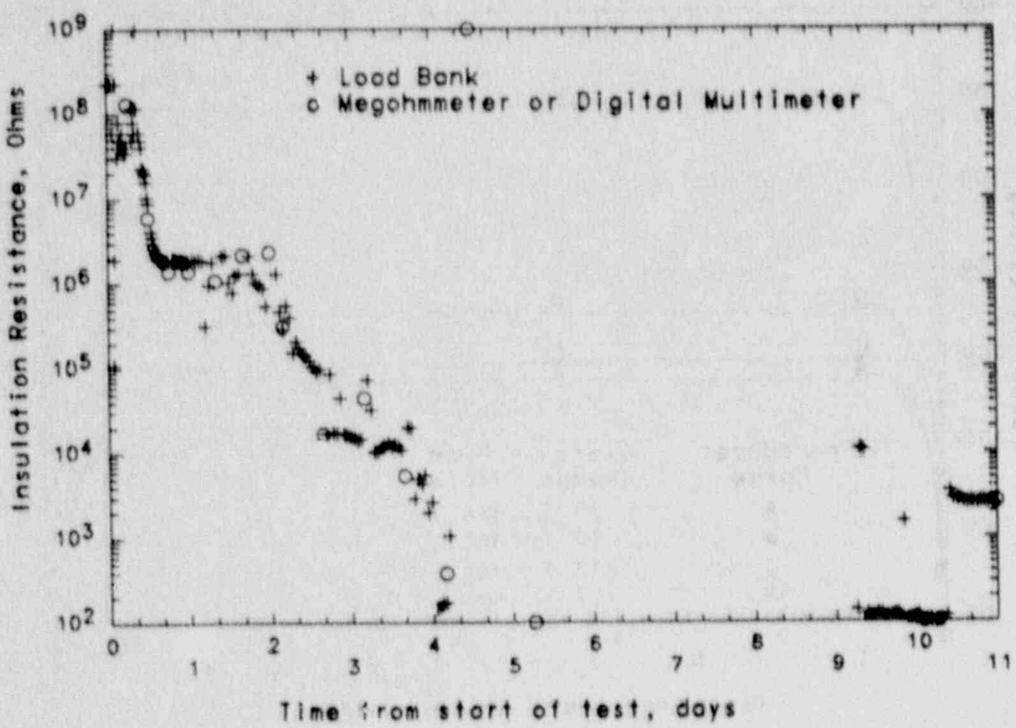

Figure 5-41 Insulation Resistance--ITT Suprenant Type KX, Red Conductor

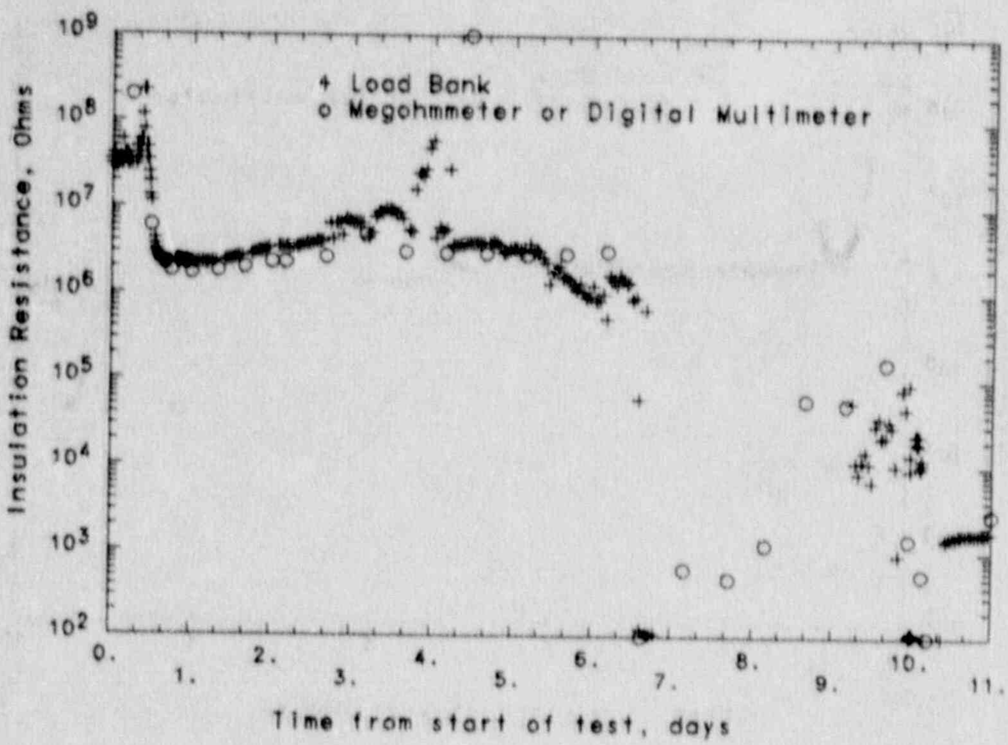

Figure 5-42 Insulation Resistance--ITT Suprenant Type KX, Yellow Conductor

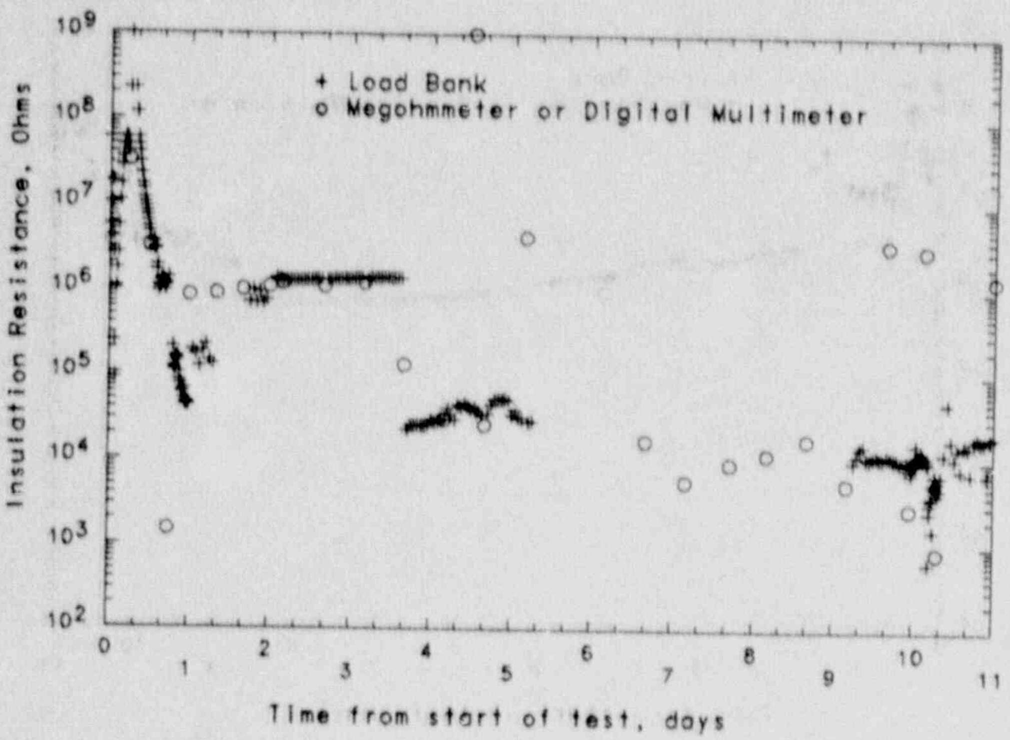

Figure 5-43 Insulation Resistance--ITT Suprenant Type EX, Red Conductor

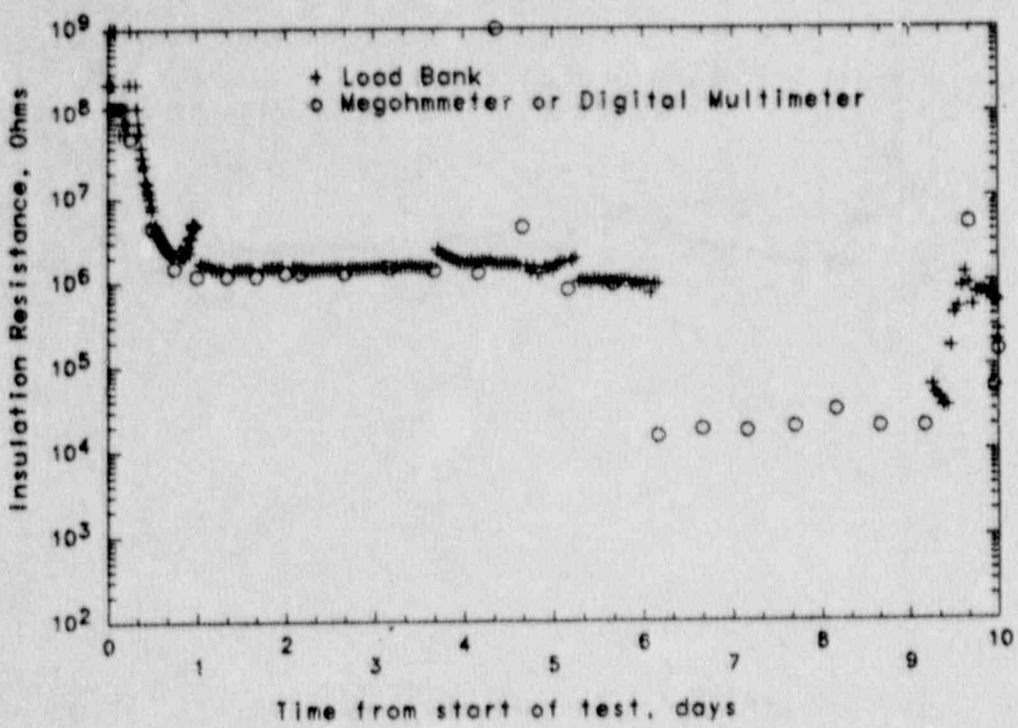

Figure 5-44 Insulation Resistance--ITT Suprenant Type EX, Purple Conductor

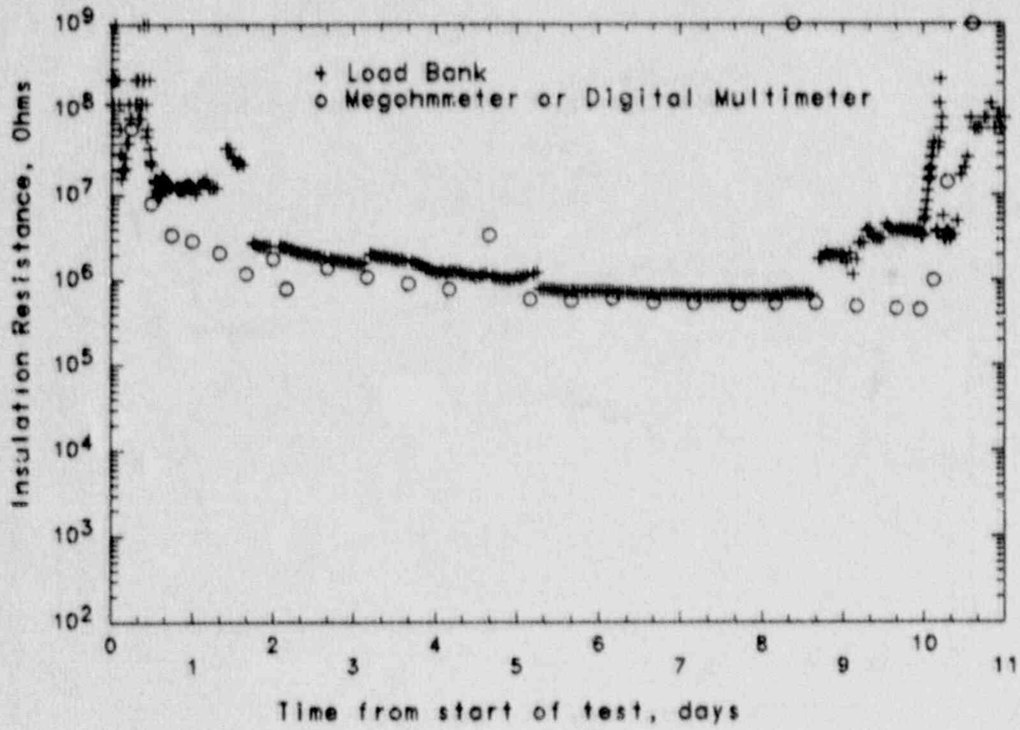

Figure 5-45 Insulation Resistance--Rockbestos, Black Conductor

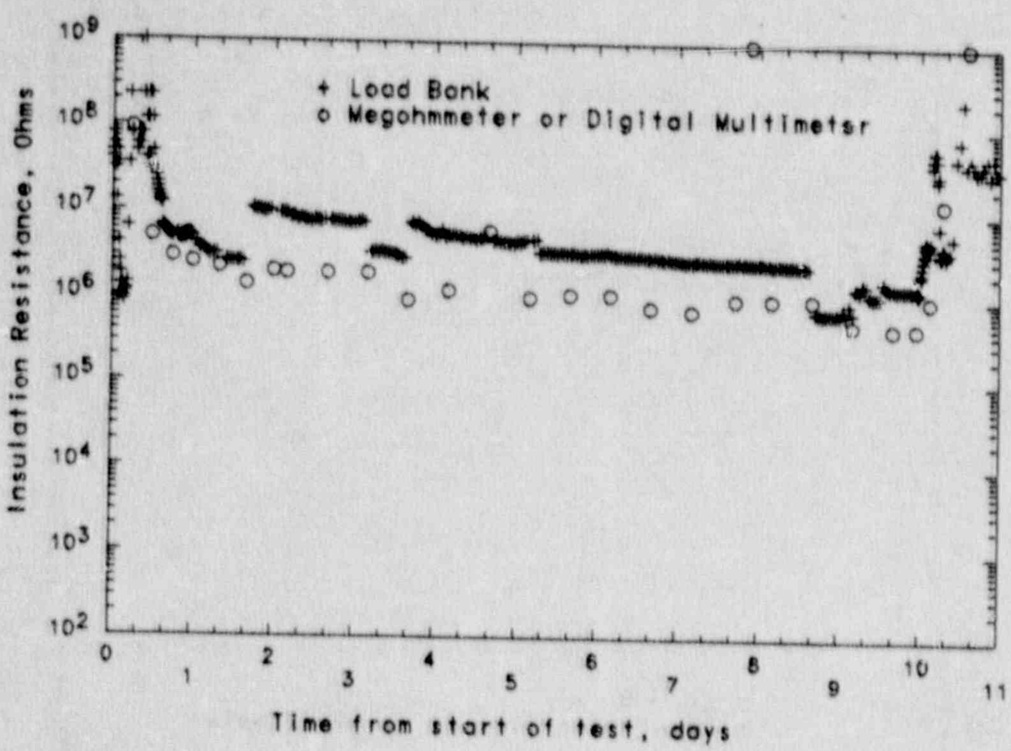

Figure 5-46 Insulation Resistance--Rockbestos, White Conductor

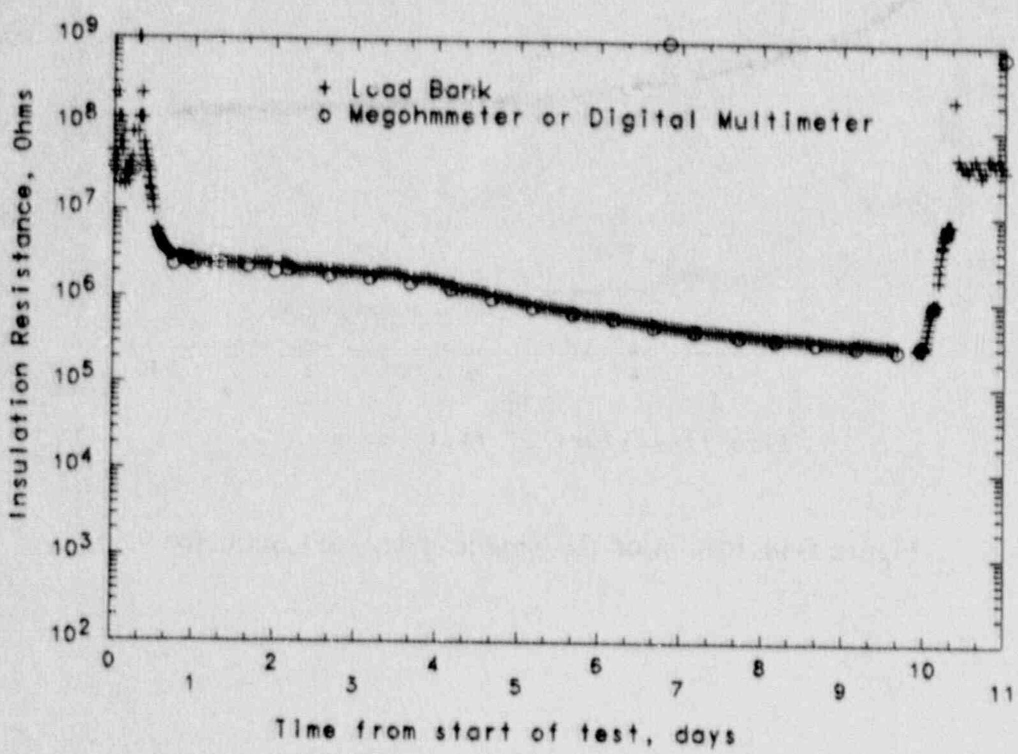

Figure 5-47 Insulation Resistance--Raychem Conductor

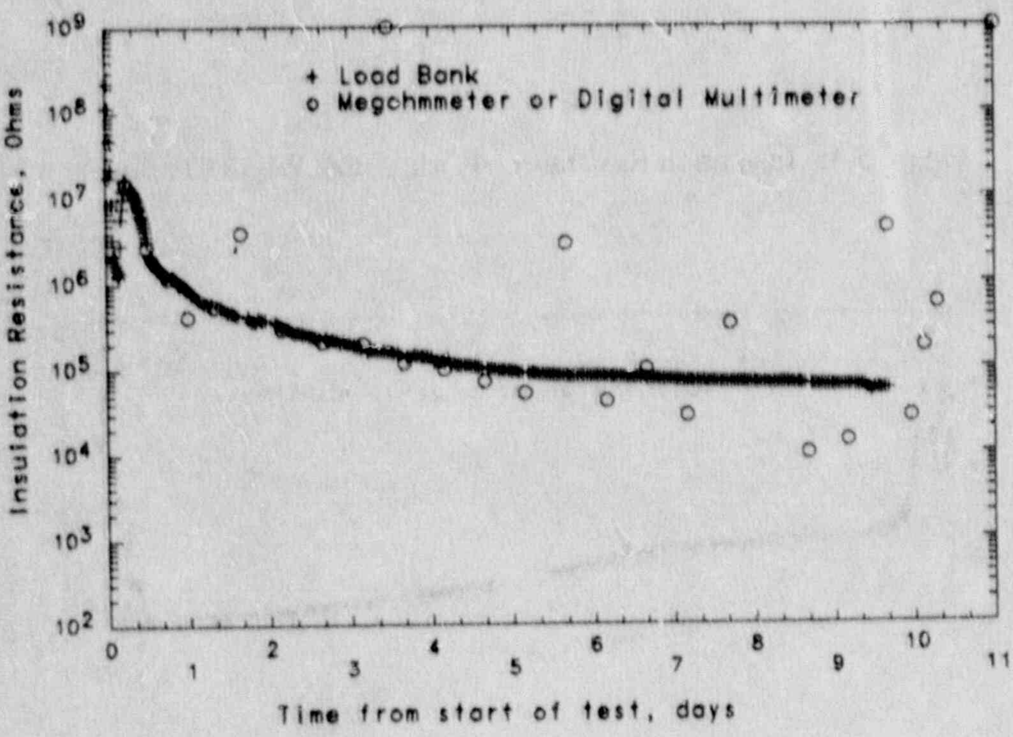

Figure 5-48 Insulation Resistance--Okonite Conductor

Figure 5-49 Post-SAC Test: Condition of Cables Inside Junction Box

6.0 CONAX EPA[11]

6.1 Design and Certification

The design of the Conax EPA tested in this program (Conax C/N 7789) is similar to that used in BWR Mark I plants such as Brown's Ferry 1 and 2 and Fermi 2 nuclear power stations. The EPA was a Low Voltage Penetration Assembly with twelve modules, which represented a typical cable mix for power, control, and instrumentation functions. The qualification standards were IEEE 317-1976 and IEEE 323-1974.

The EPA consisted of seven major components as shown in Figure 6-1: twelve electrical penetration modules, a header plate fabricated from a 12 in.-150# blind flange, a 12 in.-150# weldneck flange, a nozzle fabricated from 12 in. Schedule 80 pipe, support plates for the modules, a 12 in.-150# slip on flange, and a junction box on the inside end.

The header plate was attached to the weldneck flange with twelve 7/8 in. nuts and bolts, which were torqued in five increments to a final value of 70 ft-lbs. Two viton O-rings were used to maintain a seal. Details of the sealing surfaces and the bolt torquing sequence are shown in Figure 6-2. Note that the header plate is installed on the outboard (outside containment) end of the sleeve, which is opposite of the location of the header plate in the D.G. O'Brien and Westinghouse EPAs. The modules and the header plate were not installed in the nozzle until after thermal aging of the inside containment seals was completed. The annular area between the two O-rings was pressurized to 15 psig with nitrogen gas and the pressure was monitored to check leak integrity.

A junction box with overall dimensions of 22 x 22 x 24 in. deep was installed on the inside containment end of the penetration assembly. The junction box was bolted to the slip-on flange with twelve 1/2 in. nominal diameter nuts and bolts. The slip on flange was welded to the inboard end of the nozzle. As is normally the case (to facilitate cable installation and to allow direct access to connectors), the junction box was removable and an access cover was provided. The access cover made it much easier to inspect the cables and modules during the various stages of the test sequence. Note that a vent and drain hole was provided in the junction box, which was not designed to be leak-tight.

The EPA nozzle and its connection to the mounting plate for the test chamber approximated the heat sink at the junction of the EPA nozzle and the containment shell, i.e., the test EPA is connected to the mounting plate and test chamber at approximately the same position that Conax EPAs are welded to the steel containment shell in the Brown's Ferry and Fermi nuclear power plants. Since the EPA nozzles in these plants are not insulated in the annulus between the containment shell and the shield building, the nozzle was not insulated in any manner for the severe accident condition test.

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11. Mention of specific products and/or manufacturers in this document implies neither endorsement or preference nor disapproval by the U.S. Government, any of its agencies, or Sandia Corp., of the use of a specific product for any purpose.

There were a total of 16 ports in the header plate as shown in Figure 6-3. Four of these ports were plugged (5, 6, 11, and 16). A module was installed in each of the remaining ports; eight of these were low voltage feedthroughs and the other four were thermocouple feedthroughs. Each module consists of a length of stainless steel tubing with polysulfone plugs in each end of the tubing. Single strand Kapton FEP insulated wires feed through holes in the polysulfone plug. The wires are not supported within the stainless steel tubes, however, the tubes are supported by five plates (the header plate and four support plates) at approximately equal intervals along the EPA nozzle. The tubing is swaged around the plug to seal the wire in the plug and the plug to the tubing. The tubes are sealed in the header plate with Midlock connectors, which are Conax designed fittings, as shown in Figure 6-4.

The EPA was prewired by Conax using nuclear qualified polyimide (Kapton, a Dupont trademark) cable. A net series circuit was created for each module by looping the outboard and inboard ends with cables 1 foot in length, as shown in Figure 6-5. Two cables from each module, both 25 feet in length, exited the test chamber through a cable seal system developed by Sandia to prevent neck-down problems and degradation due to high temperatures. The number of conductors, wire size, and wire type used in each module are listed in Table 6-1. The type K (chromel and alumel) cables were joined to simulate thermocouple junctions at the inside containment side and were monitored as thermocouples during the severe accident condition test. The copper cables were energized during the severe accident test using the load bank, as described in the following section.

Table 6-1
Cables Used in the Conax EPA

Module	Wires per Module	Wire Size	Wire Type
1&2	12	#18 AWG	Type K
3&4	12	#12 AWG	Copper
7&8	12	#16 AWG	Copper
9&10	8	#16 AWG	Type K
12&13	30	#14 AWG	Copper
14&15	4	#8 AWG	Copper

The Conax installation manual IPS-1249 [9] required that the minimum insulation resistance from the copper cables to ground and from the copper cables to other feedthroughs be at least $1x10^8$ Ω.

6.2 Test Preparations and Procedures

Test Overview

The primary purpose of this test was to generate engineering data to evaluate the leak behavior of the EPA under severe accident conditions. As a secondary effort, the electrical degradation of the EPA cables was observed by monitoring the insulation resistance. The test profile for the Conax EPA was representative of the severe accident conditions (SAC) in a boiling water reactor (BWR) Mark I containment with steam at 135 psia and 700°F. Prior to the SAC test, the EPA was irradiated and thermally aged.

Since this was not considered a qualification or a verification test, there was no pass/fail criteria. The effects of chemical sprays, seismic loading, fault currents, preload pressure cycling, thermal cycling, and operating the cables at rated current and voltage were not addressed. The EPA was not subject to the normal LOCA qualification test profile prior to the SAC test. It must be emphasized that the SAC test is much more severe than the LOCA test.

The significant dates in the test sequence (in late 1985 and 1986) were:

Accepted EPA and nozzle assembly at Conax Corp, Buffalo NY	November
EPA stored at Conax Corp.	November to February
EPA received at Georgia Tech for irradiation	February 7, 1986
Radiation--200 Mrad dose (air)	February 12-24
EPA received at Sandia	March 10
Initial Inspection and Baseline Measurements	March 10-14
Thermal Aging of inside seals--302°F for 100 hours	May 6-10
Trial runs with modified steam system	May 22-27
Install EPA in nozzle and instrument	May 28 -June 2
Thermal aging of outside seals--250°F for 100 hours	June 2-6
Final preparations for SAC test	June 9-13
Air Leak Test at 60-100°F and 70-80 psia	
Severe Accident Test (steam)	June 16-26
Cool-down to room temperature	June 26-30
Air Leak Test at 135 psia	June 30
Tear down and inspection	June 30 - July 3

Test Equipment

The SAC loads were applied in an environmental chamber, which was modified to accept the EPA fixture as shown in Figure 6-6. For this test, a portable steam system was rented to supplement the steam system used for the D. G. O'Brien and the Westinghouse EPA SAC tests because of the higher temperature and short rise required by the test profile for the BWR Mark I.

Pressure gages connected to lines to the O-ring aperture seal and the modules were monitored to detect leakage into the gap between the two O-rings on the header plate and into the modules, respectively. However, these systems monitor leak-integrity of components of the EPA; failure of these components does not necessarily indicate a loss of containment integrity. Therefore, a system to measure the total leakage to outside of the containment boundary was developed[12]. Leakage past the EPA must flow into the chamber formed by the EPA nozzle where it would then be piped through condensing equipment. The measurement technique relied on measuring condensate over a known period of time. This system proved accurate and reliable for the range of approximately 1 scc/sec to 10,000 scc/sec. Since leakage past the EPA was not detected during the steam (SAC) test, details of this measurement system are not included in this report.

Type K thermocouples were installed after the EPA was received at Sandia and before the EPA was installed in its nozzle. The locations of gages are indicated in Figures 6-7 through 6-10.

Each copper cable circuit (Modules 3, 4, 7, 8, 12, 13, 14, and 15) was matched with a separate electrical power supply and a monitoring circuit, which are collectively referred to as the load bank. By observing the voltage drop in the monitoring circuit, the insulation resistance and continuity of each cable circuit could be determined, as described later in this section. A direct current of 1/2 amp from the 28 volt power supply was applied to all copper cables during the severe accident condition test. The cables were not energized during either radiation aging or thermal aging. A wiring schematic for the load bank is shown in Figure 6-11. The output from the monitoring circuit was recorded on an automatic datalogger.

Insulation resistance was also measured at 50 to 500 VDC with a Hippotronics Megohm Meter for all cable loops except the thermocouple cables (modules 1-2 and 9-10), which were monitored with the Digital Multimeter. Thermocouples are normally low impedance sources and it was felt that high voltage measurements could cause atypical damage to the insulation. If the insulation resistance of a copper cable dropped below 0.1 MΩ at 50 VDC, the Digital Multimeter was used to measure insulation resistance of that cable. These insulation resistance measurements were made at regular intervals before, during, and after thermal aging and the severe accident condition test.

Radiation Aging

The EPA was irradiated at Neely Nuclear Research Institute, Georgia Institute of Technology for Irradiation because it was too large to be irradiated at Sandia's facility. Only the inboard end of the EPA was irradiated. The source consisted of eight rectangular trays (8 x 13 in.) that each held eight flat strips of cobalt 60. The trays were positioned around the inside containment seals of the modules as shown in Figure 6-12. The trays were removed twice so that irradiation could be completed during normal working hours. The dose rate measured at the center of the EPA near the end support plate was about 0.8 Mrad/hr (air equivalent). The total exposure time was 248.6 hours and the cumulative dose was approximately 200 Mrads.

The module pressure remained at about 17 psig during and after irradiation and there was no detectable leakage past the module seals. (The EPA was not installed

12. This system has been documented in a draft report available in the NRC PDR by J. W. Grossman, F. V. Thome, and G. M. Dibisceglie, "Flow Measurement Techniques for Evaluating Leak Behavior Through Electrical Penetration Assemblies Under Severe Accident Conditions," Sandia National Laboratories, Albuquerque, NM, February 1987.

in its nozzle during irradiation so obviously the aperture seal pressure was not monitored. This also means that the viton O-rings were not irradiated; degradation of the viton O-rings due to irradiation was not considered in the severe accident test.)

Initial Inspection

Upon receipt at Sandia on March 10, the EPA was inspected and found to be in good condition. The module pressure was about 20 psig; the increase of about 3 psig from the last value recorded at Georgia Tech is reasonable when differences in altitude and temperature are considered. There was no measurable drop in the module pressure during the ensuing one week period.

The insulation resistance to ground of the copper cables was measured with the Megohm meter at 500 VDC. The Digital multimeter was used to measure the insulation resistance to ground of the thermocouple cables. The copper cables had insulation resistances from $2.9x10^{11}$ Ω to $1.1x10^{12}$ Ω at the time of the initial inspection. The insulation resistances of the thermocouple cables were all above the maximum range of the digital multimeter, which was approximately $3x10^7$ Ω.

Thermal Aging of the Inside Containment Seals

The polysulfone seals in the modules at the inside containment end were thermally aged at 302°F for 100 hours. The control temperature was the average value from six thermocouples (gages 23-28, see Figure 6-8) attached to the feedthrough modules. The start of thermal aging was taken to be that time when the control temperature first reached 291°F. The section of the EPA that was enclosed in the aging oven included about a 10 in. length of the modules at the inside containment end, as shown in Figure 6-13. The size of the oven was based on the length of the polysulfone seal in the stainless steel tubing, which was about 7 in.. The cables were not energized during thermal aging.

Just prior to thermal aging of the inside containment seals, the copper cables had insulation resistances to ground from $0.43x10^{12}$ Ω to $2.5x10^{12}$ Ω at 500 VDC (measured with the Megohm meter). During thermal aging, the copper cables had insulation resistances to ground from $0.34x10^{11}$ Ω to $7.5x10^{11}$ Ω at 500 VDC. Immediately after cooling from thermal aging, the copper cables had insulation resistances to ground from $0.5x10^{12}$ Ω to $2.5x10^{12}$ Ω at 500 VDC. Details of the insulation resistance measurements are given in Table 6-2. The insulation resistance of all the copper cables decreased by about an order of magnitude after the first day of thermal aging and then slowly recovered. However, the insulation resistance of all copper cables exceeded the minimum design requirement throughout the thermal aging process.

The insulation resistance to ground for all thermocouples cables was above the maximum range of the digital multimeter ($3x10^7$ Ω) before, during, and after thermal aging of the inside seals.

The module pressure initially increased during thermal aging, but then remained constant once thermal equilibrium was achieved. However, during or after cooling, the module pressure dropped to 0 psig. The module volume was pressurized to 75 psig and the leak was isolated to the #1 module. The leak rate at 75 psig was roughly 5 scc/sec; at 20 psig, the leak rate was about 1 scc/sec. The #1 module was removed and sent to Conax for evaluation. Conax provided a plug so that the header plate could be sealed.

Table 6-2
Insulation Resistance Measurements--Thermal Aging of Inside Containment Seals

Module Number	Before Aging	Insulation Resistance (x10⁹ Ω) at Indicated Time After Aging for 1 Day	2 Days	3 Days	4 Days	5 Days	Before SAC Test
3	2000	99	200	290	250	330	2000
4	1200	82	160	250	230	290	1500
7	1400	130	190	300	350	410	1400
8	1300	98	250	350	300	320	1200
12	650	44	61	80	65	72	900
13	430	34	51	75	65	340	500
14	2500	210	340	400	500	470	2500
15	2500	340	510	550	700	750	2200

With the plug installed, the module was pressurized to 75 psig and pressure drop tested over 5 days. The leak rate over this period was $1x10^{-5}$ scc/sec, which was less than the maximum permissible leak rate (specified by Conax) of $1x10^{-2}$ scc/sec. A drop test at 20 psig produced no noticeable change in gauge pressure and consequently the leak rate was too small to be calculated accurately.

Although the #1 module developed a leak, it occurred at an inside containment seal and the SAC test demonstrated that the outside containment seals would have prevented leakage beyond the EPA pressure boundary. Thus, removal of this module did not alter the results of the severe accident condition test. The leak was probably a result of a combination of factors including an improperly swaged tube, differential thermal expansion of polysulfone and stainless steel, and compression set retention in the polysulfone. The results of Conax's evaluation were inconclusive.

EPA Setup in Nozzle

The EPA was installed into the nozzle according to the Conax Installation Manual, IPS-1249. See section 6.1 or Reference 9 for additional information.

Thermal Aging of the Outside Containment Seals

The polysulfone seals in the modules at the outside containment end and the viton O-rings that seal the header plate and weldneck flange were thermally aged at 250°F for 100 hours. The pressure vessel used to collect leakage past the EPA (see Figure 6-6) was used as an oven for thermal aging of the outside containment seals. The control temperature was the average reading from four thermocouples (gages 51-54, see Figure 6-9) attached to the header plate. The cables were not energized during thermal aging.

Just prior to thermal aging of the outside containment seals, the copper cables had insulation resistances to ground from $5.0x10^{11}$ Ω to $3.5x10^{12}$ Ω at 500 VDC (measured with the Megohm meter). During thermal aging, the copper cables had insulation resistances to ground from 1.2×10^{11} Ω to 1.2×10^{12} Ω at 500 VDC. Immediately after cooling from thermal aging, the copper cables had insulation resistances to ground from 7.5×10^{11} Ω to 2.5×10^{12} Ω at 500 VDC. Details of the insulation resistance measurements are given in Table 6-3. The insulation resistance of all the copper cables decreased by a factor of 3 to 5 after the first day of thermal aging and then slowly recovered. However, the insulation resistance of all copper cables exceeded the minimum design requirement throughout the thermal aging process.

Table 6-3
Insulation Resistance Measurements--Thermal Aging of Outside Containment Seals

	Insulation Resistance ($\times 10^9$ Ω) at Indicated Time						
Module Number	Before Aging	After Aging for 1 Day	2 Days	3 Days	4 Days	After Cooldown	Before SAC Test
3	1800	350	380	500	550	2000	3700
4	1800	400	430	580	700	2500	2200
7	1600	400	480	550	600	950	2000
8	900	330	400	470	450	1200	1900
12	550	190	210	230	250	750	1600
13	500	120	150	180	210	1500	1600
14	3500	580	650	750	900	2000	1400
15	2000	650	750	900	1200	1500	2300

The insulation resistance to ground for all thermocouples cables was above the maximum range of the digital multimeter (3×10^7 Ω) before, during, and after thermal aging of the inside seals.

After steady-state conditions had been reached, the module and aperture seal pressure remained nearly constant at about 18 and 16 psig, respectively. After cooling, the module volume was pressurized to 130 psig. The polysulfone seals were checked with Leak Tec; no leaks were observed. Pressure drop tests were then conducted on both the module and aperture seals with the initial pressures at 78 and 15 psig, respectively. Over a period of 44 hours, the calculated leak rate from the modules was less than 1×10^{-4} scc/sec. The leak rate from the aperture seals could not be calculated since there was no measurable drop in pressure.

Air Leak Test

Prior to conducting the SAC test, the cable penetrations through the test chamber were filled with epoxy and insulation resistance measurements were made. The measurements made at this time are given in Table 6-3 under the heading "Before SAC Test."

The test chamber was sealed and pressurized to 135 psia with air at room temperature. The module and O-ring monitoring volumes were pressurized to about 15 psig. No leaks were detected and the pressure in the O-ring aperture and the pressure in the modules did not increase.

6.3 Conduct of the Severe Accident Test

The severe accident condition test was started at 10:30 on June 16, 1986. The control temperature for the chamber was defined as the average reading from 8 thermocouples located at the outside corners of the junction box (gages 3-10, see Figure 6-7). In the first 25 minutes, temperature and pressure were ramped to 640°F and 85 psia from ambient conditions. In the next 20 minutes, temperature was increased to 700°F. Meanwhile, pressure was raised at the approximate rate of 0.3 psi/min until the pressure reached 135 psia. The chamber temperature and pressure profiles for the first several hours of the test are compared with the target test profiles in Figure 6-14a.

This pressure and temperature were maintained for the remainder of the test (8 days, 18 hours) except for two brief periods on June 18 when the pressure dropped due to problems with the steam system. During the first occurrence, which lasted for about 40 minutes, the pressure dropped to 102 psia. The second occurrence lasted only 15 minutes and the pressure drop was quite small. In both cases, the temperature in the test chamber did not drop significantly.

The cool-down was scheduled to start at 06:30 on June 25, however, the boiler burner of the rental steam system failed to ignite at about 05:30 on June 25 and could not be started. The temperature was allowed to decrease during this time since the first plateau during the cool-down was 500°F and 135 psia. The temperature and pressure profiles during cool-down are shown in Figure 6-14b. There were four steps or plateaus during cool-down:

- 500°F at 135 psia
- 350°F at 135 psia (saturated steam conditions)
- 302°F at 70 psia (saturated steam conditions)
- 250°F at 30 psia (saturated steam conditions)

The test chamber was maintained for approximately eight hours at each plateau before proceeding to the next step. After eight hours at the fourth plateau, the chamber was pressurized with air at 30 psig and allowed to cool naturally until June 30.

There are two obvious deviations in the pressure profile planned for cool-down. The first occurred during step 1 and was related to the failure of the boiler burner to ignite. Before the electric boilers were connected, started, and began to build up pressure, the chamber pressure dropped to about 38 psia at 06:30. By 07:45, the pressure was returned to 135 psia. The second deviation occurred at about 15:30 on June 25 (during step 2); the pressure inadvertently dropped to about 113 psia when electric power was lost to one of the boilers for about 30 minutes. Pressure was increased back to 135 psia by 16:30.

No problems were experienced with any of instrumentation or data acquisition systems during the entire period of the severe accident condition test.

6.4 Test Data and Results

Data collected during the SAC test consists of leakage measurements (including the O-ring aperture seal pressure, the module seal pressure, and condensate collection of leakage through the EPA), insulation resistance and continuity of the cables, and temperature at various locations. It should be noted that the datalogger was initiated 29 minutes before heating and pressurization began; thus, time zero in Figures 6-14 through 6-39 is actually 29 minutes before the official start of the SAC test.

Leakage Measurements

There was no evidence of significant leakage past the aperture seals. The pressure in the monitoring volume between the two viton O-rings is plotted as a function of time in Figure 6-15. Much of the increase in pressure can be attributed to the increase in temperature of the monitoring gas (nitrogen); there is very little change in the aperture seal pressure after the second day, by which time temperatures had stabilized. Unfortunately, the temperature of the nitrogen gas is not known precisely. However, even if it is assumed that the nitrogen does not heat up at all, the average leak rate over the period where the pressure increased most rapidly (from the first to seventh hour of the test) was only 4.1×10^{-4} scc/sec. Alternately, the calculated leak rate would be zero if the nitrogen increased in temperature by approximately 70°F, which seems quite reasonable given the increase in temperature of the header plate. In either case, it seems quite clear that their was no significant leakage past the viton O-rings in the header plate. Since the header plate temperature never exceeded 360°F, which is within the service limits of viton [10], the lack of any significant leakage is not surprising.

The module seal pressure, test chamber pressure, and temperatures on module #4 near the inside containment seals are plotted in Figure 6-16. Initially, the increase in pressure tracks the temperature rise in a manner that is qualitatively consistent with the ideal gas law, and there is no evidence of significant leakage into the module. However, about one hour from the start of the test, the module seal pressure increased rapidly until it was equal to the chamber pressure. The temperature of the inside polysulfone seals in module 4 at this time was between 485°F and 565°F and the pressure differential across the seals (chamber pressure minus module pressure) was 47 psig. A sudden failure of the polysulfone seals on the inside containment end at this temperature and differential pressure that allowed steam from the test chamber to pass into the modules is indicated. Module 4 temperatures are used because one or more of the inside seals on the top row of modules (2, 3, 4, and 5) probably failed first since they were subject to higher temperatures than the other modules.

However, the polysulfone seals at the outside containment end were subject to much lower temperature than the inside seals, as shown in Figure 6-17. The maximum temperature of the module seals on the outside containment end was approximately 280°F, which is below the service limit for this polymer. Thus, the outside containment module seals prevented leakage past the EPA. No leakage past the EPA was detected at any time during the test, including the heat-up and cool-down.

Temperature Measurements

The thermocouple data is plotted in Figures 6-18 through 6-28. The data include both the SAC test and cool-down. The location of the thermocouples, by gage number, is shown in Figure 6-7 through 6-10.

The temperature on the outside corners of the junction box, which are plotted in Figure 6-18, demonstrate that the temperature in the test chamber and the outside of the junction box was quite uniform. However, there is some evidence of temperature stratification on the inside of the junction box. The temperatures on the bottom inside corners of the junction box are considerably less than those at the top inside corners, as shown in Figure 6-19. Data from thermocouples on the EPA sleeve and modules near the junction box are plotted in Figure 6-20. These figures also suggest that a condition of thermal equilibrium was reached somewhere in the range of four to six hours from the start of the test.

As expected there was a significant temperature gradient along the EPA modules. The support plates, which are also referred to as baffles, precluded any significant convective heat transfer between the air in different compartments. Thus, the axial temperature gradient within the air compartments between baffles was generally much less than that across the baffles, as indicated in Figure 6-21 through 6-23, which show the temperature at various position on modules 4, 9, and 12. By comparing these figures, it is also apparent that there is temperature stratification from top to bottom along the length of the EPA nozzle, although the stratification became less pronounced away from the inside containment end and closer to the header plate. In fact the temperature of the modules near the outside containment end is quite uniform, as shown in Figure 6-24. Air temperatures inside the EPA sleeve and outside of the header plate are given in Figures 6-25 and 6-26, respectively. These figures provide further illustration of the temperature gradients in the airlock.

The temperatures on the EPA sleeve and header plate are plotted in Figure 6-27 and 6-28, respectively. Curiously, the temperature of the header plate was roughly equal to the saturation temperature corresponding to the test chamber pressure. At the four times when the steam system malfunctioned and test pressure dropped, the temperature of the header plate also fell such that it was always approximately equal to the saturation temperature at the current test pressure **even though the chamber temperature did not change significantly during these events**. The most graphic examples of this occurred during cool-down. Figure 6-29 shows the average temperature of the header plate as well as the chamber temperature and pressure as a function of time. This seems to suggest that the header plate temperature depended more strongly on pressure than on temperature; superheat in the chamber only affected the temperature gradient along the nozzle. Figure 6-30 supports this idea; the steady-state temperature is plotted as a function of position for several points during cooldown that include both superheat and saturated steam conditions in the test chamber. Clearly, the addition of superheat affected the gradient, but it did not have a significant effect on the average temperature of the header plate. Since the performance of seal materials is very sensitive to temperature, this observation has important ramifications: it suggests that the temperatures of seals in or near header plates located outside containment may be restricted to levels not significantly higher than the steam saturation temperature at a given pressure.

Electrical Performance

The insulation resistance of the copper cables degraded rapidly during the SAC test, as can be seen from Table 6-4. Figures 6-31 through 6-38 show the insulation resistance calculated from the load bank data using Equation 4-1 together with the data obtained from the Hippotronics Megohm meter and the Digital Multimeter. About five hours into the test, the insulation resistance of the cables in modules 3 (#12 AWG), 12 (#14 AWG), and 14 (#8 AWG) had dropped below 1 kΩ. The load bank data for Modules 12 and 14 (Figures 6-35 and 6-37, respectively) show that the insulation resistance of these cables tended to recover after a measurement with the Hippotronics Megohmmeter or the Digital multimeter. The insulation resistance of the other five cables remained above 100 kΩ for the first nine hours of the SAC test. There is no obvious correlation with wire size or module temperature that would explain why the insulation resistance of some cables degraded more rapidly than others.

The cables were removed from the load bank because of erratic readings about 11 hours into the test and no insulation resistance measurements were recorded between the 9th hour of the SAC test and the beginning of the cool-down cycle. By this time the insulation resistance of all the copper cables had fallen below 1 kΩ. The insulation resistance to ground for the copper cables recovered somewhat during cooling, but not above 10 kΩ, even after the SAC test was completed and the EPA had cooled to room temperature.

Table 6-4
Insulation Resistance Measurements of Copper Cables for SAC Test

Module Number	Before SAC (GΩ)	Insulation Resistance at Indicated Time — Hours from Start of SAC Test: 2.5 (kΩ)	5[a] (kΩ)	9 (kΩ)	Begin Cooldown[b] (kΩ)	After Cooldown (kΩ)
3	370	3800	1.747	0.00523	0.200	0.65
4	220	4500	102.0	485.0	0.300	0.85
7	200	11200	608.0	459.0	0.120	1.3
8	190	3200	1340.0	563.0	0.034	5.8
12	160	12600	0.192	1.789	0.028	4.6
13	160	6000	108.40	379.0	0.260	7.3
14	230	6800	0.000272	0.00074	0.036	0.0034
15	250	4700	108.1	323.0	0.013	7.8

Notes:

a) Measurements made at five hours and afterwards were made with the Digital Multimeter. Earlier measurements were made with the Hippotronics Megohm meter.

b) No readings were taken from 9 hours until cool-down. This measurement was made after the first stage of the cooldown when the chamber temperature and pressure were held at 500°F and 122 psig, respectively (9.12 days from start of SAC test).

The insulation resistance to ground of the EPA thermocouple cables measured with the digital multimeter is recorded in Table 6-5. The insulation resistance of the cables just prior to the SAC test exceeded the range of the digital multimeter and are therefore not included in the table. As in the copper cables, there was significant degradation in the insulation resistance of the thermocouple cables very early in the SAC test. However, insulation resistance is only an indirect measure of electrical performance. In this test, the Type K cables in the EPA (modules 2, 9, and 10) were wired to simulate the output from thermocouples inside the junction box. This was intended to give additional insight into the electrical performance of the cables and the reliability of electrical signals during a severe accident. The output from the EPA thermocouple cables is shown in Figure 6-39. This figure shows that, despite the significant degradation in the insulation resistance of the cables, the signal still closely approximates the true temperature inside the junction box. Except for three brief periods during the first day of the SAC test, the output from the EPA thermocouples was within the range of temperatures recorded by the test thermocouples inside the junction box. The implication is that insulation resistance is not necessarily a good indicator of electrical performance as measured by the accuracy of the signal.

Table 6-5
Insulation Resistance Measurements of EPA Thermocouple Cables for SAC Test

Module Number	Insulation Resistance at Indicated Time Hours from Start of SAC Test 2.5 (kΩ)	5 (kΩ)	9 (kΩ)
2-A	OVLD	0.547	0.0170
2-B	OVLD	520.0	0.0446
9-A	13150	0.0284	0.0171
9-B	11600	0.0215	0.0186
10-A	OVLD	2020.0	3.80
10-B	21000	1750.0	3.68

Notes:
1. OVLD indicates IR above the range of the Digital Multimeter.

6.5 Posttest Observations

After the EPA had cooled to ambient conditions, the test chamber was pressurized with air to 125 psig. There were no detectable leaks past the EPA.

Figures 6-40 and 6-41 show the condition of the modules and the cables at the junction box (inside containment end) before and after the SAC test. The insulation on the cables inside containment had degraded to a black varnish-like coating that had high electrical resistance if the coating was not mechanically disturbed or measured with a potential greater than a few volts. If a measuring potential greater than two to three volts was applied for several minutes, the resistance would decrease.

Figures 6-42 and 6-43 show the inside containment ends of the electrical modules after the cables were cut off. The polysulfone had oozed out of the tubing and run to the bottom of the junction box. The polysulfone had degraded (or combusted) and the remains were a shiny black, brittle material (the photograph does not reproduce the true color).

The condition of the outside containment end of the EPA after the SAC test is shown in Figure 6-44. There was not an obvious change in the appearance of the seals or the cables, although the polysulfone module seals were cracked to a much greater extent than was evident before the SAC test. The polysulfone was definitely more brittle than before the SAC test. Nevertheless, the outside containment module seal was maintained during the SAC test and after cool-down.

6.6 Summary and Conclusions

A Conax EPA typical of those used in BWR Mark I nuclear power plants was tested under severe accident conditions simulated with steam at temperatures and pressures up to 700°F and 135 psia. The EPA was first radiation and then thermally aged. The primary test objective was to generate engineering data that could be used to evaluate the leak integrity of the EPA. A secondary objective was to investigate the EPA's electrical performance.

The structural and leak integrity of the Conax EPA was maintained during the entire 10 day period of the severe accident test and for the air leak tests at ambient temperature before and after the SAC test. Although the module seals on the inside containment end failed, the module seals on the outside containment end prevented leakage. A significant temperature gradient existed along the length of the EPA; the header plate and outer module seals were subject to temperatures of less than 340°F, considerably less than the 700°F to which the inside containment end of the EPA was subjected. At 340°F, the seal materials are within their serviceability limits, which is the primary reason why the leak integrity of the EPA was maintained.

The insulation resistances of several of the EPA cables dropped below 1 kΩ between 5 and 9 hours into the SAC test (the temperature and pressure reached their maximum values, 700°F and 135 psia, about 45 minutes and about 3 hours into the test, respectively). By the end of the test, the insulation resistances of all of the cables were below 1 kΩ. Despite this, the signal from the EPA thermocouples compared favorably with measurements from test thermocouples throughout the duration of the SAC test and afterwards. This is evidence that insulation resistance by itself may not always be a good indicator of electrical performance. The specific voltage, current, and impedance requirements for a given application must also be considered in assessing a conductor's electrical performance.

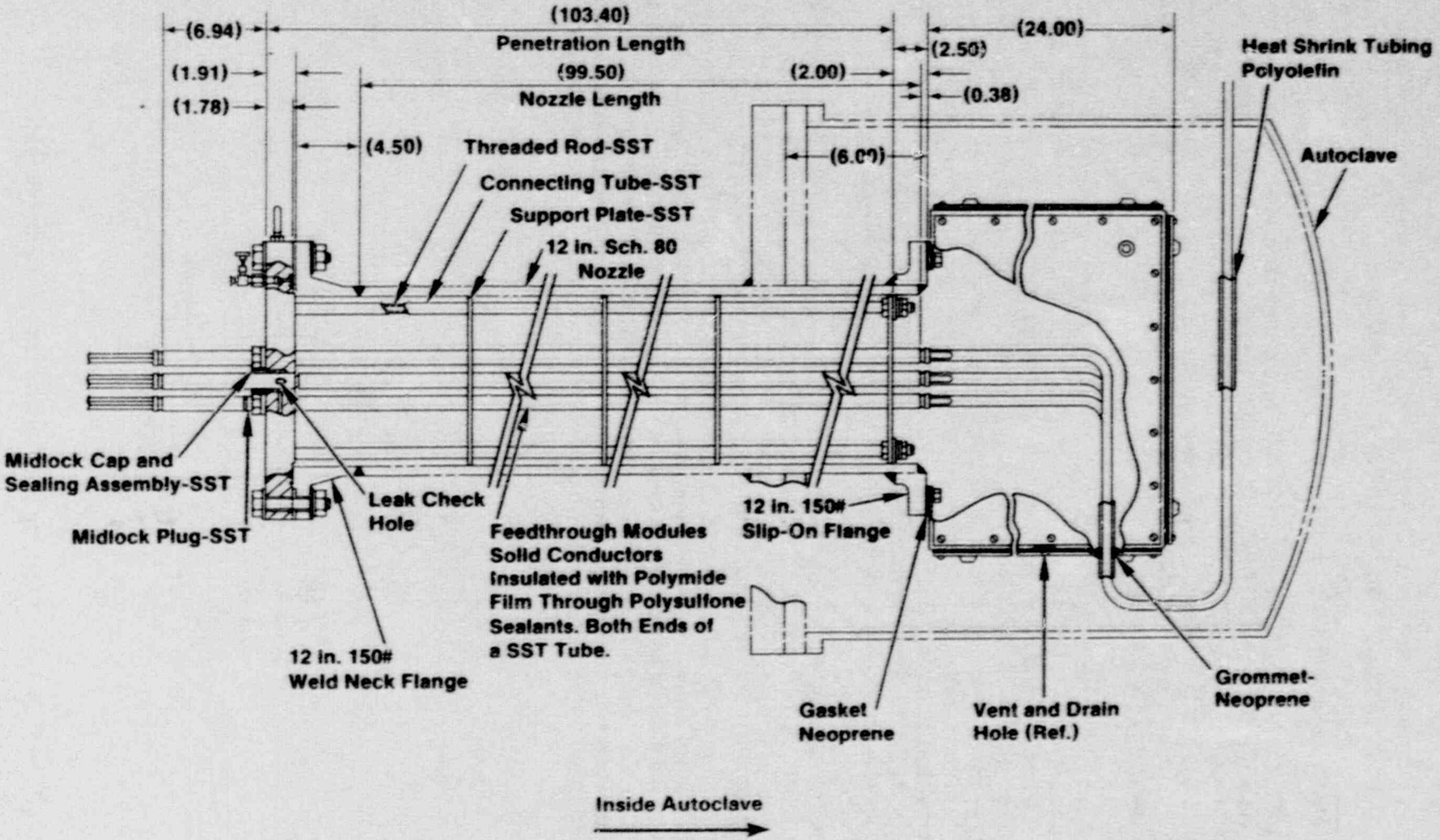


Figure 6-1 Conax EPA Design

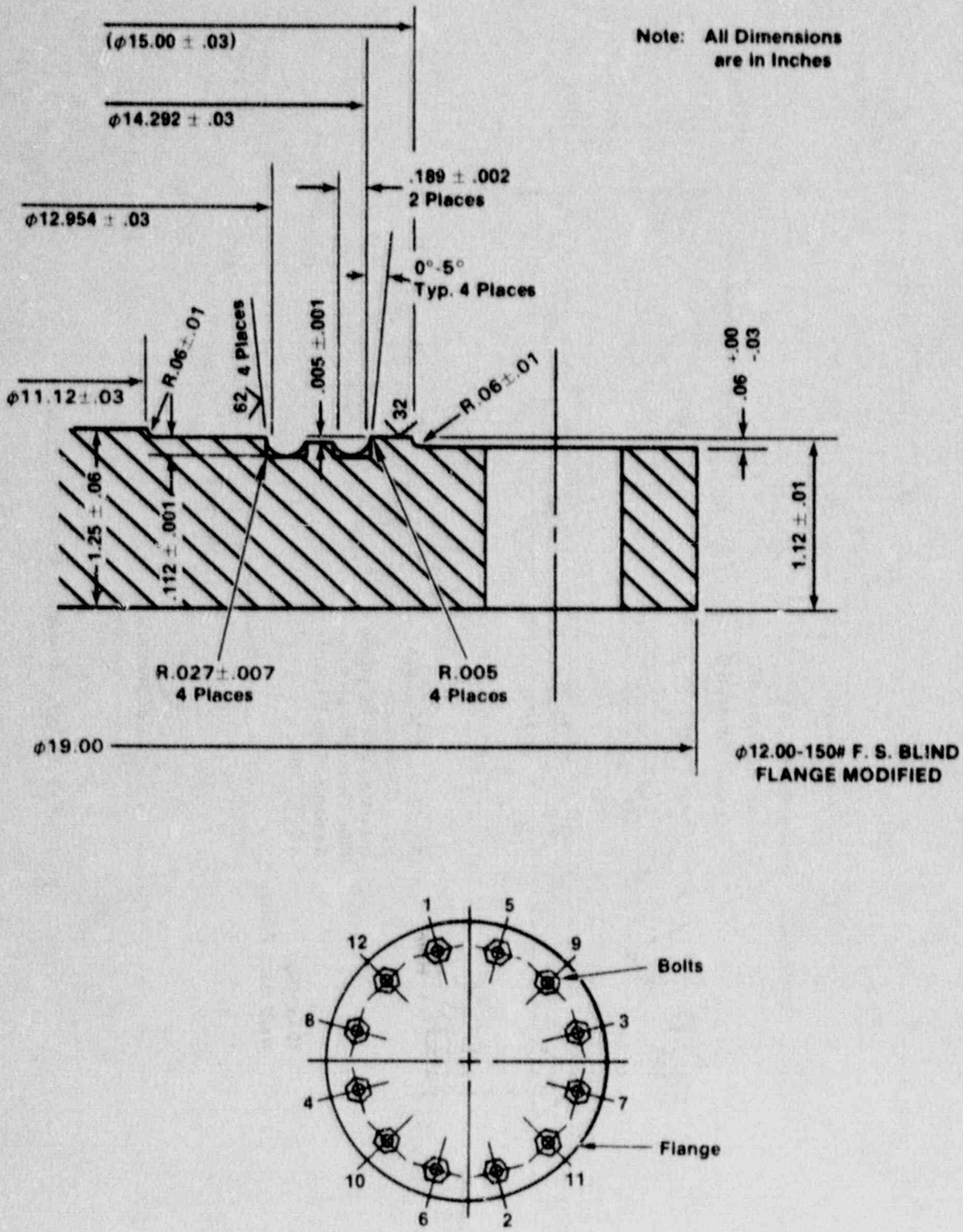


Figure 6-2 Details of Sealing Surface and Bolt Torquing Sequence

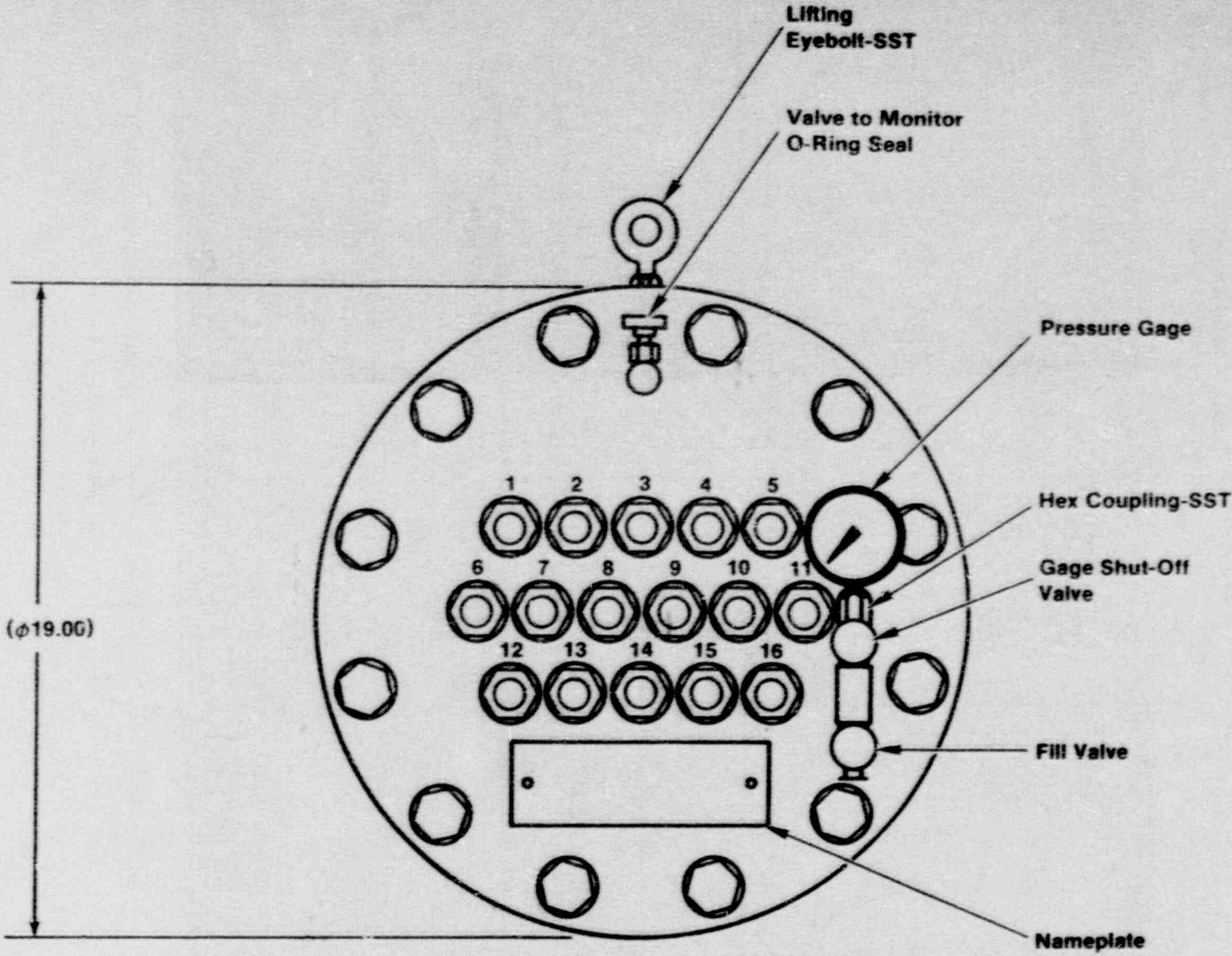


Figure 6-3 Location of Modules in Header Plate

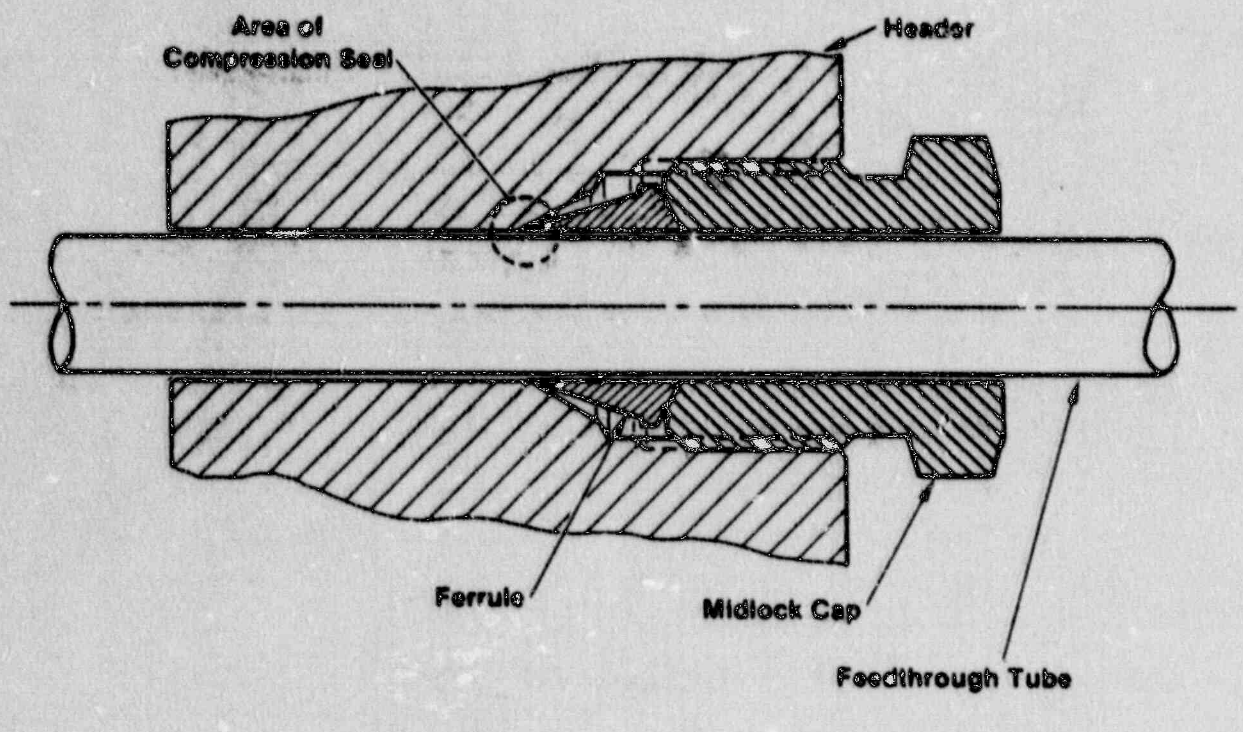
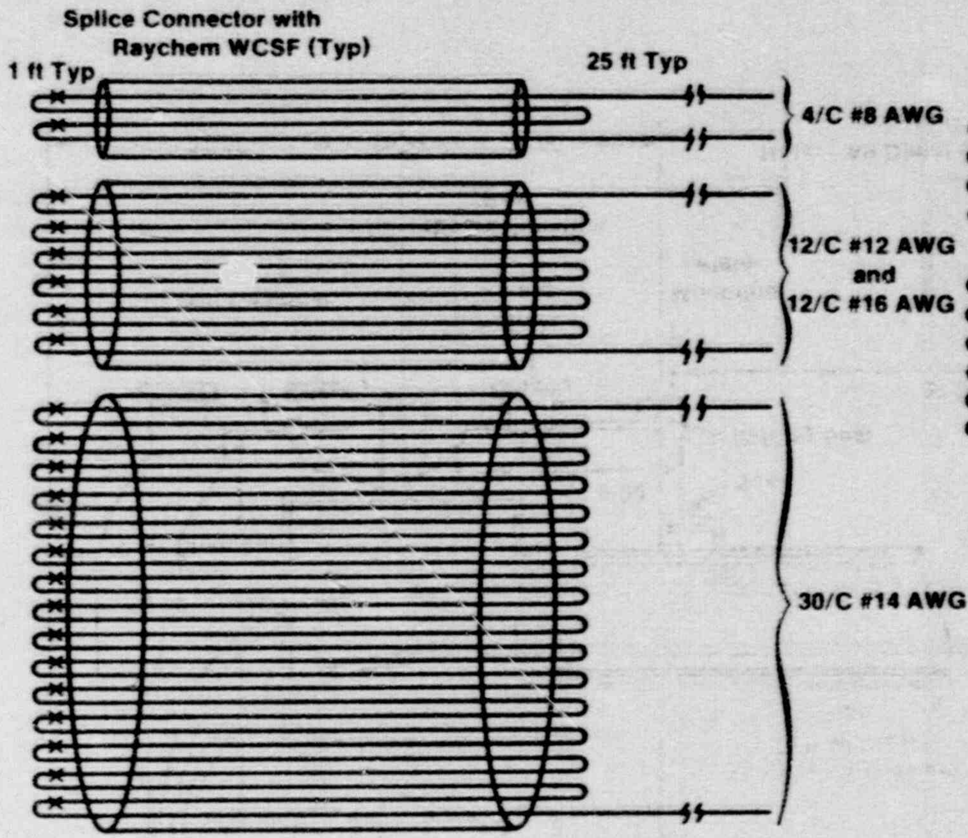
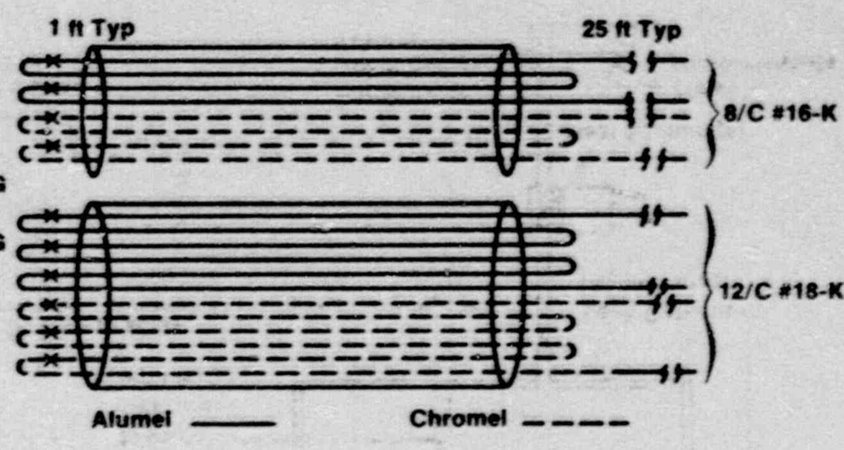


Figure 6-4 Conax Midlock Connector Design





Conductor Size	Conax P/N	Dia. Over Insulation	Min. Bend Radius (in.)
# 8 AWG	N-45067-01	0.146	1.500
# 12 AWG	N-45065-01	0.099	0.750
# 14 AWG	N-45064-01	0.082	0.500
# 16 AWG	N-45063-01	0.069	0.500
# 16 AWG-Chromel	N-45076-01	0.069	0.500
# 16 AWG-Alumel	N-45079-01	0.069	0.500
# 18 AWG-Chromel	N-45110-01	0.058	0.375
# 18 AWG Alumel	N-45111-01	0.058	0.375

Figure 6-5 Wiring Diagram for Modules

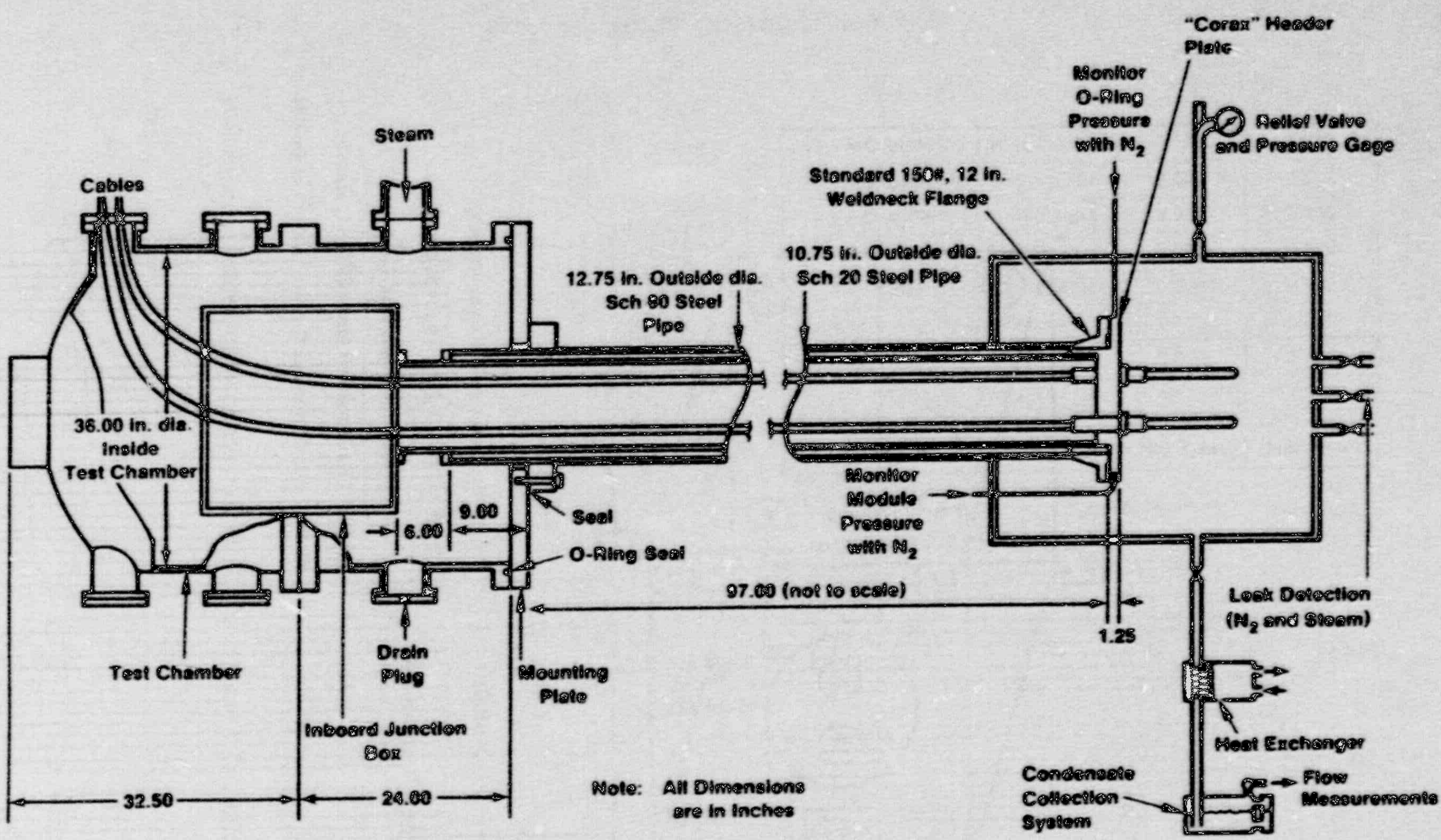
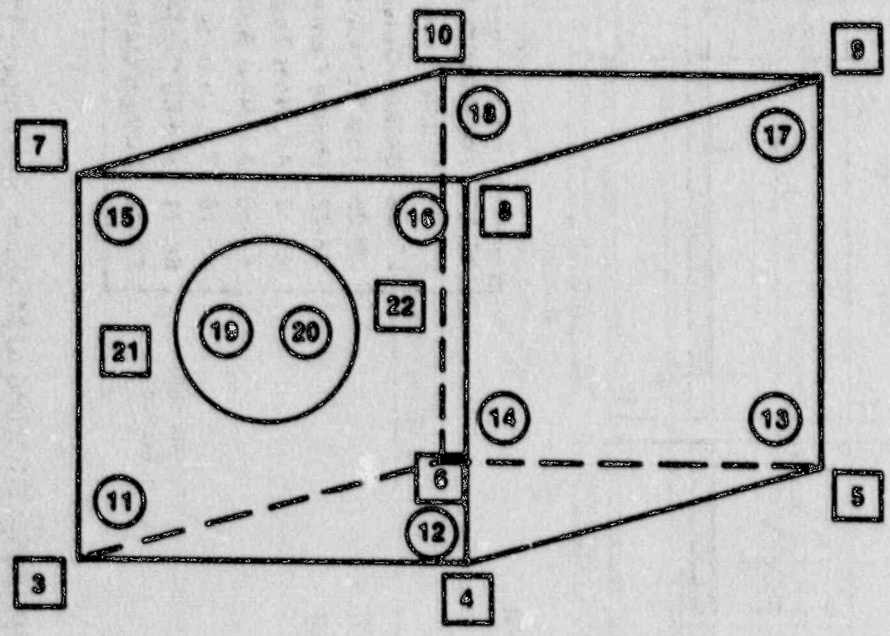


Figure 6-6 Schematic of Conax EPA Test Setup



○ Inside Junction Box

□ Outside Junction Box

1-2 System Control (not shown)

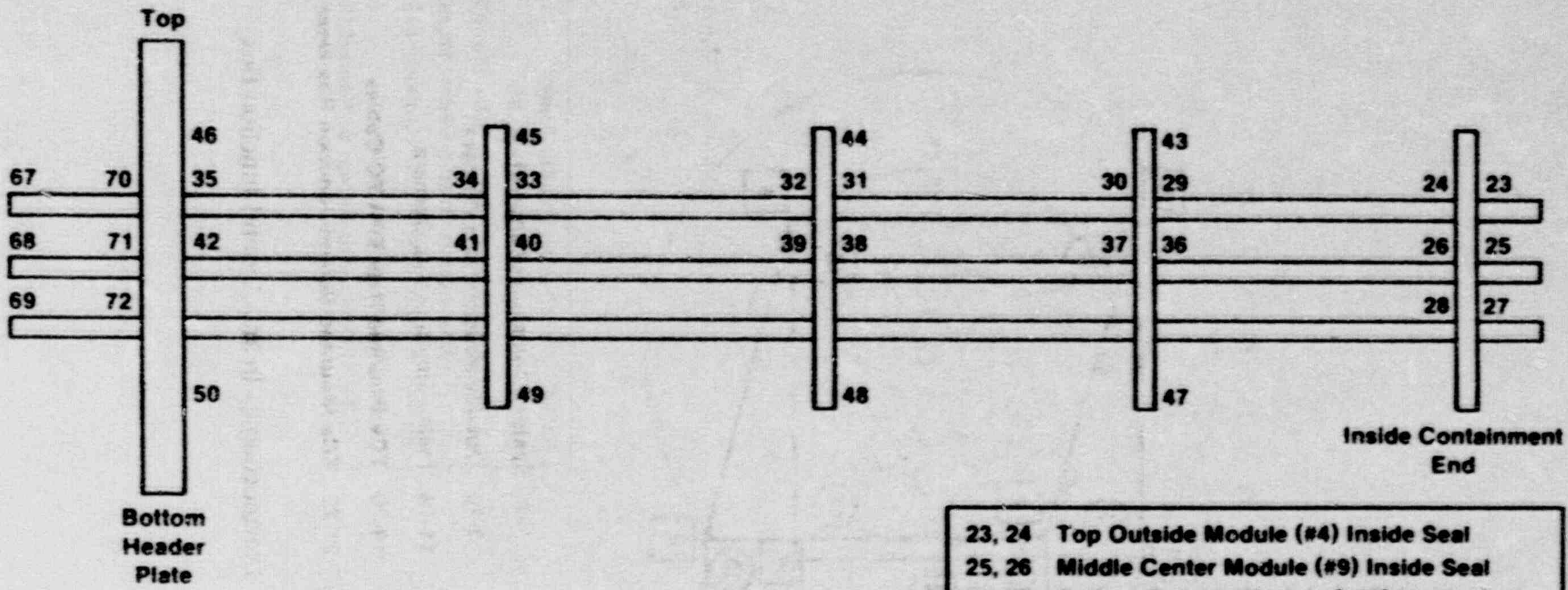
3-10 Outside Junction Box Corners

11-18 Inside Junction Box Corners

19-20 TCs Mounted Near EPA TC Cables

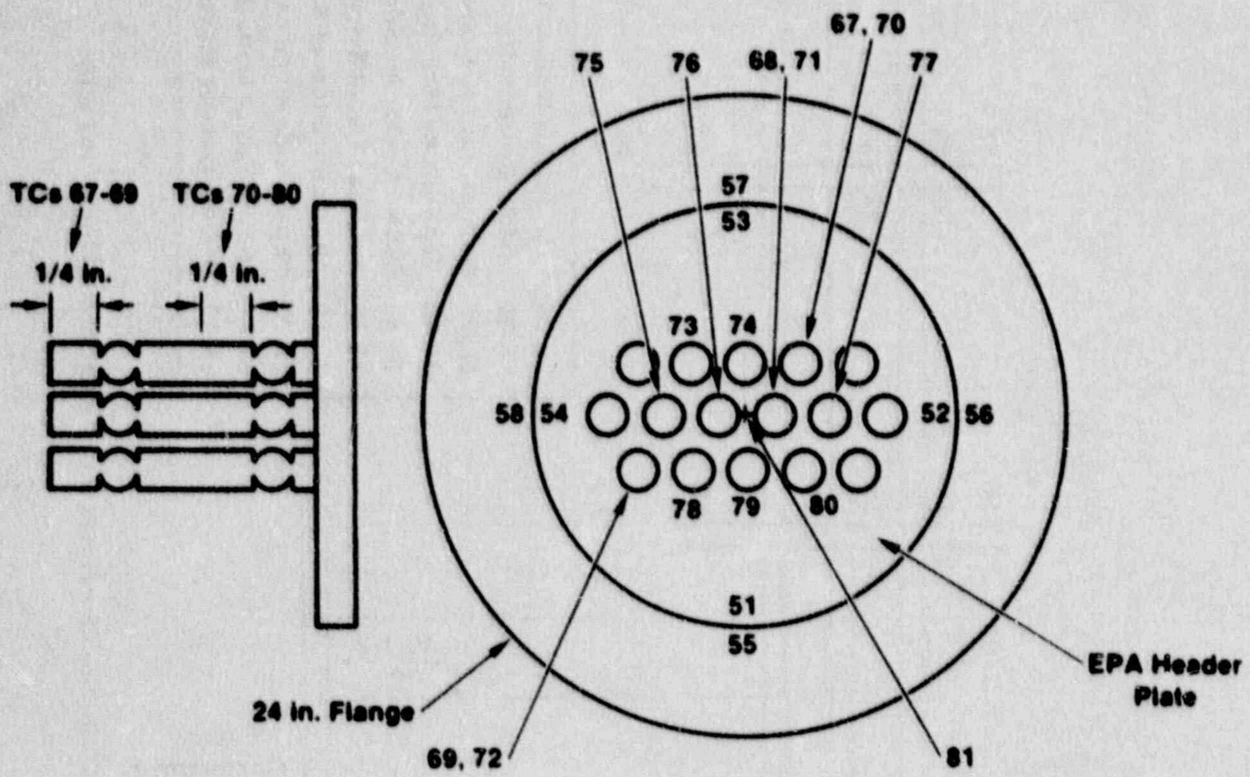
21-22 TCs Mounted Behind Junction Box Near Sleeve

Figure 6-7 Location of Thermocouples In and Around Junction Box



23, 24	Top Outside Module (#4) Inside Seal
25, 26	Middle Center Module (#9) Inside Seal
27, 28	Bottom Outside Module (#12) Inside Seal
29-35	Top Outside Module (#4)
36-42	Middle Center Module (#9)
43-46	Air, Near Top of Sleeve
47-50	Air, Near Bottom of Sleeve
67, 70	Top Outside Module (#4) Outside Seal
68, 71	Middle Center Module (#9) Outside Seal
69, 72	Bottom Outside Module (#12) Outside Seal

Figure 6-8 Location of Thermocouples Attached to Modules and Support Plates



51-54	Attached to Header Plate
55-58	Around Header Plate, Air
67, 70	Attached to Top-Outside Module #4
68, 71	Attached to Middle Center Module #9
69, 72	Attached to Bottom Outside #12
73-80	Attached to Modules
81	Attached to Center of Header Plate

Figure 6-9 Location of Thermocouples on Header Plate and Outboard Module Seals

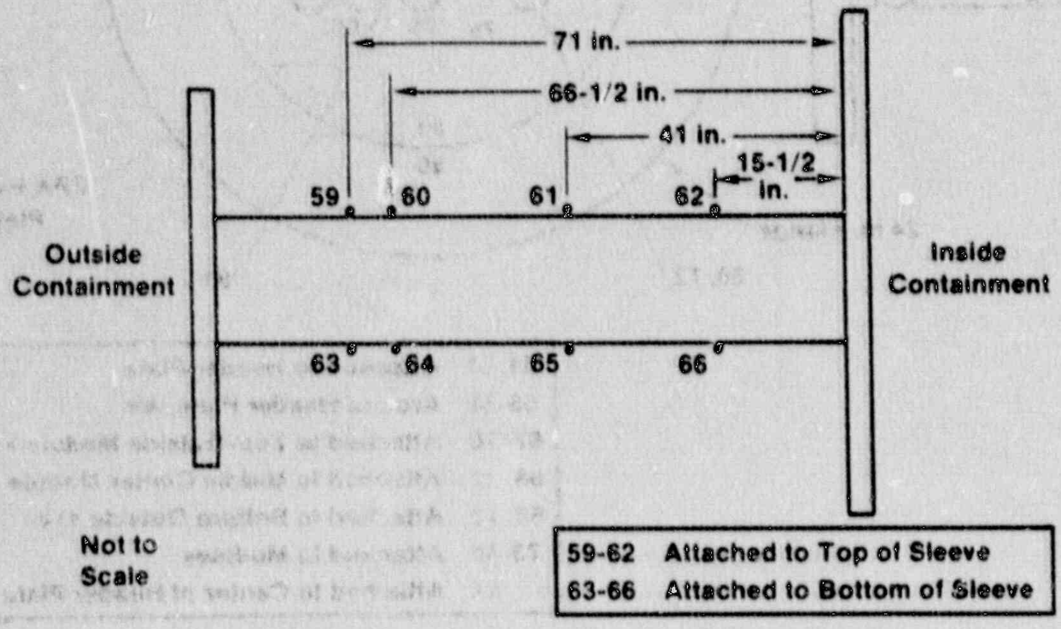


Figure 6-10 Location of Thermocouples Attached to EPA Sleeve

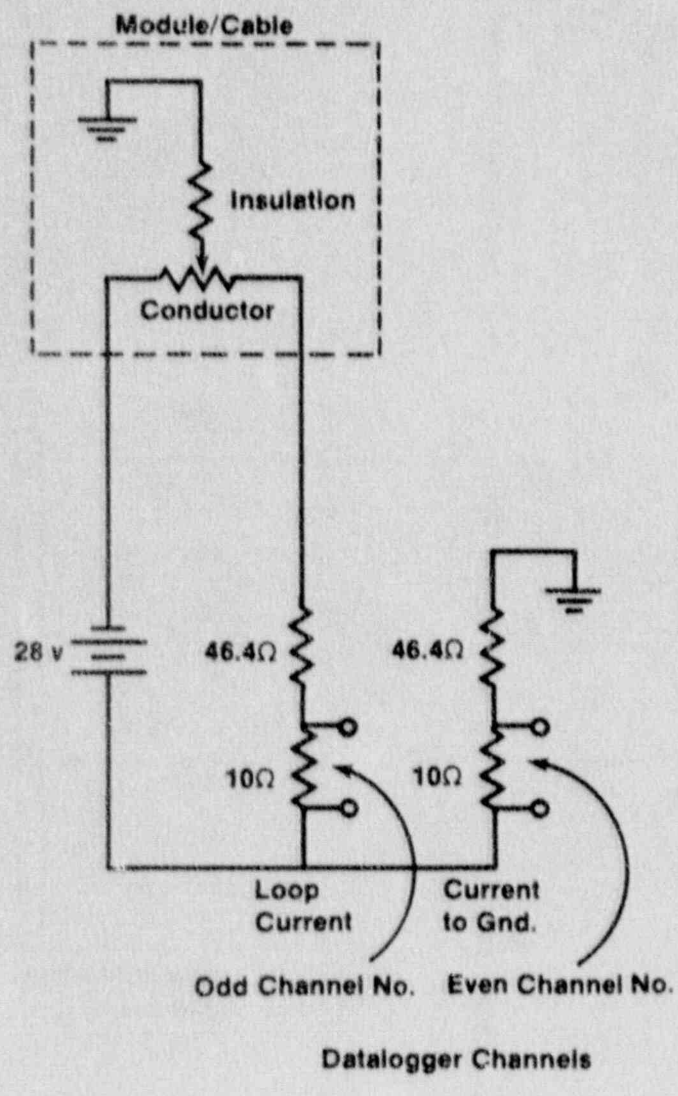
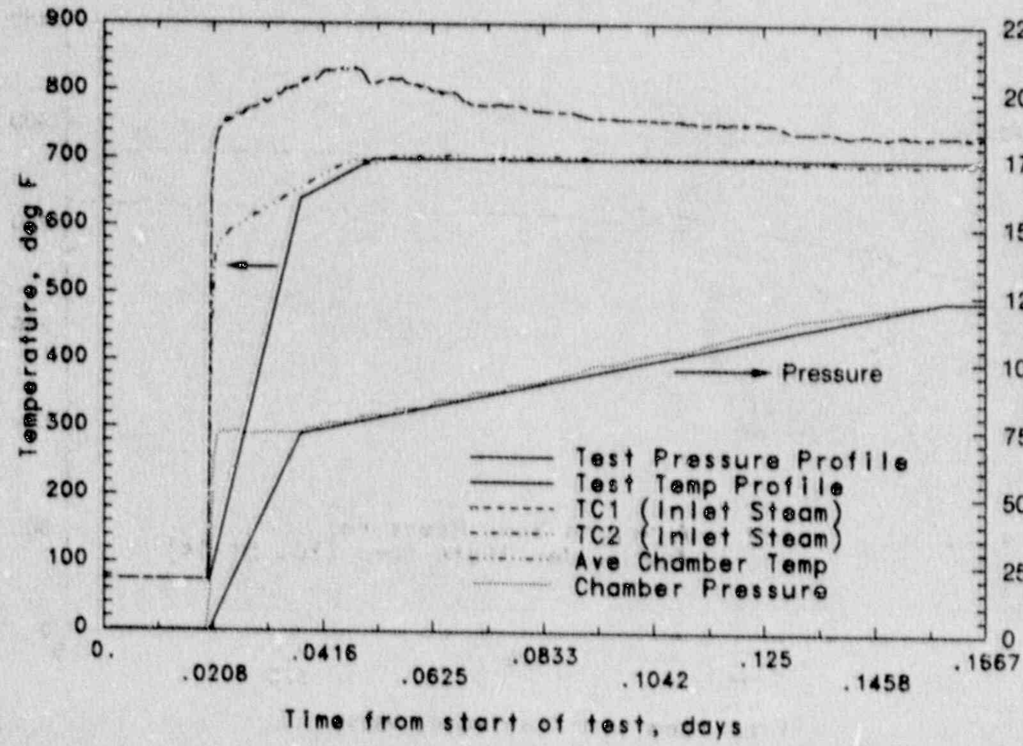


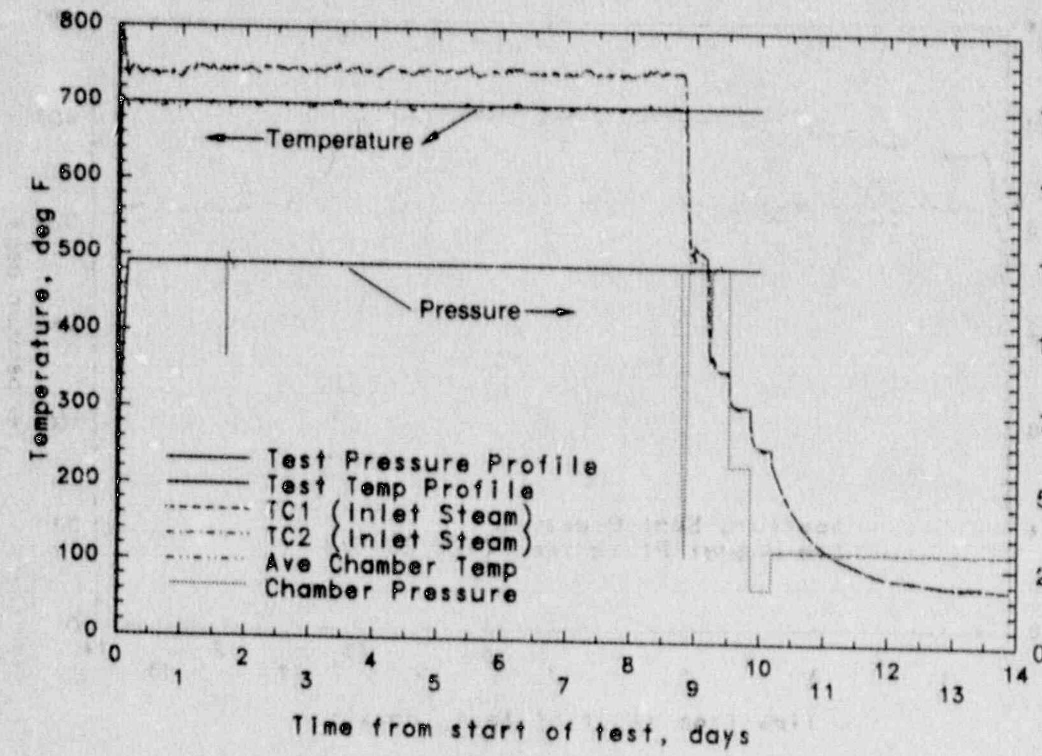
Figure 6-11 Circuit for Monitoring Continuity and Insulation Resistance

Figure 6-12 Radiation Aging

Figure 6-13 Thermal Aging of Outside Containment Seals

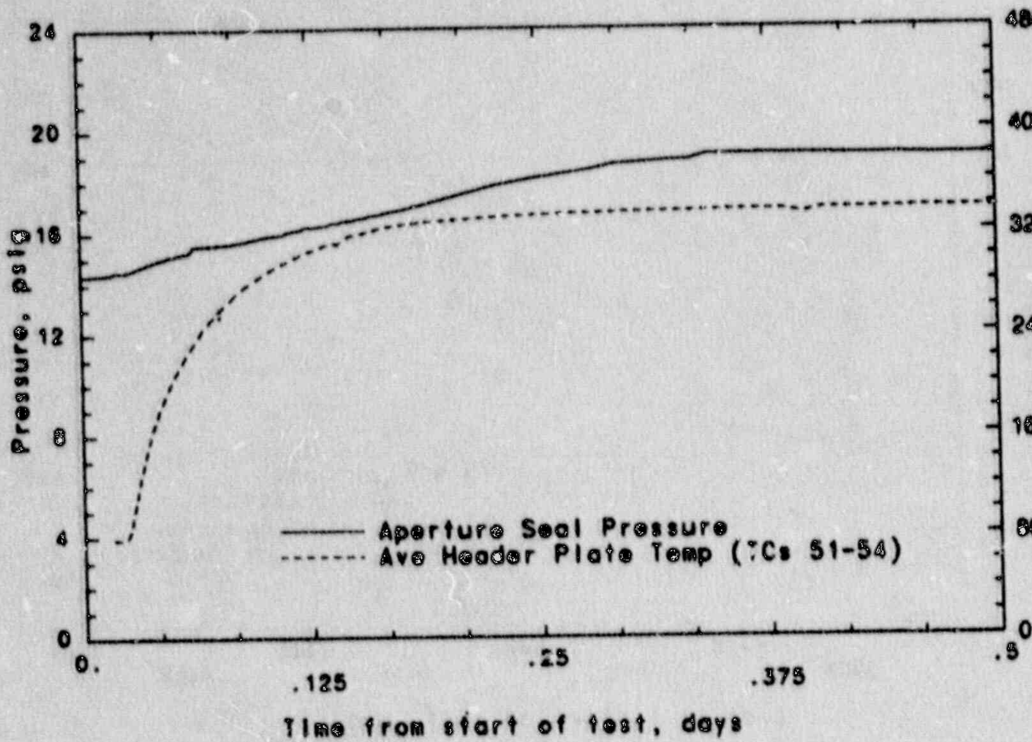


(a) First 4 Hours of SAC Test

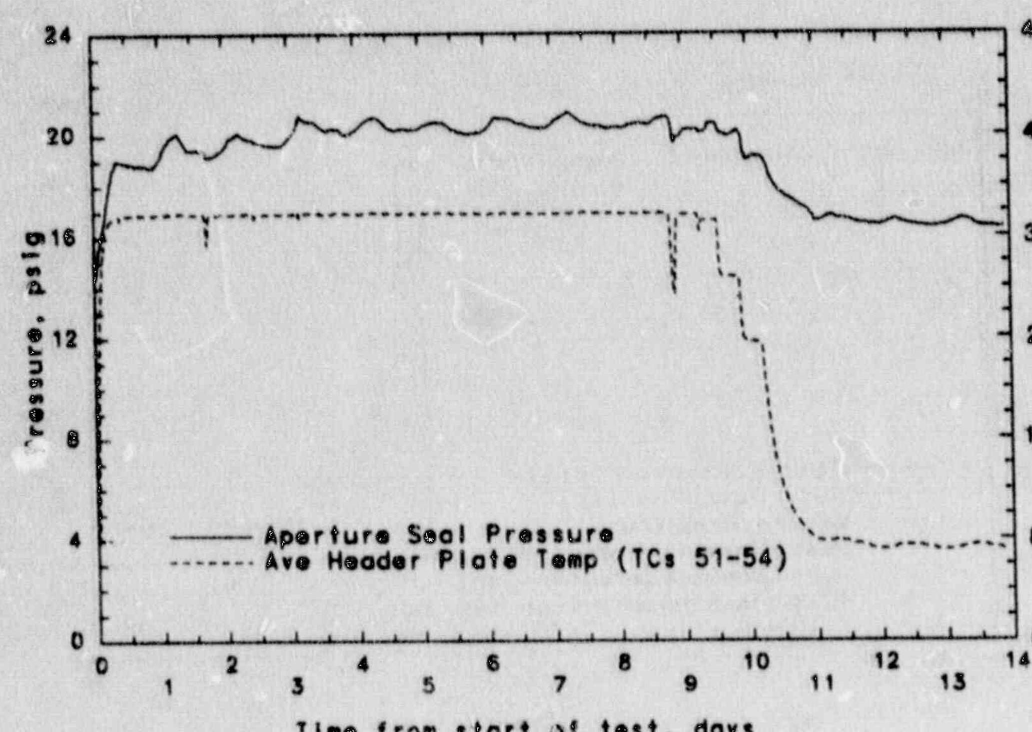


(b) 10 day SAC Test and Cool-down

Figure 6-14 SAC Test Temperature and Pressure Profiles

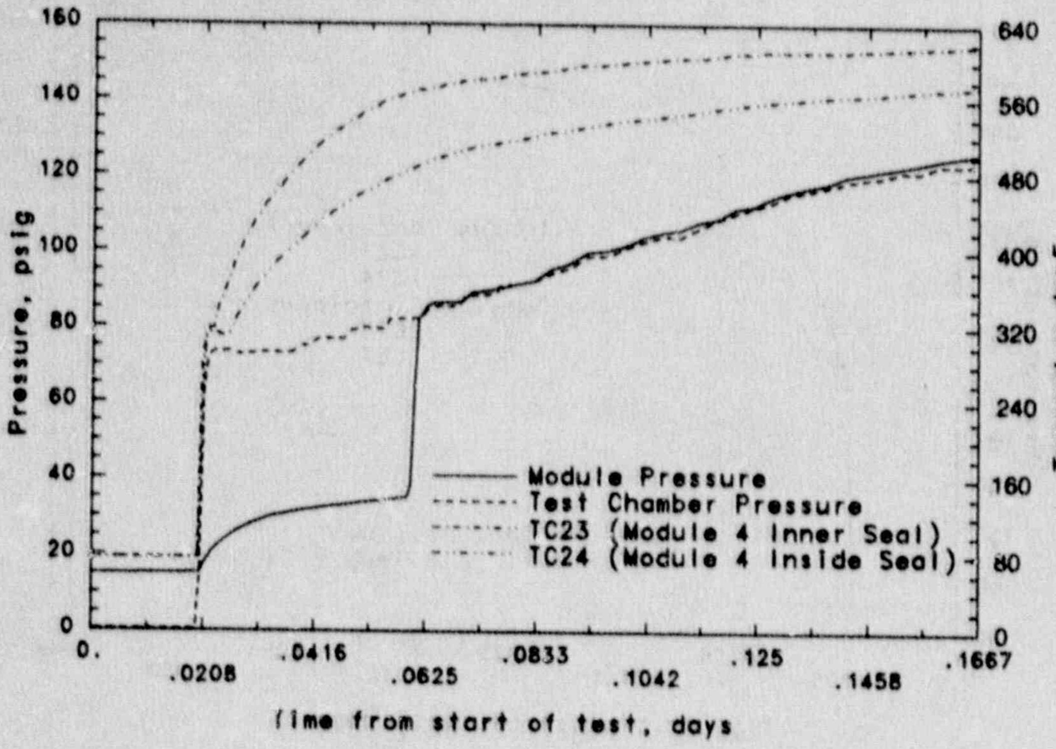


(a) First 12 Hours of SAC Test

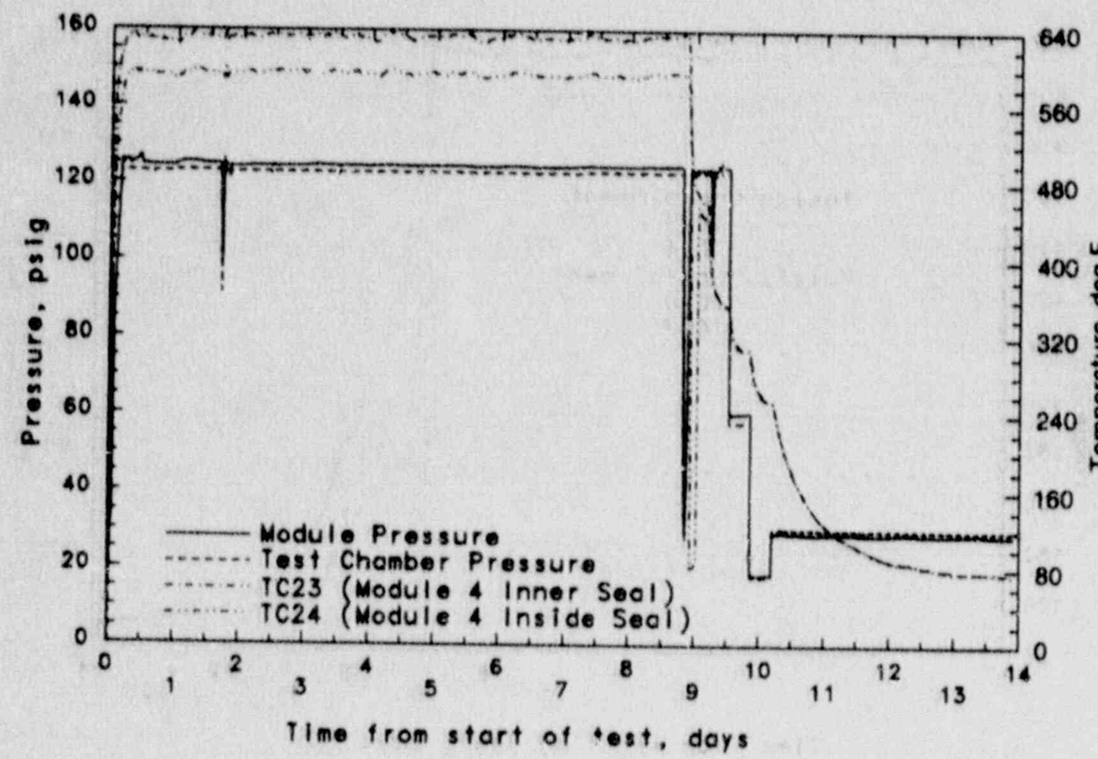


(b) 10 day SAC Test and Cool-down

Figure 6-15 Aperture Seal Pressure

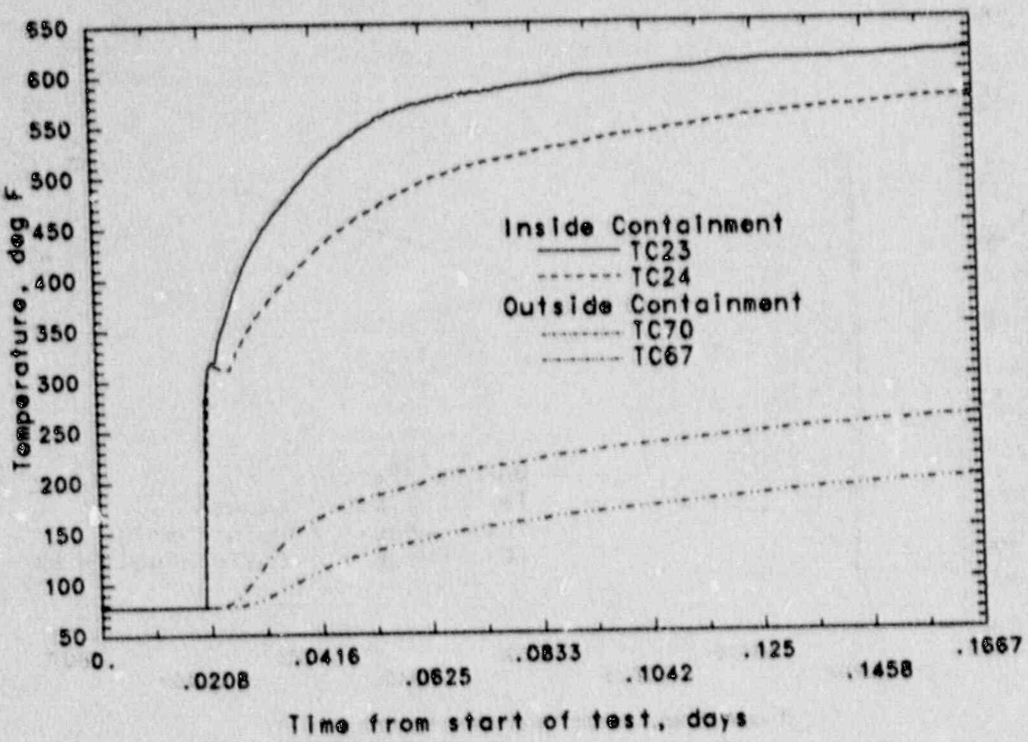


(a) First 4 Hours of SAC Test

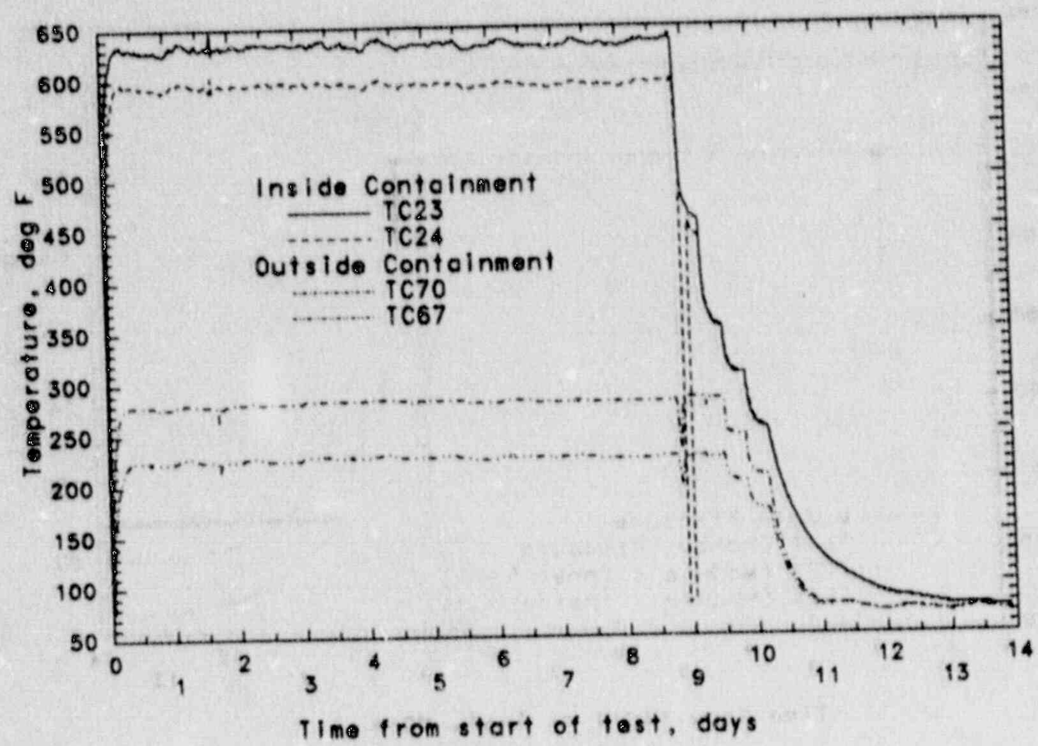


(b) 10 day SAC Test and Cool-down

Figure 6-16 Module Seal Pressure

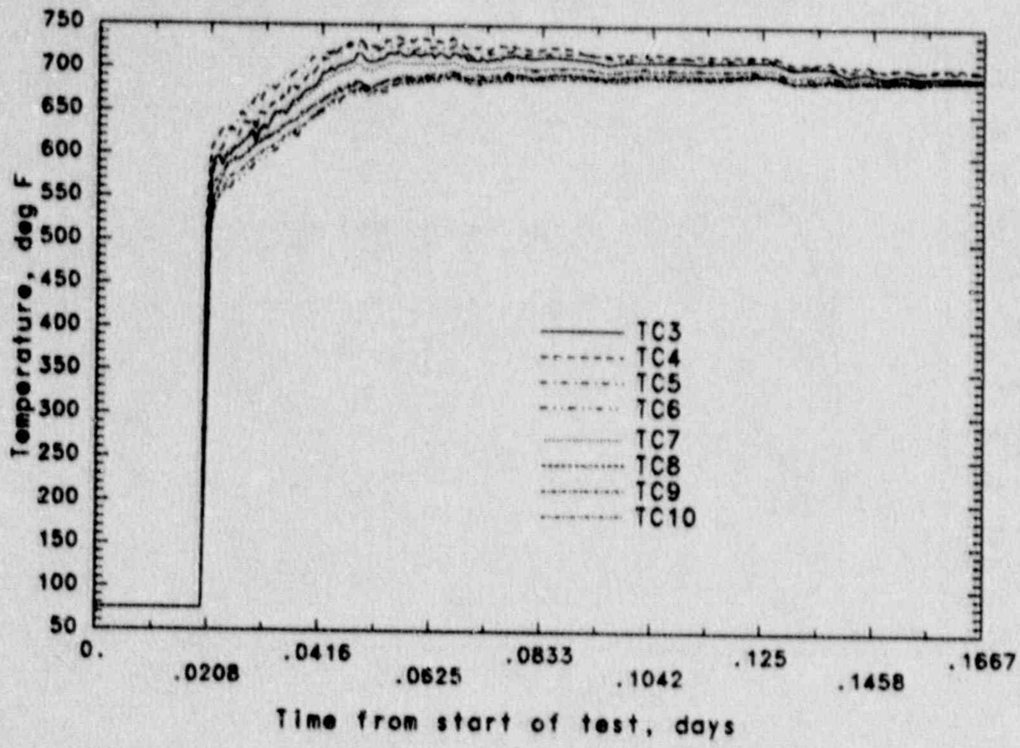


(a) First 4 Hours of SAC Test

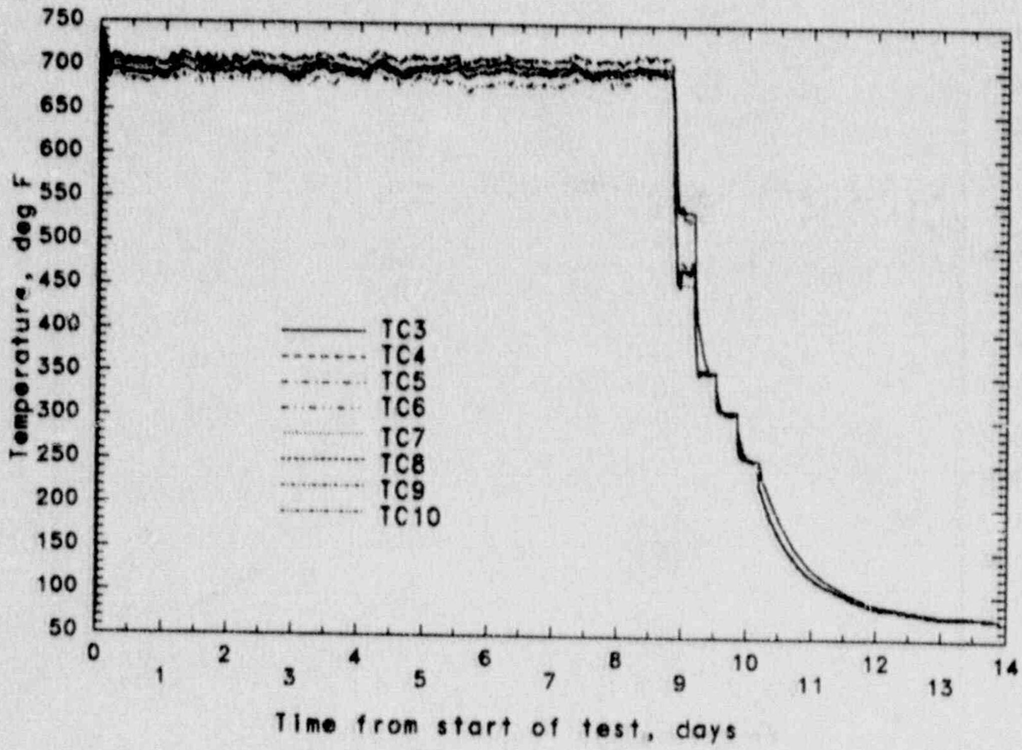


(b) 10 day SAC Test and Cool-down

Figure 6-17 Temperature of Inboard and Outboard Seals of Module #4

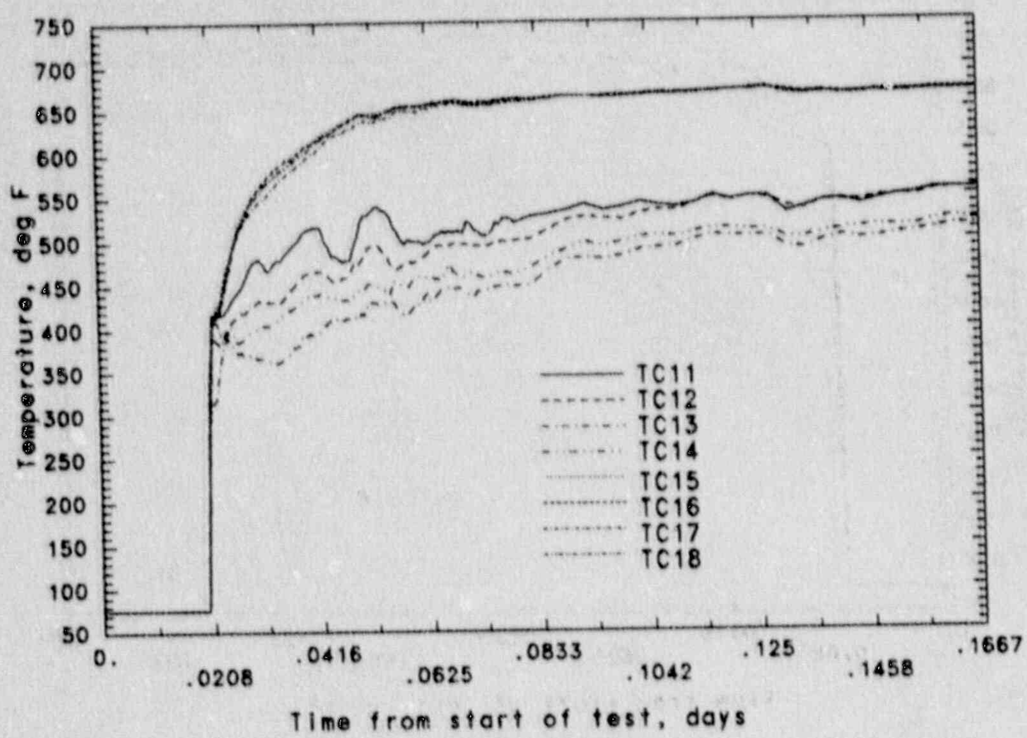


(a) First 4 Hours of SAC Test

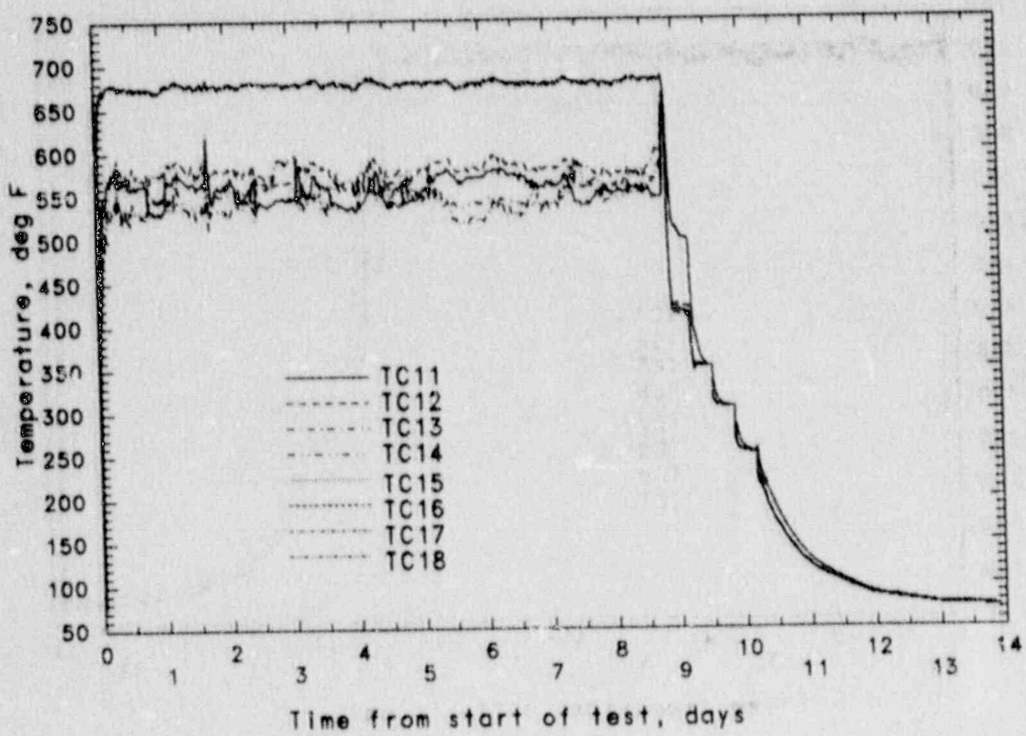


(b) 10 day SAC Test and Cool-down

Figure 6-18 Air Temperature Near Outside Junction Box Corners

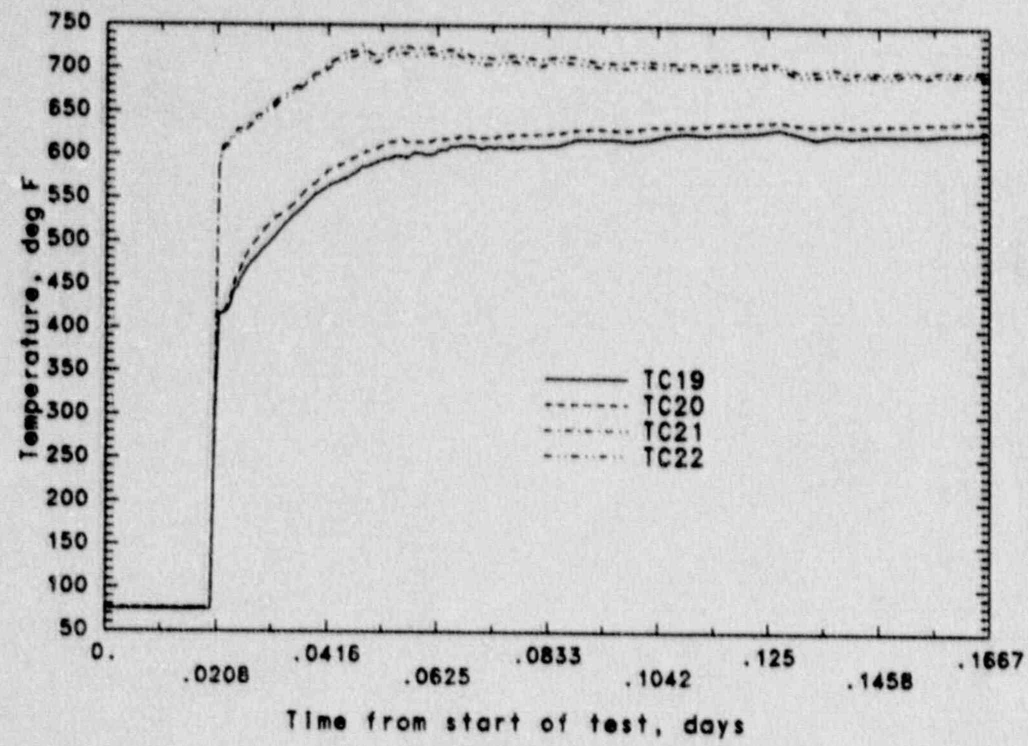


(a) First 4 Hours of SAC Test

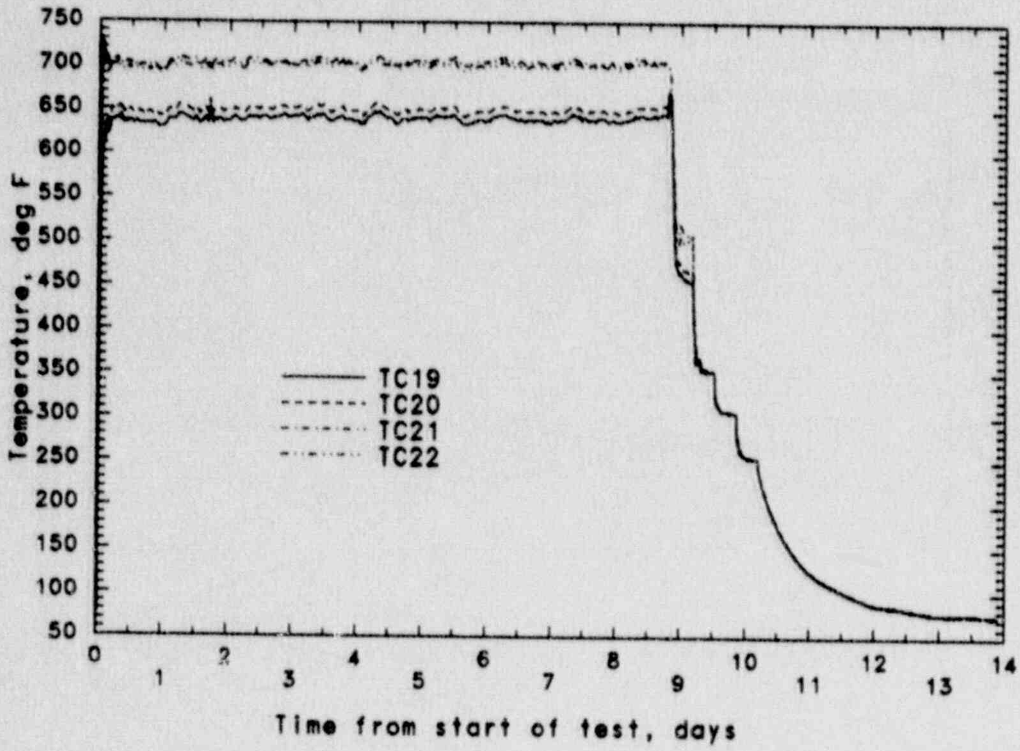


(b) 10 day SAC Test and Cool-down

Figure 6-19 Temperature at Inside Junction Box Corners

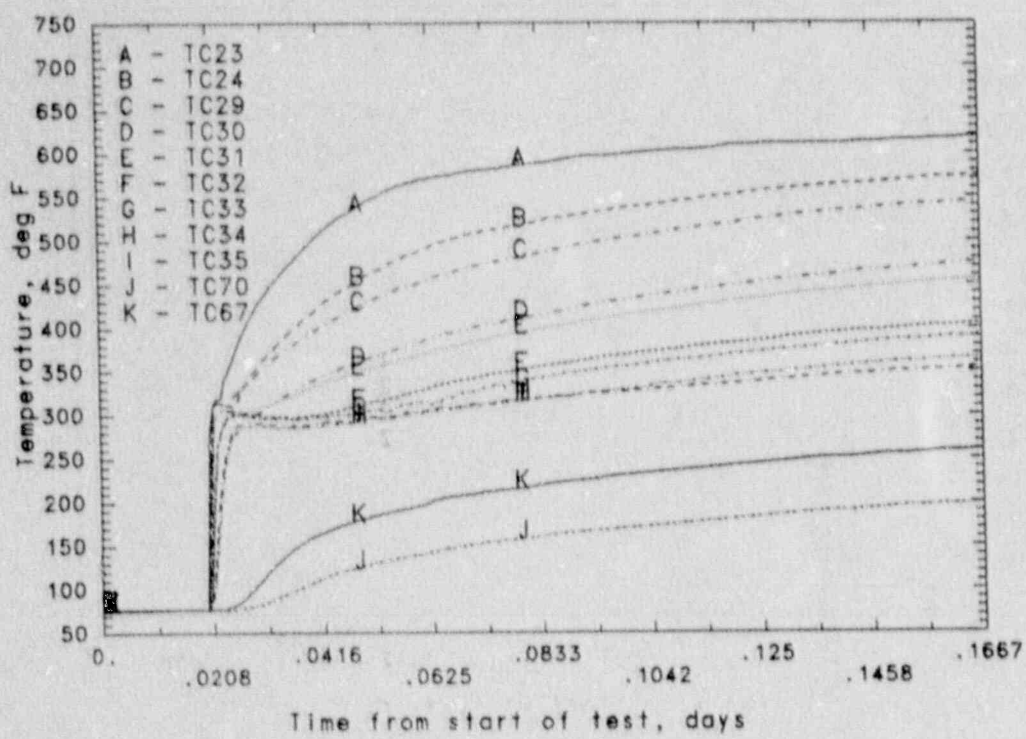


(a) First 4 Hours of SAC Test

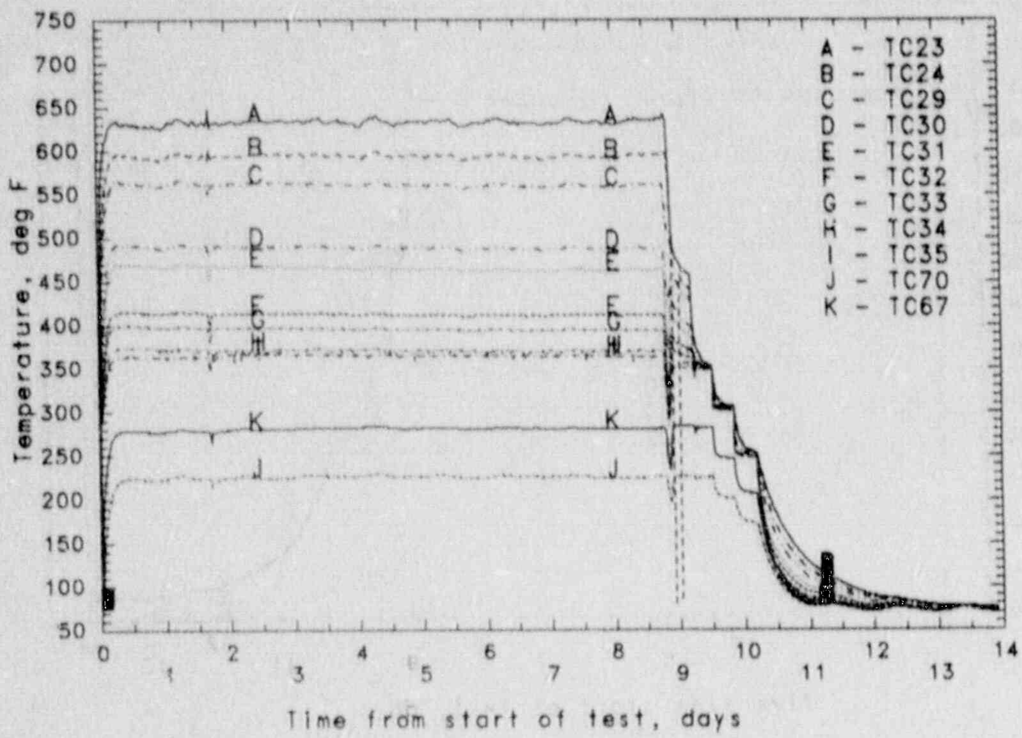


(b) 10 day SAC Test and Cool-down

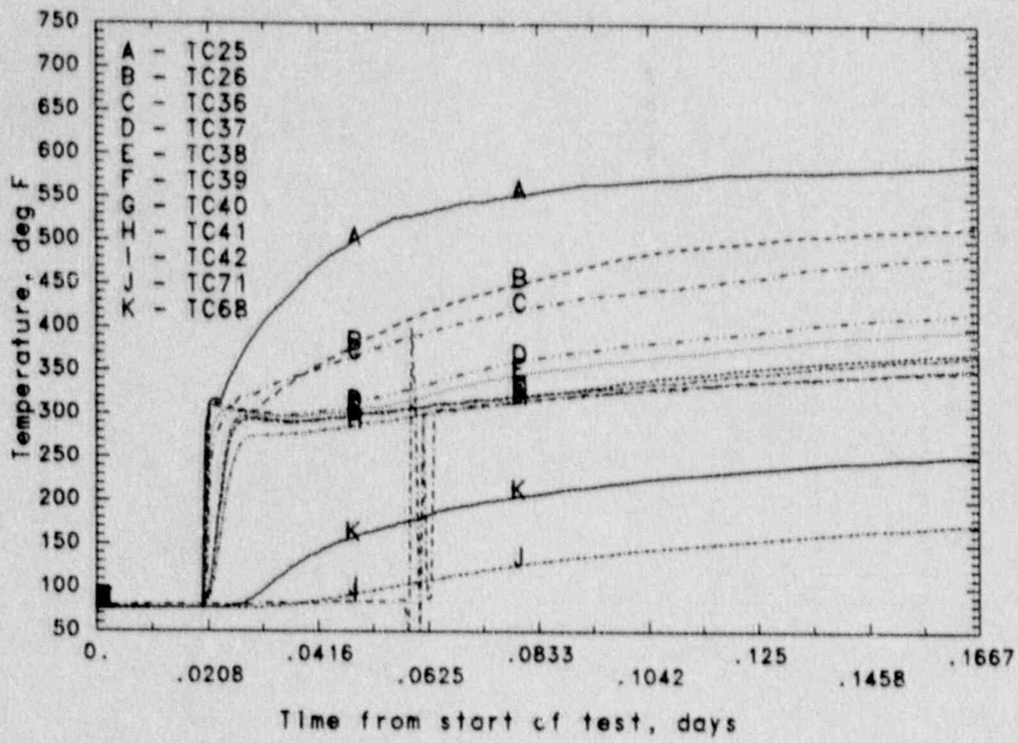
Figure 6-20 Temperature Near Intersection of Junction Box and EPA Sleeve



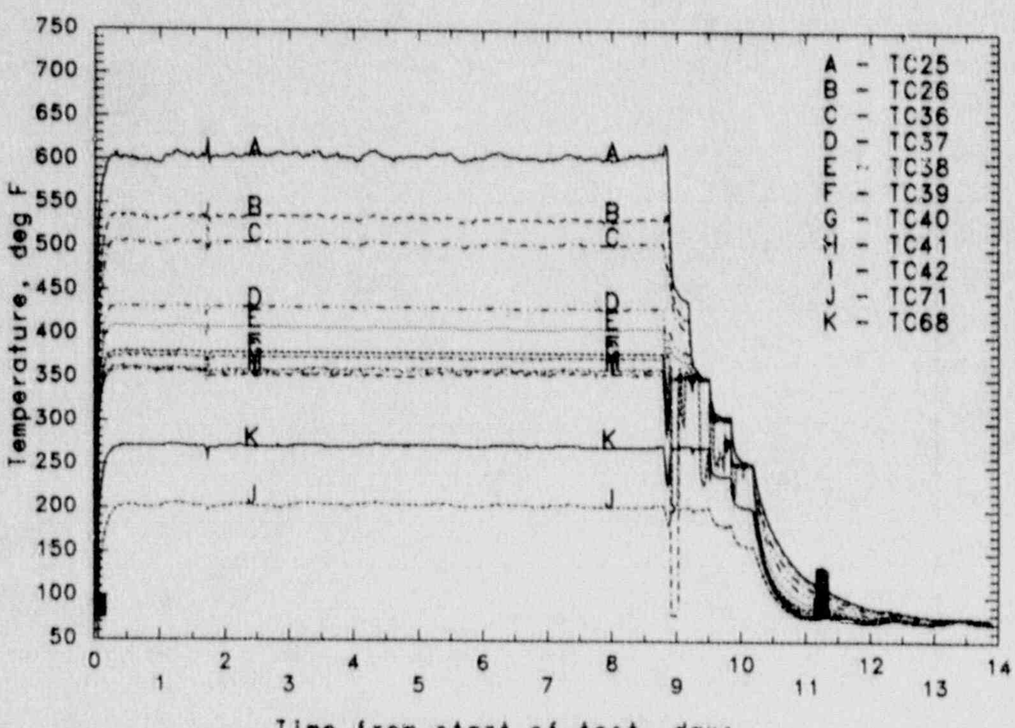
(a) First 4 Hours of SAC Test



(b) 10 day SAC Test and Cool-down
Figure 6-21 Temperature Profile Along Module #4

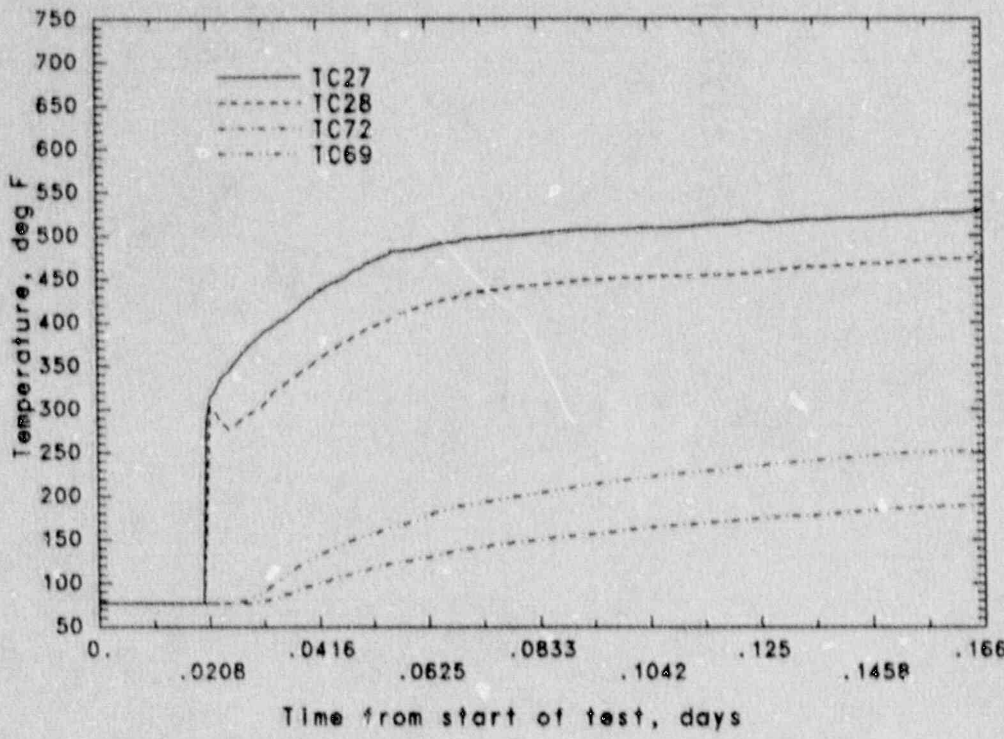


(a) First 4 Hours of SAC Test

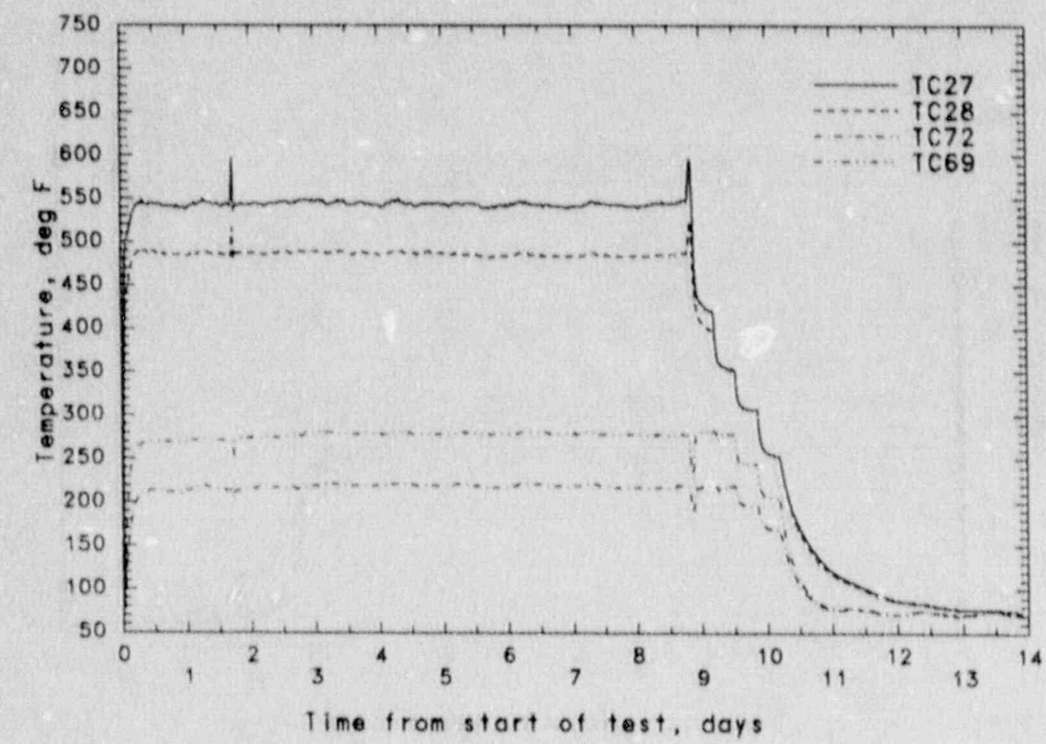


(b) 10 day SAC Test and Cool-down

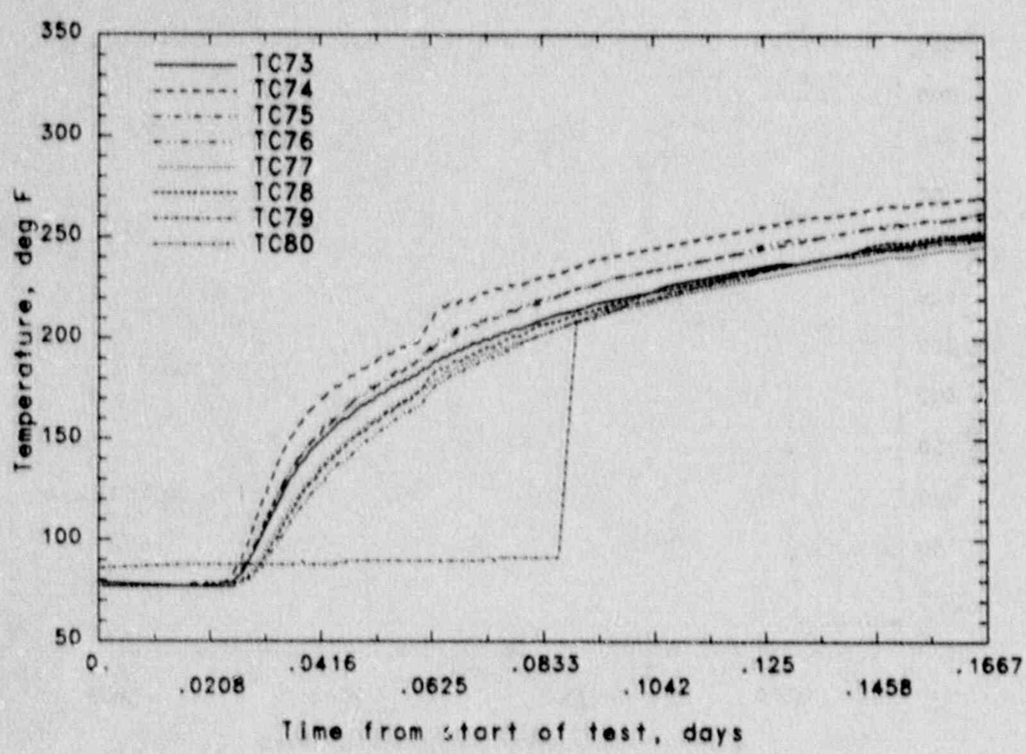
Figure 6-22 Temperature Profile Along Module #9



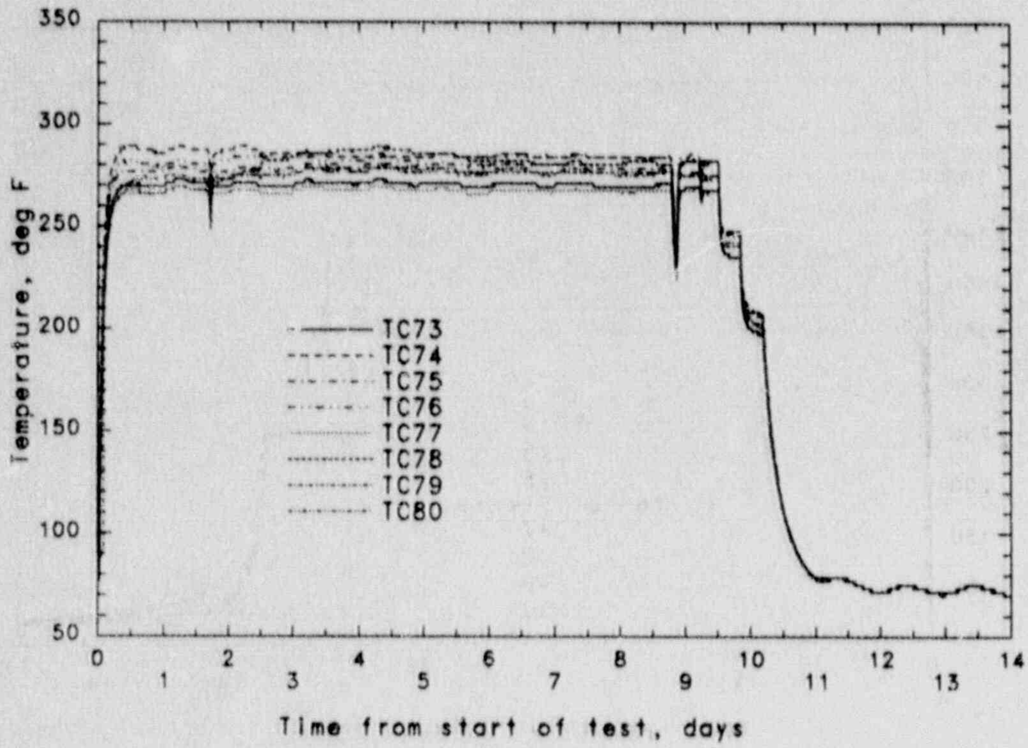
(a) First 4 Hours of SAC Test



(b) 10 day SAC Test and Cool-down
Figure 6-23 Temperature Profile Along Module #12

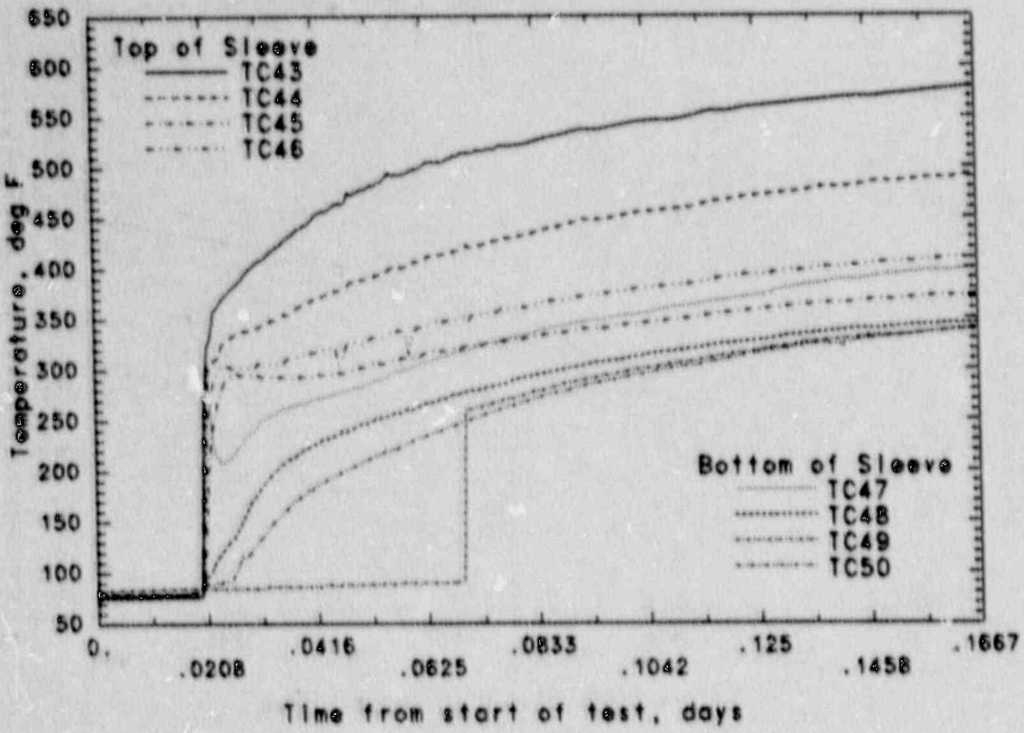


(a) First 4 Hours of SAC Test

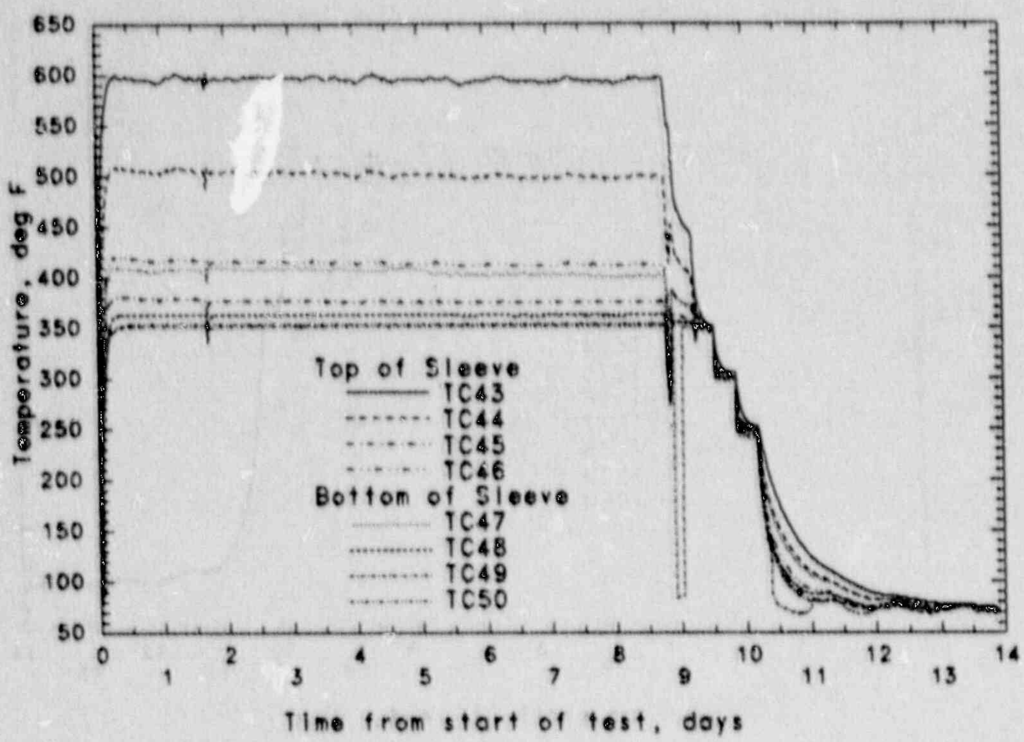


(b) 10 day SAC Test and Cool-down

Figure 6-24 Temperature of Module Outer Seals

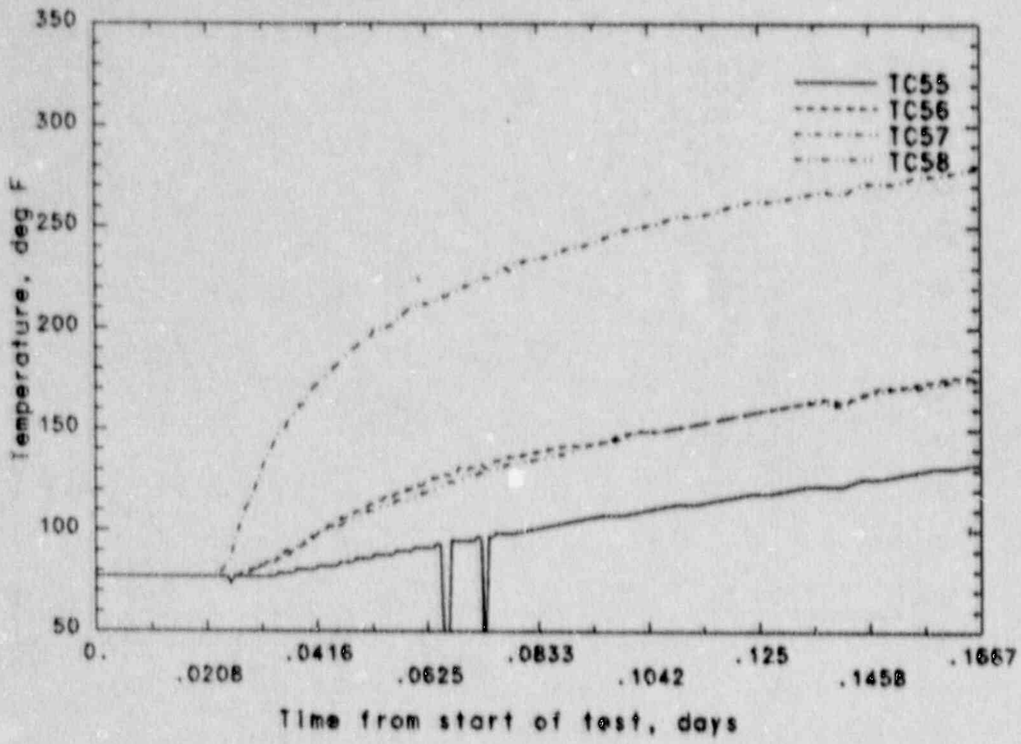


(a) First 4 Hours of SAC Test

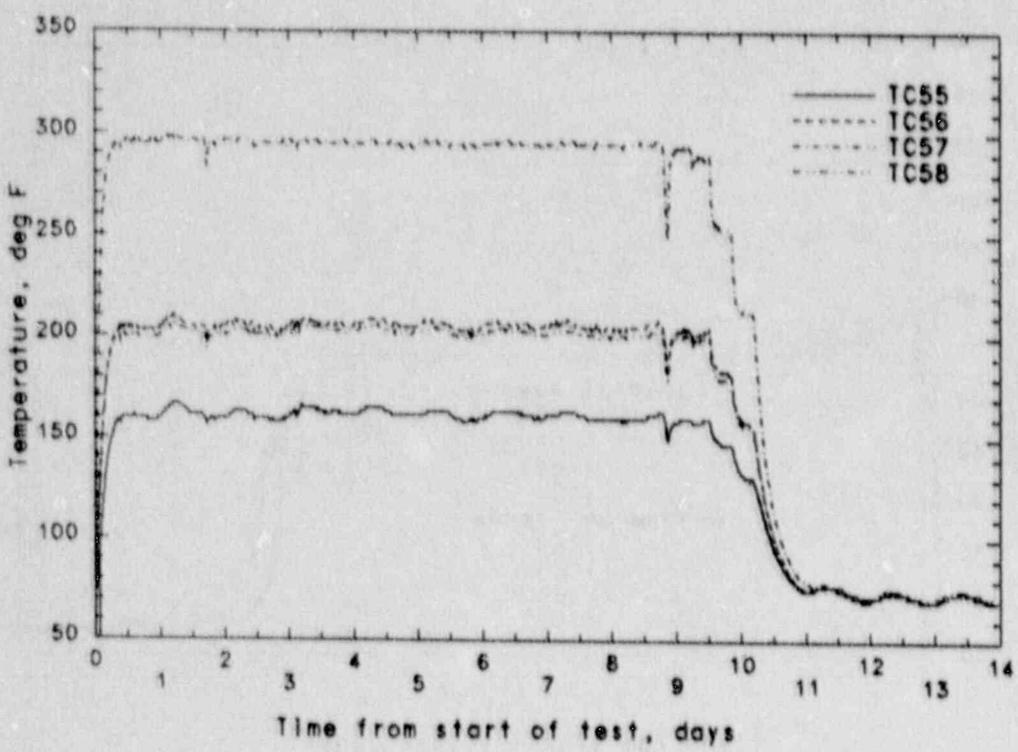


(b) 10 day SAC Test and Cool-down

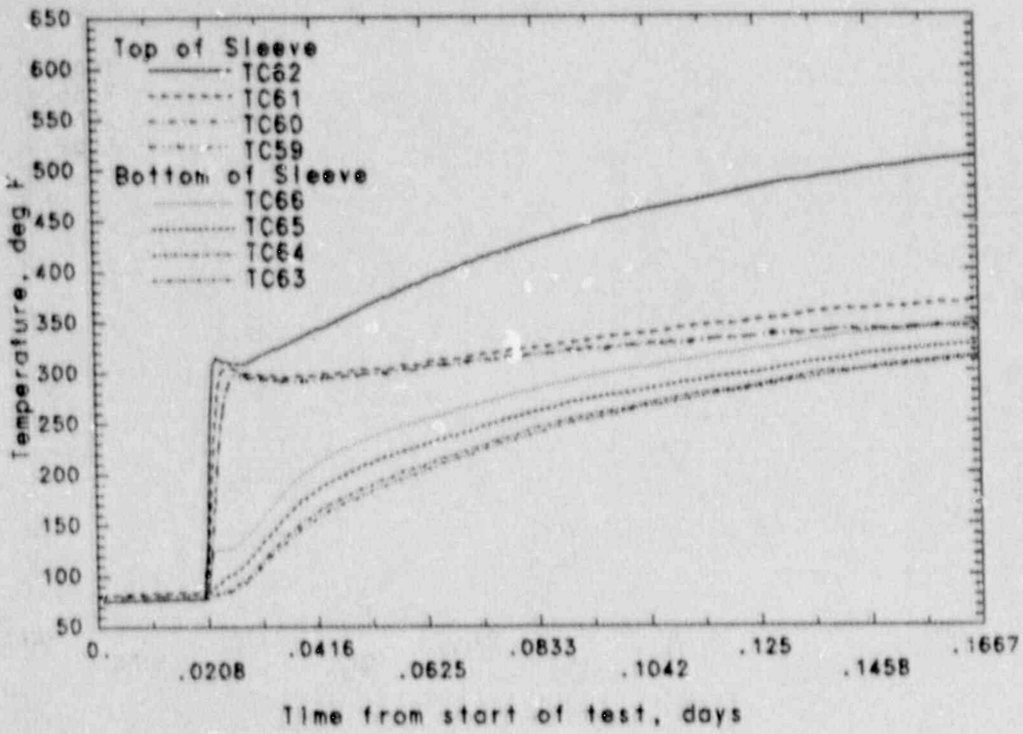
Figure 6-25 Air Temperature Inside EPA Sleeve



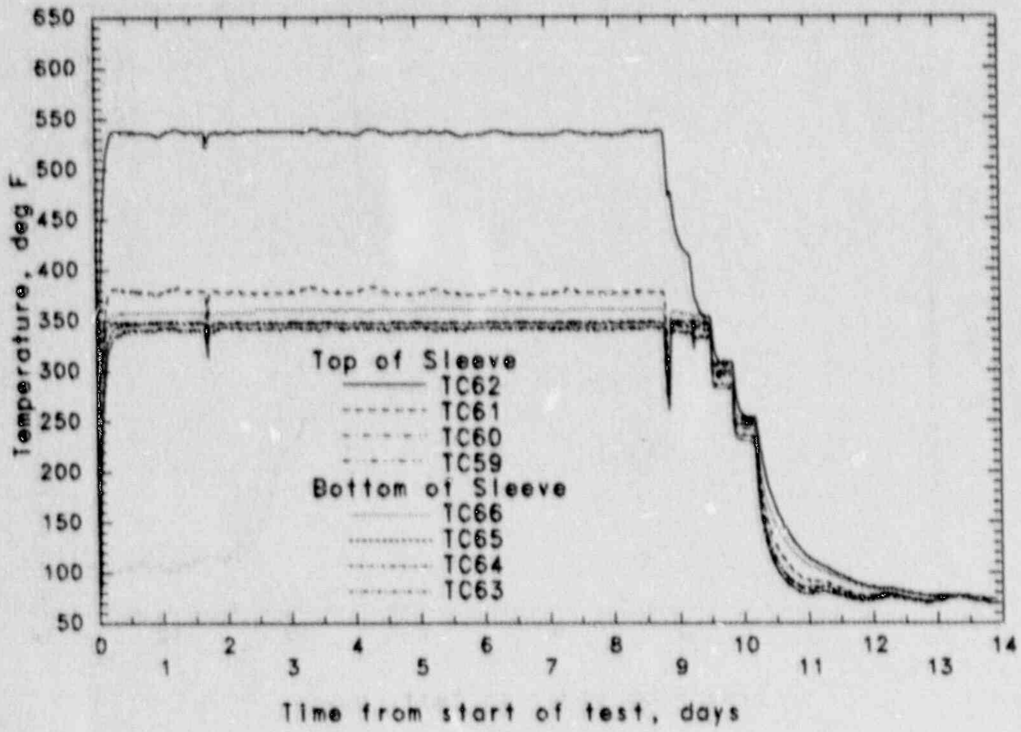
(a) First 4 Hours of SAC Test



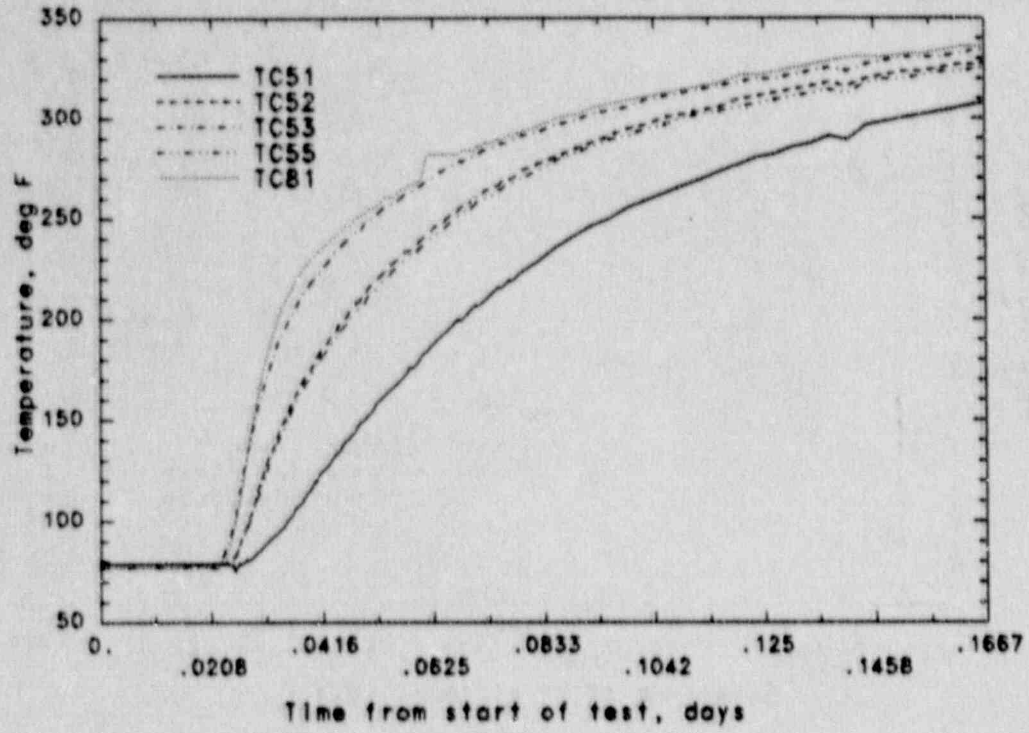
(b) 10 day SAC Test and Cool-down
Figure 6-26 Air Temperature Around Header Plate



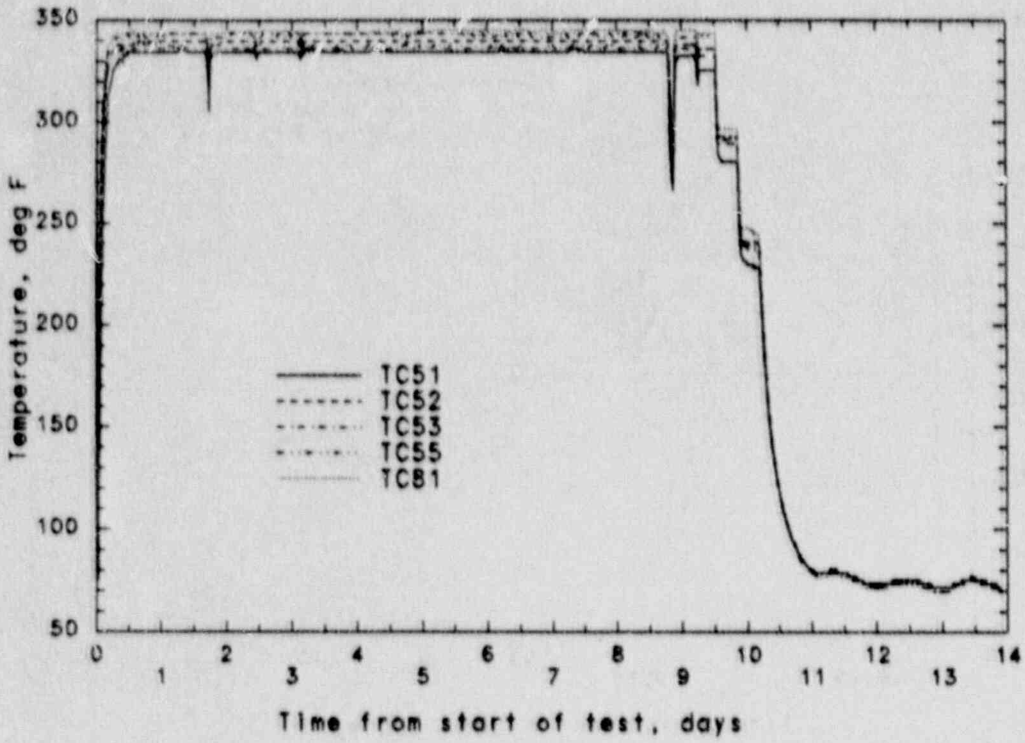
(a) First 4 Hours of SAC Test



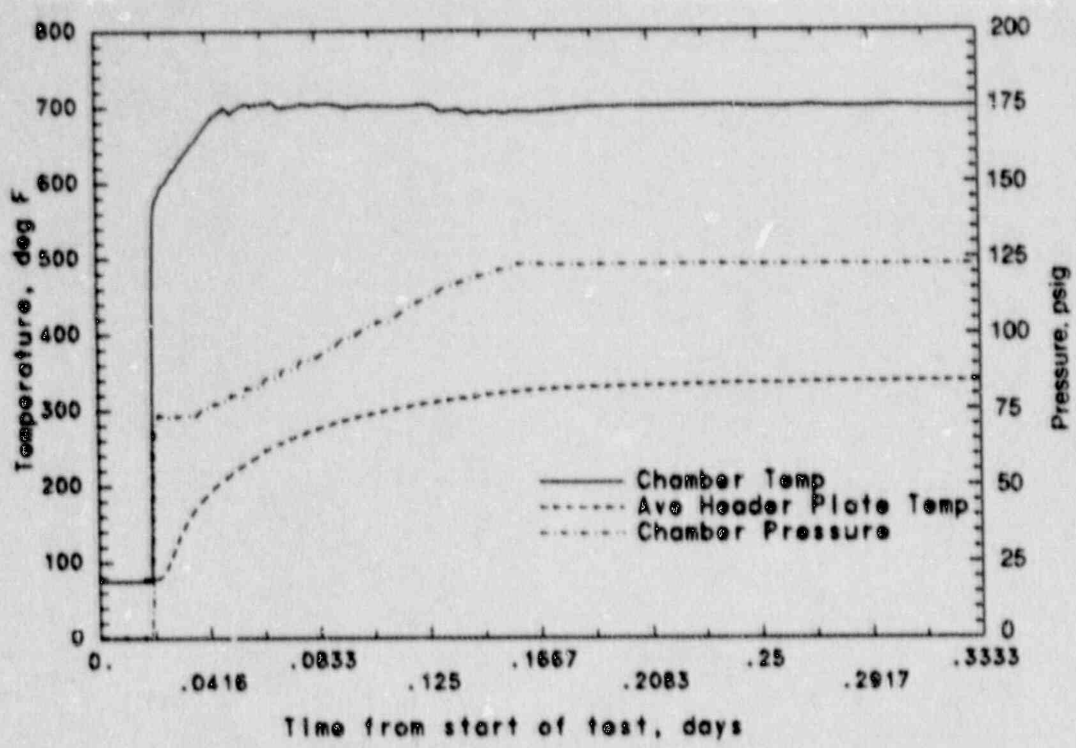
(b) 10 day SAC Test and Cool-down
Figure 6-27 Temperature Profile Along EPA Sleeve



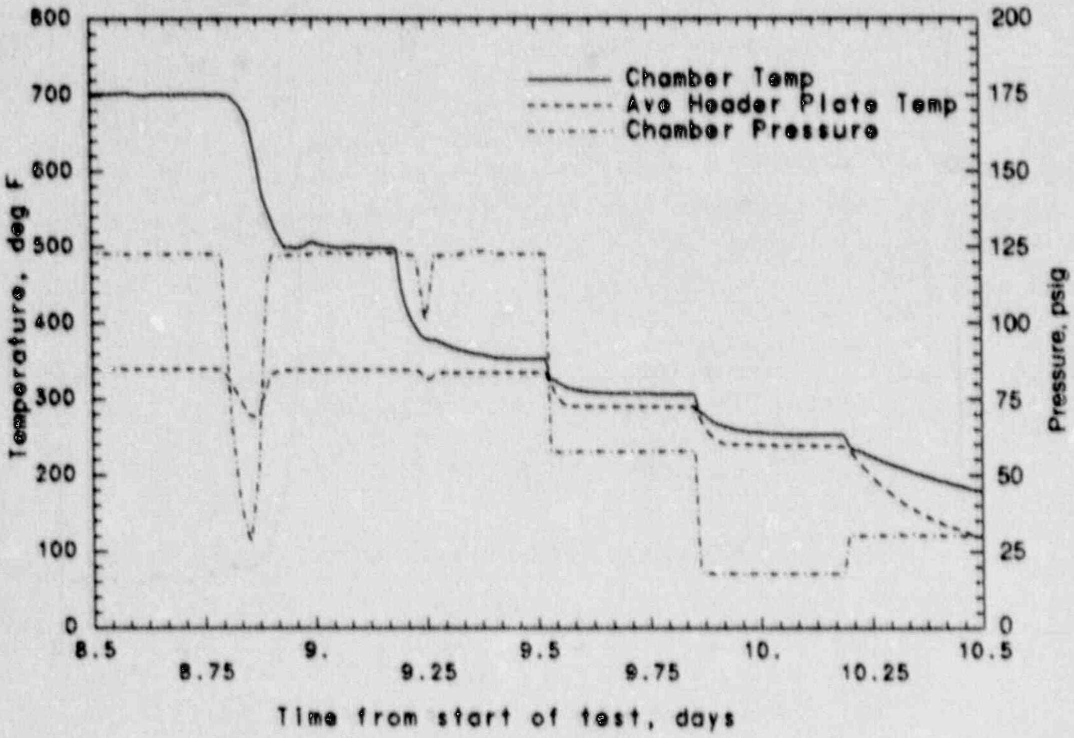
(a) First 4 Hours of SAC Test



(b) 10 day SAC Test and Cool-down
Figure 6-28 Temperature of Header Plate



(a) First 8 Hours of SAC Test



(b) 10 day SAC Test and Cool-down

Figure 6-29 Dependence of Header Plate Temperature on Chamber Pressure

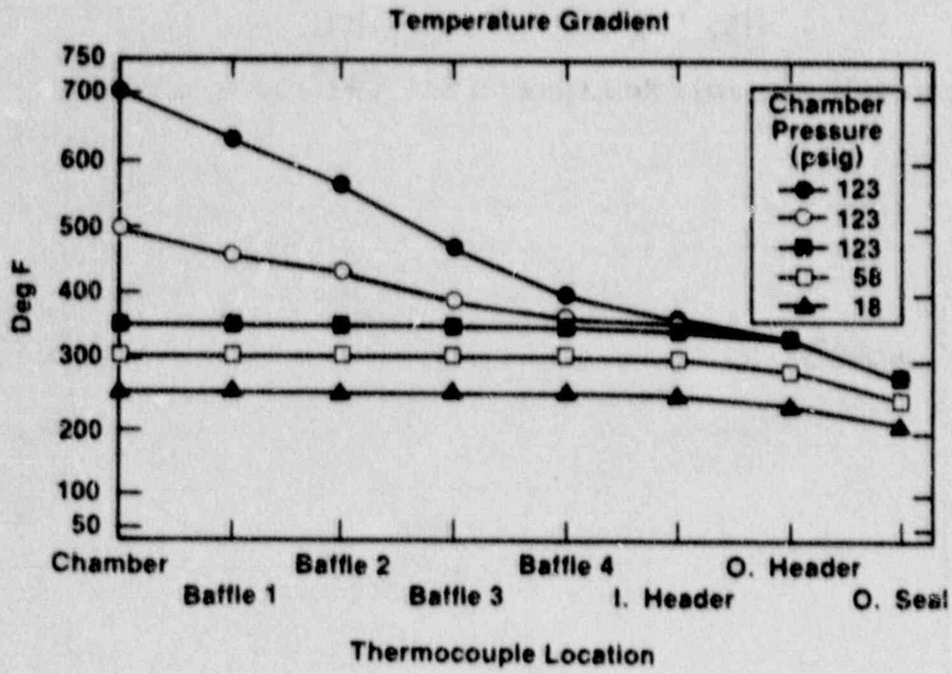


Figure 6-30 Temperature Gradient Along EPA Sleeve

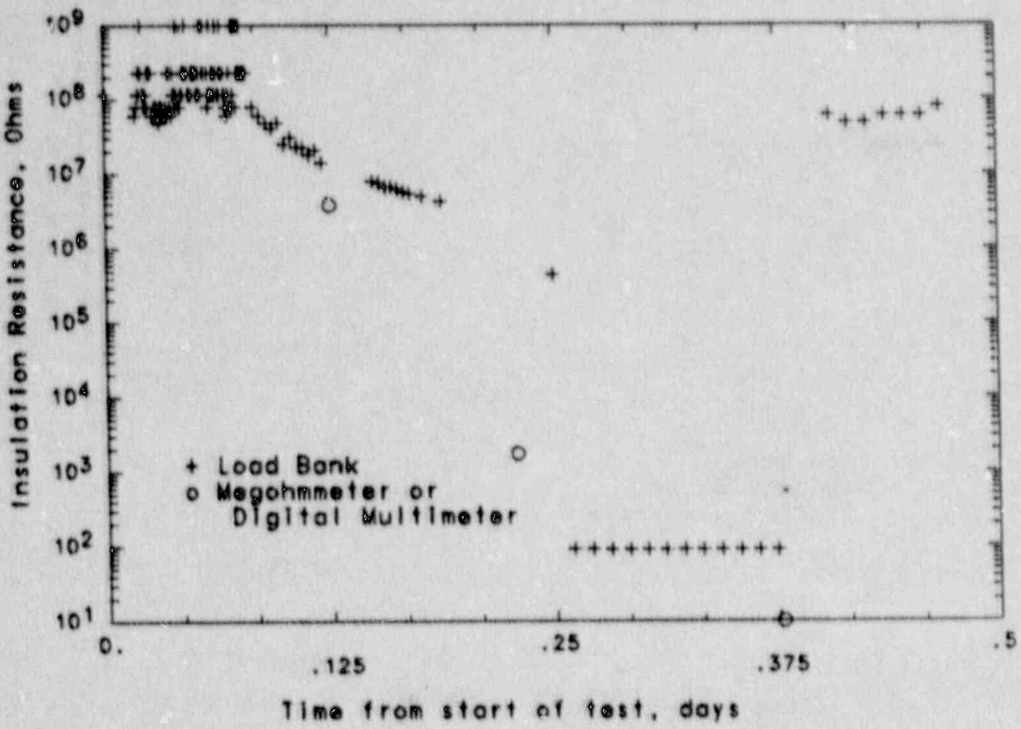


Figure 6-31 Insulation Resistance for #12 AWG Cable, Module #3

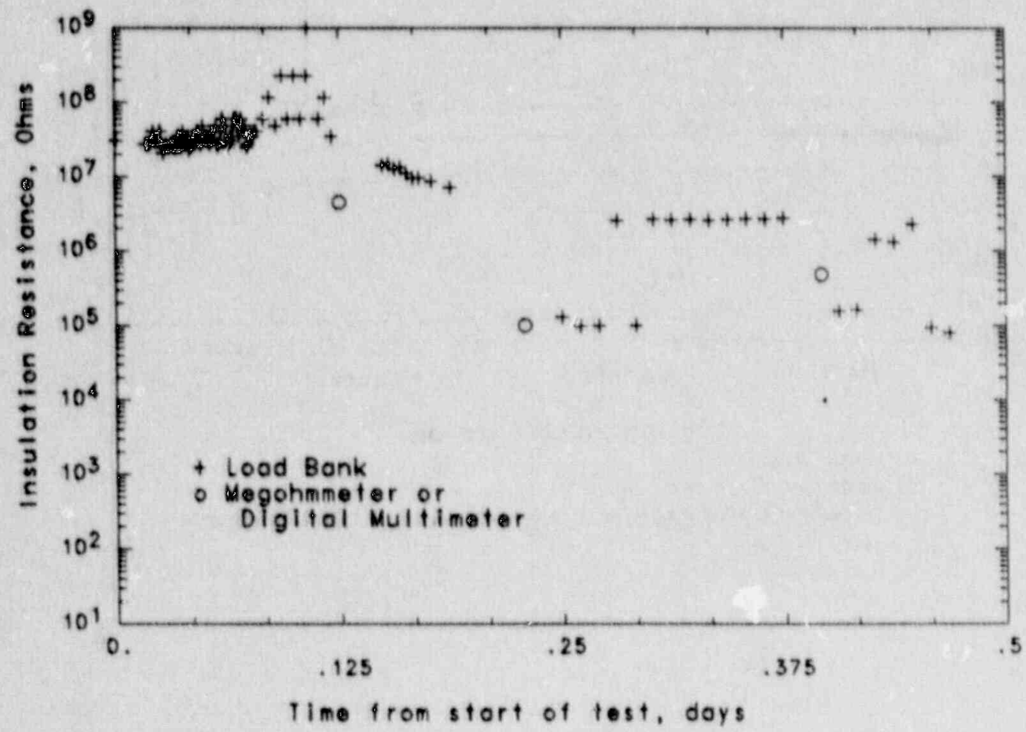


Figure 6-32 Insulation Resistance for #12 AWG Cable, Module #4

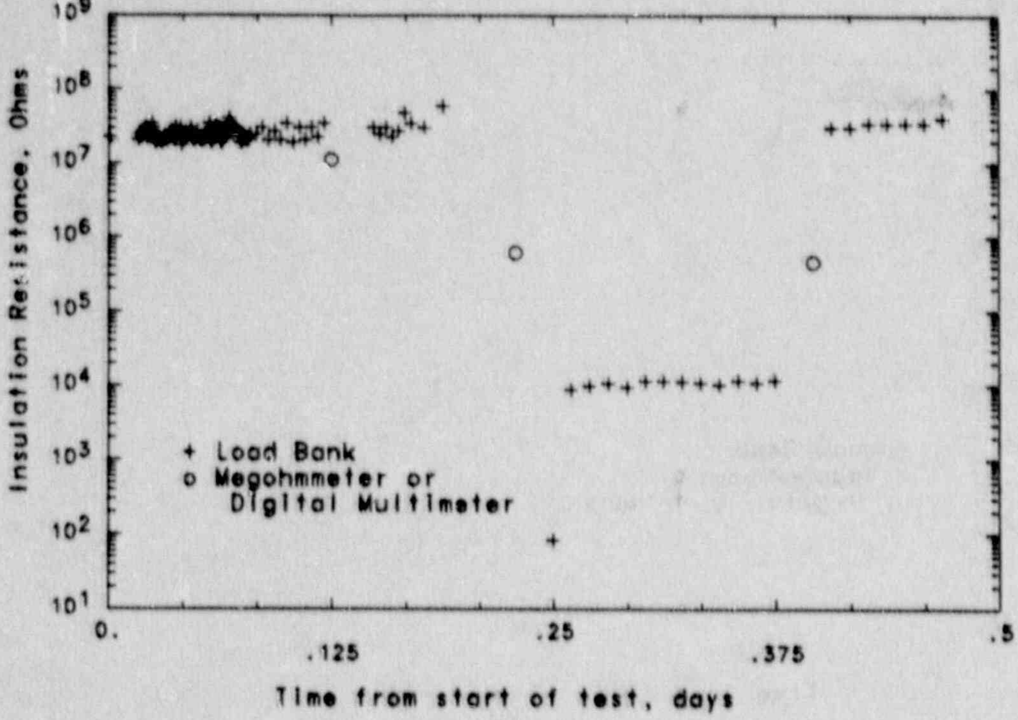


Figure 6-33 Insulation Resistance for #16 AWG Cable, Module #7

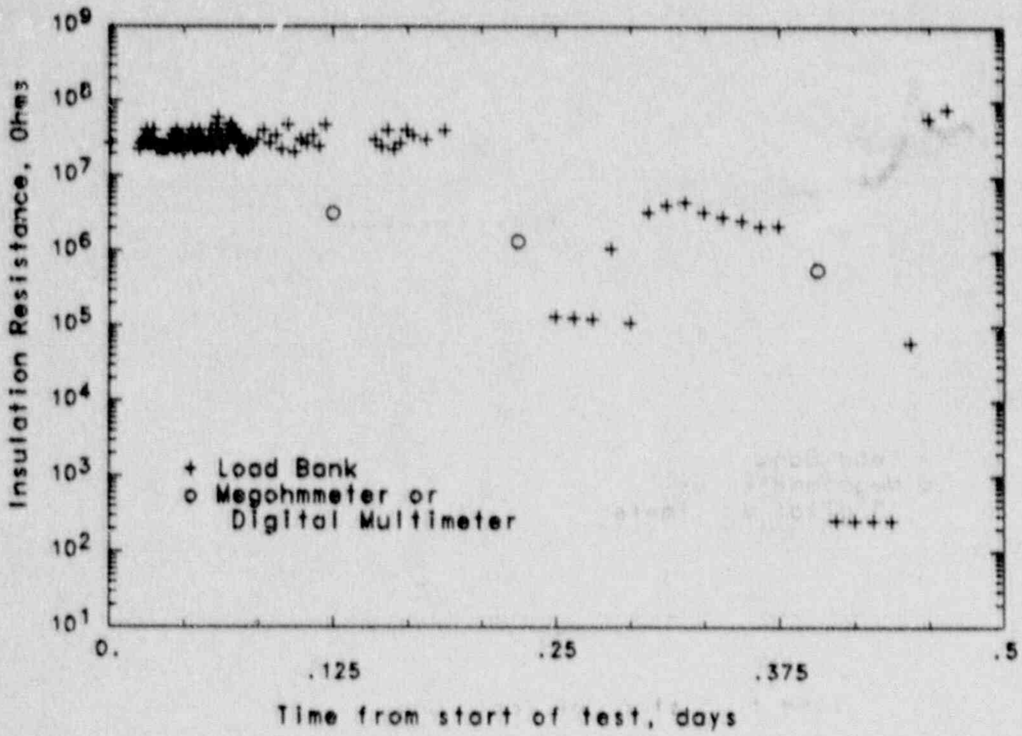


Figure 6-34 Insulation Resistance for #16 AWG Cable, Module #8

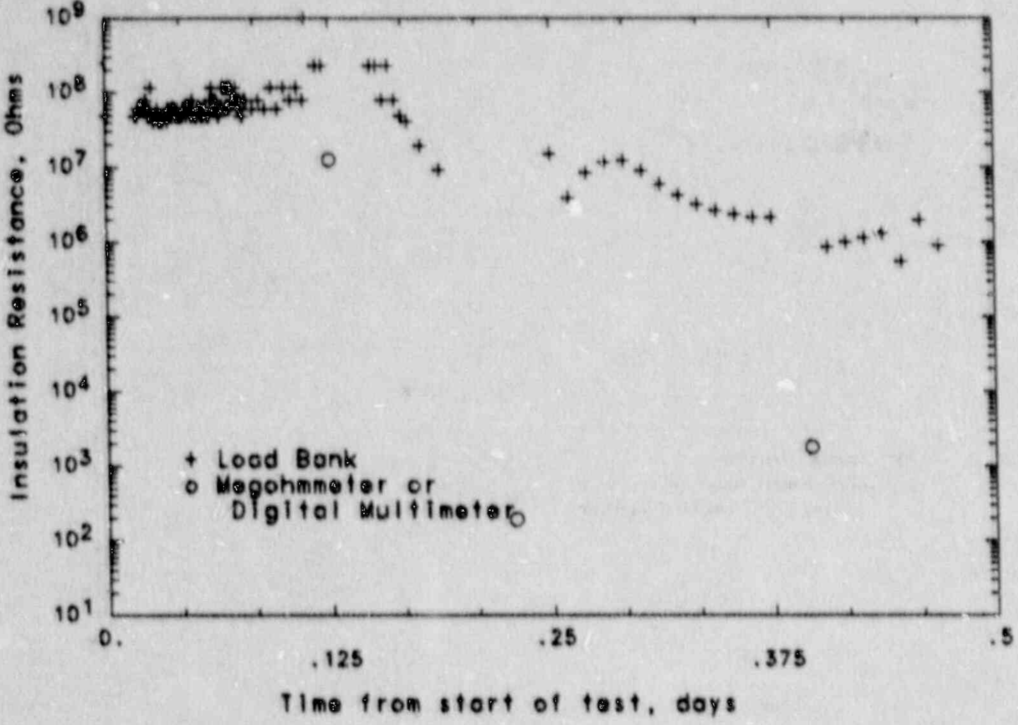


Figure 6-35 Insulation Resistance for #14 AWG Cable, Module #12

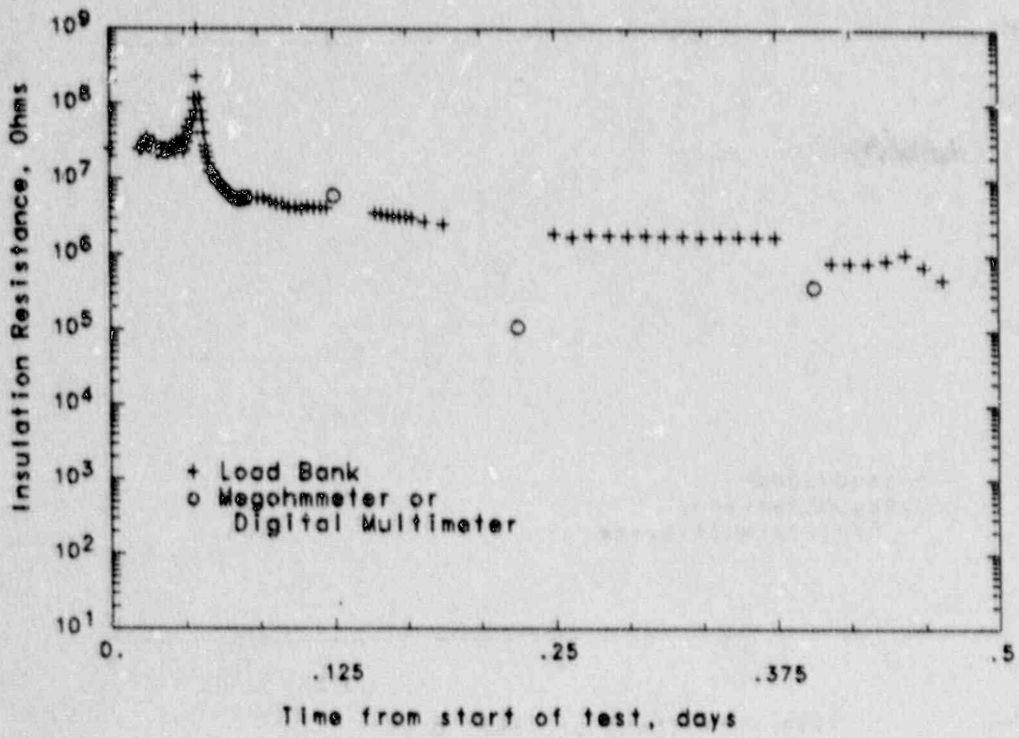


Figure 6-36 Insulation Resistance for #14 AWG Cable, Module #13

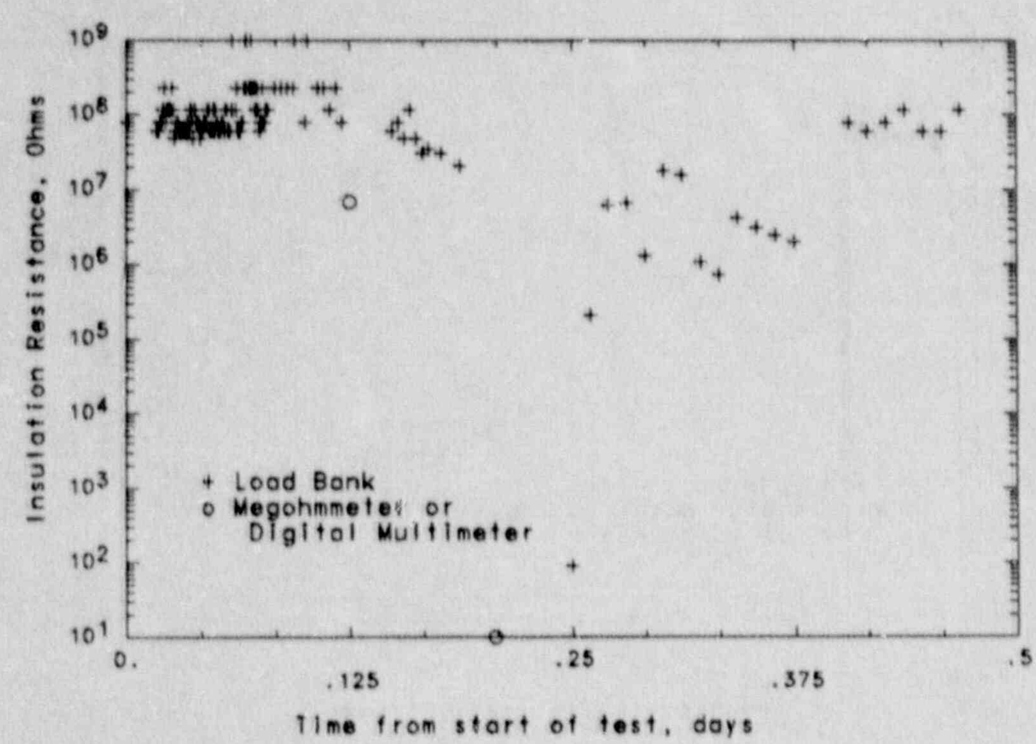


Figure 6-37 Insulation Resistance for #8 AWG Cable, Module #14

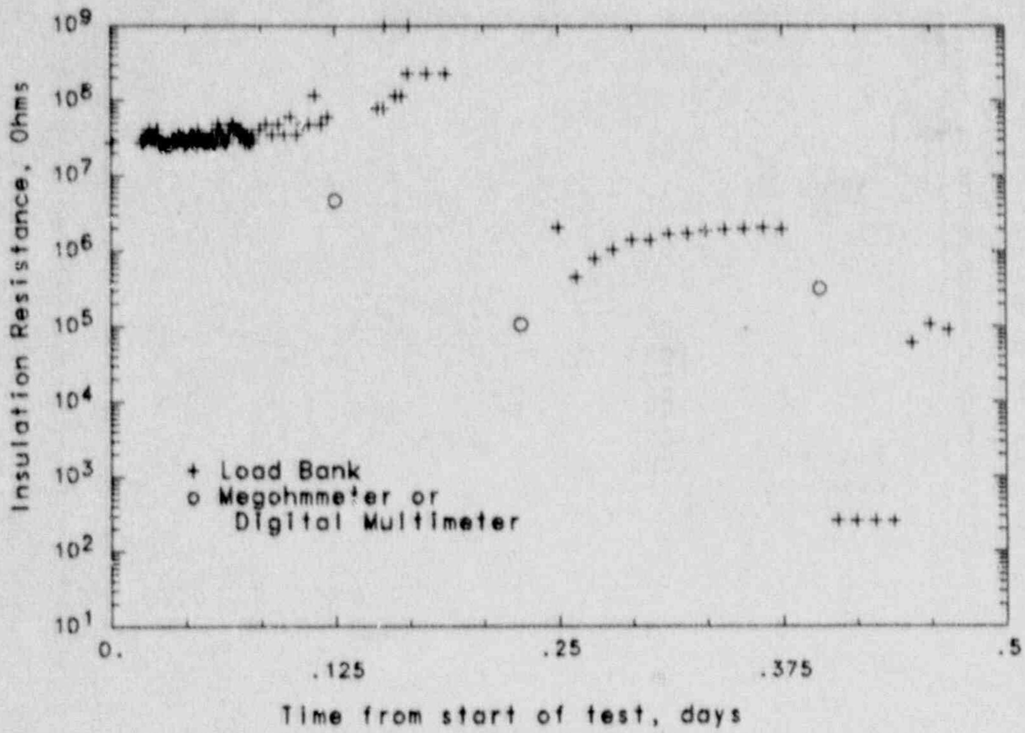
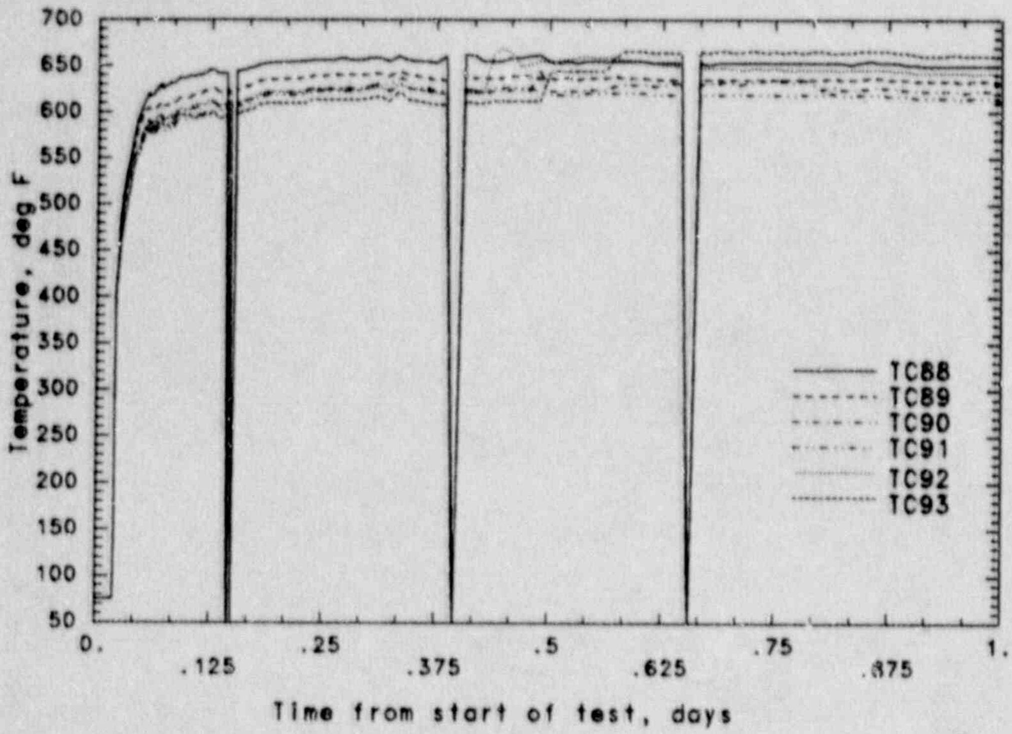
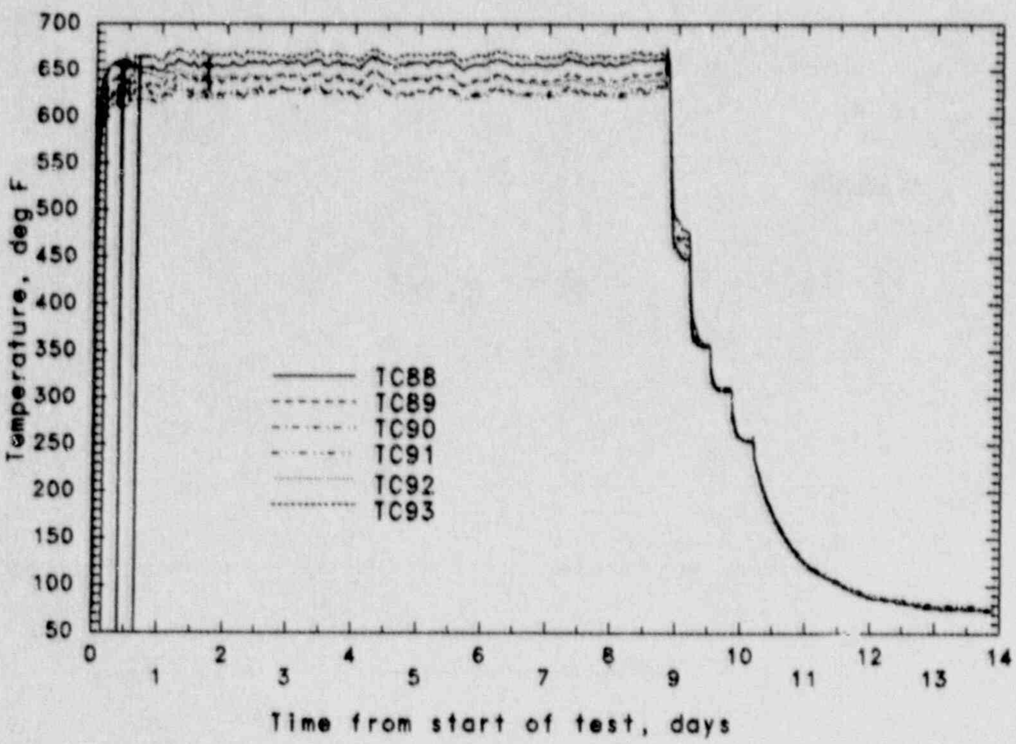


Figure 6-38 Insulation Resistance for #8 AWG Cable, Module #15



(a) First Day of SAC Test



(b) 10 day SAC Test and Cool-down

Figure 6-39 Output from Conax EPA Thermocouples

Figure 6-40a Photograph of Inside Junction Box, Before SAC Test

Figure 6-40a Photograph of Inside Junction Box, Before SAC Test

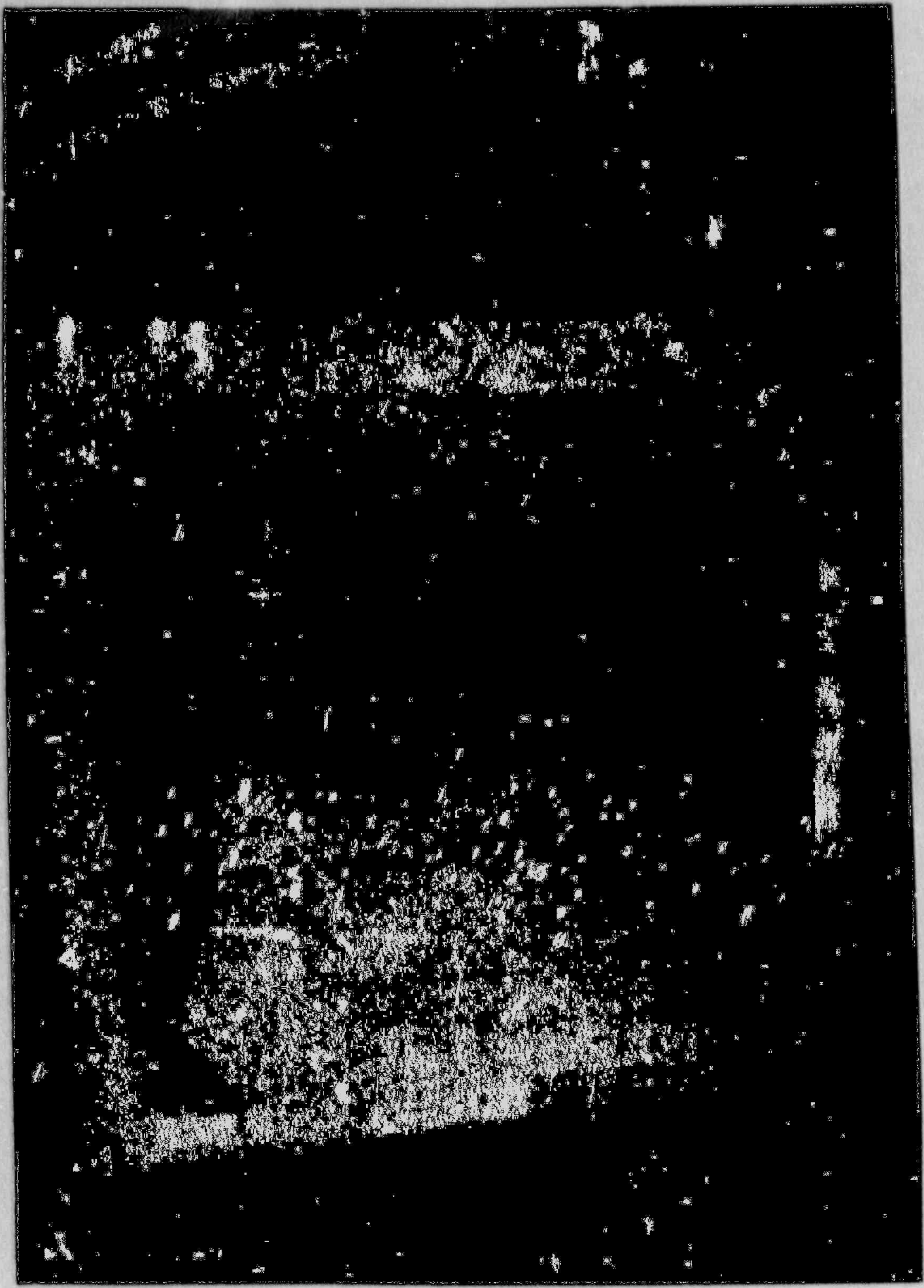


Figure 6-40b Photograph of Inside Junction Box, After SAC Test

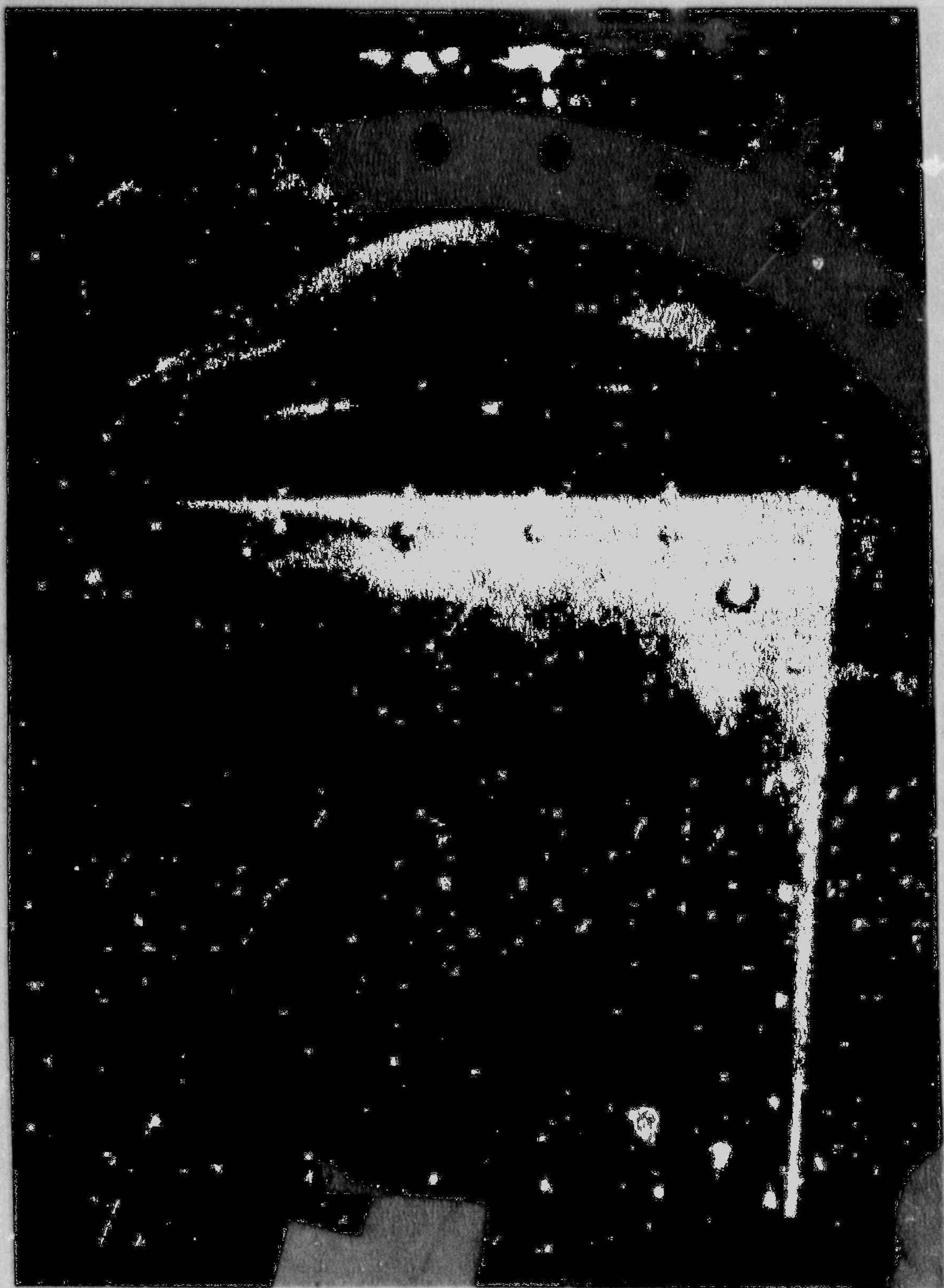


Figure 6-41a Photograph of Outside Junction Box, Before SAC Test

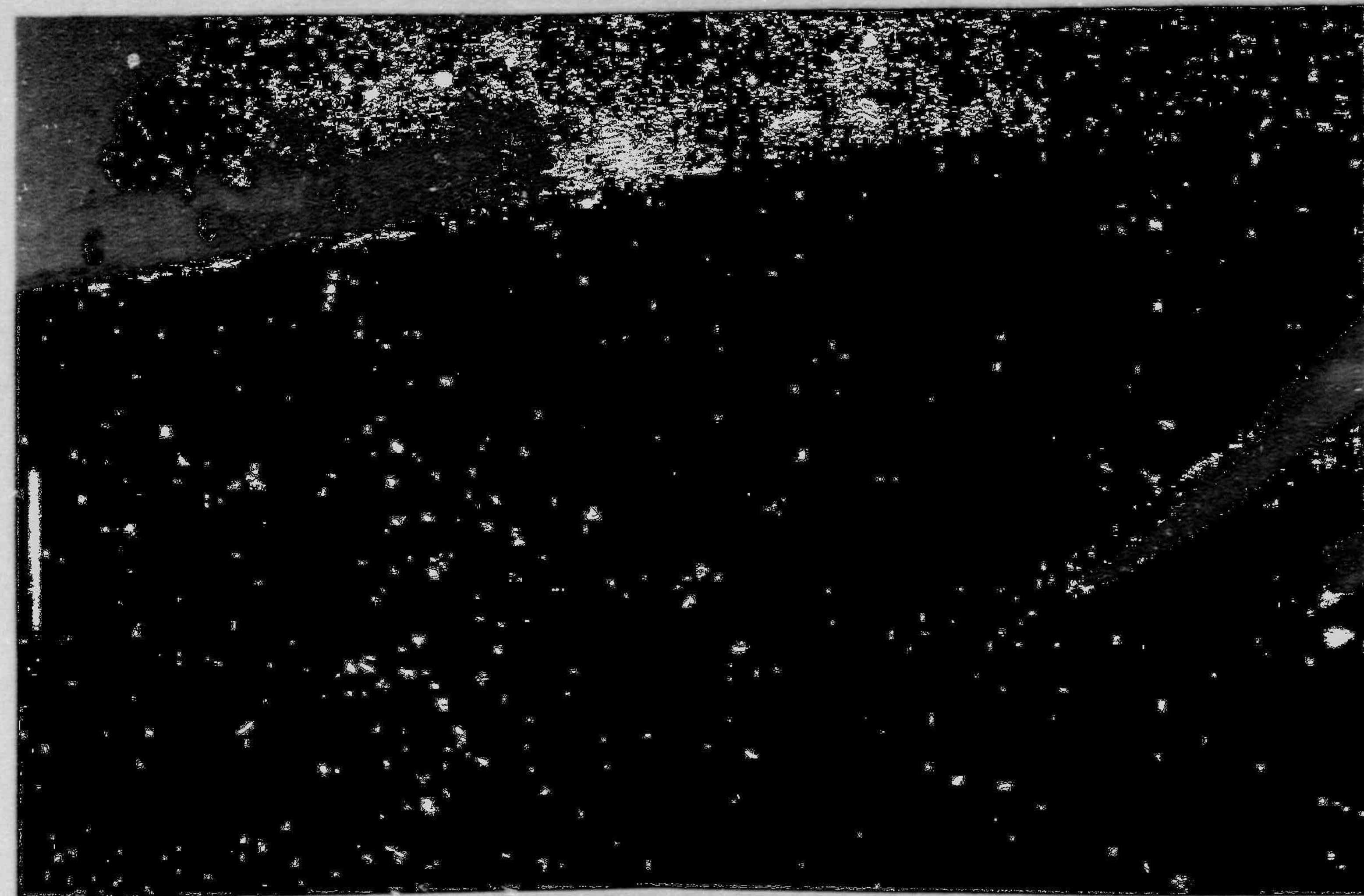


Figure 6-41b Photograph of Outside Junction Box, After SAC Test

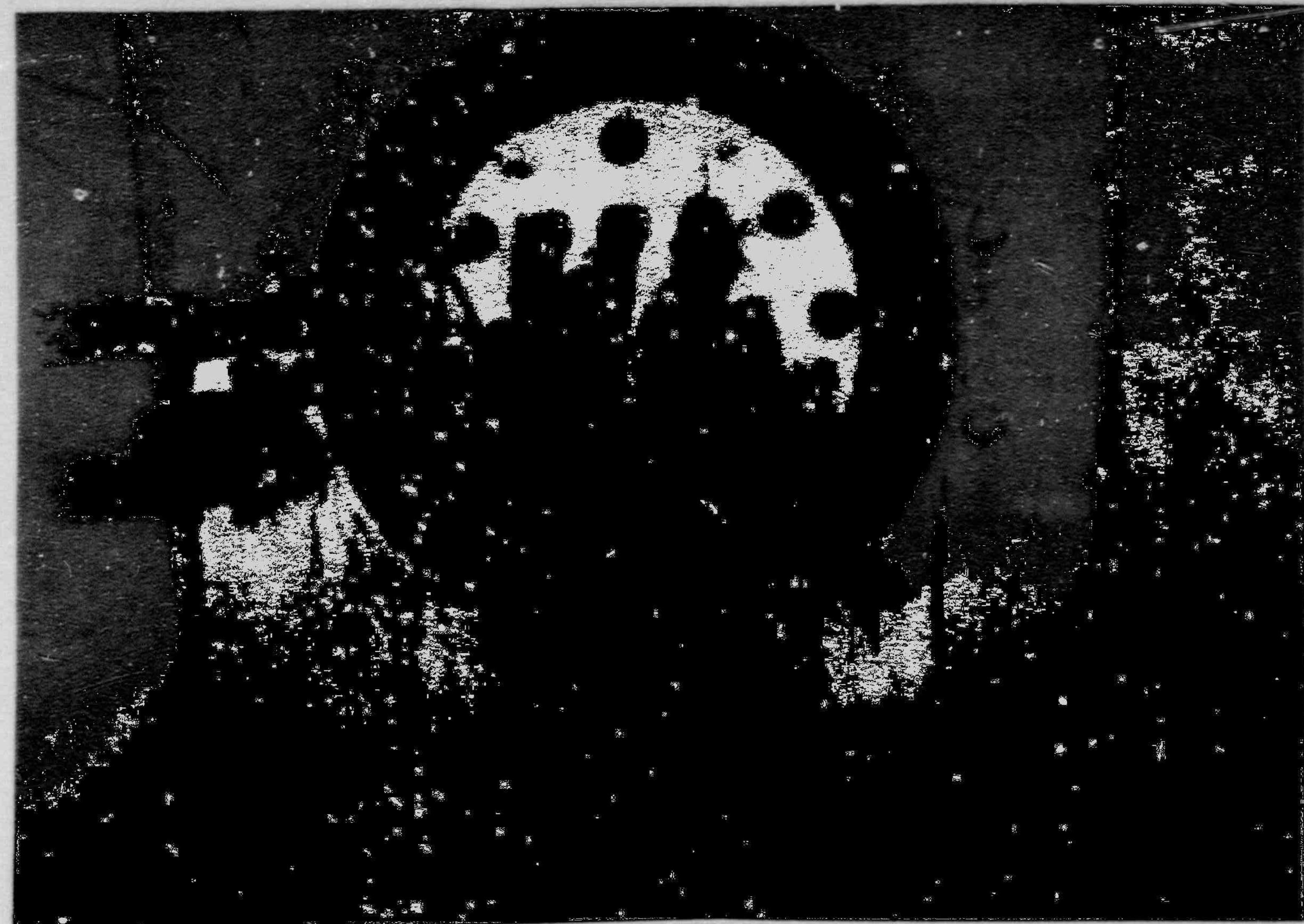


Figure 6-42 Post-SAC Test Photo of Inside Junction Box with Cables Removed

Figure 6-43 Post-3AC Test Photo of Inboard Module Seals

Figure 6-44 Post-SAC Test Photo of Outboard Module Seals

7.0 CLOSURE

Three EPA designs were tested under simulated severe accident conditions for a PWR, BWR Mark I drywell, and a BWR Mark III drywell to generate engineering data (leak rate, temperature, insulation resistance, and electrical continuity) to assess their leak potential. None of the EPAs leaked during the severe accident tests, which can be attributed to the use of redundant seals in the EPA designs and to the fact that the outboard containment seals in all three designs were never exposed to temperatures that exceeded the service limits of the seal materials. The exceptional leak integrity of the three EPAs in this program should not be assumed to apply to all other EPAs in use for at least two reasons:

1. There are a large, diverse number of EPA designs in use. In particular, EPAs manufactured prior to 1971 were not subject to national standards and were often field manufactured, whereas the EPAs tested in this program were subject to rigorous quality assurance and were designed to meet the standards of IEEE 317-1976 and IEEE 323-1974.

2. The leak potential is highly dependent on the temperatures to which the EPA is subject. As research continues and more severe accident sequence analyses are conducted, the "worst-case" loads may change. Therefore, the leakage potential of EPAs must be reevaluated as understanding of severe accident loads is improved. Heat transfer effects must be considered to determine the temperature of the outboard containment seals, which end up controlling leakage potential.

In short, the results of these tests should not be construed as suggesting that all EPA designs will not leak under severe accident conditions; the performance of all components of the containment pressure boundary must be evaluated on a case-by-case basis. The performance of the containment system will be dependent on the loads considered. Given good information on the containment loads, a heat transfer analysis to determine the approximate temperature profiles in the EPA, knowledge of the time-temperature thresholds for the sealant materials used in the EPA, and the proper exercise of engineering judgement, a reasonable evaluation of the leakage potential of other EPA designs can be made. These tests may provide a basis for such an appraisal.

The electrical performance of the EPAs was monitored in these tests by measuring the insulation resistance and electrical continuity of the conductors. The measured insulation resistance degraded rapidly during the severe accident tests, although the rate depended more on the type of cable and loads than on the particular module design being tested. Under the specific severe accident conditions that were simulated, the data suggest that **all** electrical systems supplied in the Westinghouse EPA would have functioned for about 4 days; those supplied in the D. G. O'Brien EPA would have functioned for about 13 hours; and those supplied in the Conax EPA may have only functioned for about 5 hours[6] (the difference between the performance of the Conax and that of the D. G. O'Brien and Westinghouse is largely attributable to the severity of the loads--the Conax was subject to temperatures up to

6. The first few hours of a severe accident may be the most critical time from the standpoint of electrical functionality since mitigative action by the operators is generally most effective early in the accident progression.

700°F compared to 400°F or less for the D. G. O'Brien and Westinghouse). Some cables would be expected to function beyond the times indicated above. However, it must be noted that conclusions regarding the electrical performance of systems inside the containment building based solely on insulation resistance data must be made with caution. The performance of the electrical systems would depend on the specific voltage, current, and impedance requirements for a given application of a conductor. For instance, the thermocouple cables in the Conax EPA continued to transmit an accurate temperature signal throughout the severe accident test even though their insulation resistance had dropped to between 17 Ω to 4 kΩ by 9 hours into the test. On the other hand, the contaminants that seeped into the pins and mask in the D. G. O'Brien module connectors caused a short to ground that would almost certainly have precluded the electrical systems from functioning properly.

8.0 REFERENCES

[1] J. D. Keck and F. V. Thome, "Electrical Penetration Assemblies Severe Accident Testing," Proceedings of the Intl. Topical Meeting on Operability of Nuclear Power Systems in Normal and Adverse Environments, pp 181-186, ANS, Albuquerque, NM, September 29-October 3, 1986.

[2] J. D. Keck and F. V. Thome, "Leak Behavior Through EPAs Under Severe Accident Conditions," Proceeding of the Third Workshop on Containment Integrity, NUREG/CP-0076, SAND86-0618, Sandia National Laboratories, Albuquerque, NM, pp 569-580, August 1986.

[3] F. V. Thome and W. A. von Riesemann, "Results of Leak Rate Testing of D. G. O'Brien Electrical Penetration Assemblies Under Severe Accident Conditions," presented at the 8th International Conference on Structural Mechanics in Reactor Technology, Brussels, Belgium, August 19-23, 1985.

[4] D. H. Cook, S. R. Greene, R. M. Harrington, S. A. Hodge, and D. D. Yue, "Station Blackout at Browns Ferry Unit One--Accident Sequence Analysis," NUREG/CR-2182, ORNL/NUREG/TM-455/V1, Oak Ridge National Laboratory, Oak Ridge, TN, November 1981.

[5] "Technical Basis for Estimating Fission Product Behavior During LWR Accidents," NUREG-0772, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, June 1981.

[6] W. A. Sebrell, "The Potential for Containment Leak Paths Through Electrical Penetration Assemblies (EPAs) Under Severe Accident Conditions," NUREG/CR-3234, SAND83-0538, Sandia National Laboratories, Albuquerque, NM, July 1983.

[7] C. V. Subramanian and W. A. Sebrell, "Test Plan for Evaluating Leak Behavior Through Electrical Penetration Assemblies Under Severe Accident Conditions," Revision 3, for the USNRC Office of Nuclear Regulatory Research, Electrical Engineering Branch, by Sandia National Laboratories, February 1984

[8] W. S. Farmer, "Summary of April 30, 1984 Meeting on Proposed Test Profiles and Test Plan for Experiments with Electrical Penetration Assemblies in Severe Accident Environments," USNRC Office of Nuclear Regulatory Research, May 8, 1984.

[9] "Installation and Maintenance Manual for Electrical Penetration Assemblies for Sandia National Laboratories," P.O. No. 47783, Conax Buffalo Corporation, W.O. 7-K0400, Conax Document IPS-1249, Conax Corporation, 2300 Walden Avenue, Buffalo, NY 14225.

[10] "Parker O-Ring Handbook," Parker Seal Group, Lexington, Kentucky, pp. A3-4, 1982.

APPENDIX A
Leak Rate Calculations

In the EPA tests, the leak rate from the aperture seal and module seal monitoring volumes was calculated using ideal gas laws for a fixed control volume. Given the pressure and temperature of the monitoring gas at the start of the leak test (time t_0, p_0, T_0) and again after some specified period of time (time t_1, p_1, T_1), the leak rate, L, was then calculated using the following equation:

$$L = \left[\frac{p_1}{T_1} - \frac{p_0}{T_0}\right] \frac{T_s \cdot V}{p_s(t_1 - t_0)} \quad \text{(A-1)}$$

where p_s and T_s are standard temperature and pressure (528°R and 14.7 psia), and V is the volume of the space being monitored.

Pressures of the monitoring volumes (for both the aperture seal and module seal) were measured directly. However, the temperature of the monitoring gas could not be measured precisely; because the monitoring volumes included tubing that was external to the test apparatus, the temperature was not uniform. Since several thermocouples were always located on the header plate, the temperature of the monitoring gas was typically assumed to be equal to the temperature of the header plate. This assumption is the main source of error in the leak rate calculations.

Equation (A-1) can be modified to account for the portions of the monitoring volume that are internal (V_i) and external (V_e) to the test apparatus. The result is:

$$L = \left\{ p_1 \left[\frac{V_i}{T_{1i}} - \frac{V_e}{T_{1e}}\right] - p_0 \left[\frac{V_i}{T_{0i}} - \frac{V_e}{T_{0e}}\right] \right\} \frac{T_s}{p_s(t_1 - t_0)} \quad \text{(A-2)}$$

APPENDIX B
Fault Currents

Letter from C. V. Subramanian, Sandia,
to W. S. Farmer, NRC,
April 20, 1984,
Re: Questions on Fault Current Issues on EPAs

April 20, 1984

William S. Farmer
Electrical Engineering Branch
U. S. Nuclear Regulatory Commission
Room 270
5650 Nicholson Lane
Rockville, MD 20852

Dear Bill:

Re: Electrical Penetration Assemblies (EPA) Program (FIN No. A-1364) - Questions on Fault Current Effects on EPAs.

The enclosed attachments I and II along with Table I which address the questions on the fault current issues raised by NRC have been revised to incorporate the comments received from you. Our consultants who helped us with these attachments have been invited to attend the meeting on April 30, 1984 between SNLA and NRC to discuss the final plan for the EPAs.

Sincerely,

C. V. Subramanian
Containment Integrity
Division 6442

Copy to:
N. G. Luria, General Electric Co.
L. Korner, Consultant
6442 W. A. von Riesemann
6446 L. L. Bonzon
6446 F. V. Thome
6442 File 1363.010

ATTACHMENT I

Question: Since the bounding severe accident thermal environment in BWRs is high, will the electrical cables survive? Also identify what circuits are needed for safety functions (i.e., voltage and amperage) in the event of a severe accident.

Response: Based on published data on the qualification of electrical cables, they would not be expected to survive the severe accident thermal environment in BWRs. Since High Voltage Power (HVP) and Medium Voltage Power (MVP) modules are not believed to be required to function electrically and since they would thus also not be needed for any safety functions, only Low Voltage Power (LVP) modules are of concern after a severe accident. The voltage and amperage of the different LVP circuits that may be needed would be expected to be consistent with their design ratings which are summarized in the current version of IEEE-317.

Question: For the identified LVP circuits, will an electrical fault current be probable during the accident scenario? Consider shorts in the cable within the containment and potential whipping of the cables in the assessment.

Response: If it is assumed that the cable insulation is lost or degraded during the accident scenario, then there might be potential for faulting. However, LVP module wires because of their high resistance are more likely to exhibit a leak or short to ground than a fault. The LVP module wires which are small in size, also carry low voltages and currents. Hence, the force due to a fault current if one should occur, would be expected to be small, thereby reducing the potential for whipping of the cables. In addition, the cables within the penetrations are well supported and tied down. The cable from the penetrations to the cable tray is normally supported by conduits. This further minimizes the potential for whipping.

Question: If a fault current were to occur within the EPA, would the penetration leakage be affected?

Response: In general, it is our judgement that the effects of fault current if any, would be minimal on the leakage potential of the EPAs. (See Table I which shows the efforts of fault currents to be minimal and Attachment II which shows leak areas to be small).

Question: How would the fault current load, along with the severe accident thermal and pressure environment, be simulated in the tests?

Response: For HVP/MVP modules, it will be very complex to simulate the fault current loads simultaneously with pressure and thermal loads from severe accidents because of the large current supply requirements. However, as noted above, the HVP/MVP circuits are not expected to be required in a severe accident. For the LVP type of module, the test set-up can be made reasonably simple using small auto-claves and small currents for input. This is different than the industry fault current tests which uses different heating schemes other than auto-claves. Simulating fault current loads simultaneously with the severe accident environment in the EPA tests would significantly impact the schedule and cost of the EPA program. This is currently not possible at SNLA because there are no power sources in or near the building used for the EPA test which could provide the current required. Hence, it will be necessary to run in a larger amperage capacity cable and provide protective devices to protect SNLA electrical system from surges.

ATTACHMENT II

For low voltage power modules, consider two sizes of wires typically used in these circuits: 10 AWG and 4/0 AWG. For these -

(i) The mechanical force between wires due to a fault current is given by (Reference 1)

$$F = 34.9 \frac{I^2}{d} X 10^{-7} \qquad (1)$$

Where

F = lateral force in lb/ft.
d = conductor spacing in inches
I = current in amps

and from Reference 2,

$$\left(\frac{I}{A}\right)^2 t = 0.0297 \log \left(\frac{T_2 + 234}{T_1 + 234}\right) \qquad (2)$$

I	=	short circuit current - amps
A	=	conductor area - circular mils
t	=	time of short circuit - seconds
T_1	=	maximum operating temp. (°C)
T_2	=	maximum short circuit temp. (°C)

Using equations 1 and 2,

For T_1 = 90°C, T_2 = 250°C, (Reference 2) and t = 0.1333 sec. (8 cycles based on length of time for fuse protection).

	I_{10AWG}	=	2050 amps
	$I_{4/0AWG}$	=	41791 amps
For	$d_{10/0AWG}$	=	0.2 in (Typical dimension)
	F_{10AWG}	=	6.2 lb/in
For	$d_{4/0AWG}$	=	1.00 in (Typical dimension)
	$F_{4/0AWG}$	=	508 lb/in

These forces are provided for by the penetration manufacturers by using internal supports for the cables inside the penetration.

(ii) The maximum temperature of cable due to short circuit current is computed using equation (2) as:

$$\log\left(\frac{T_2 + 234}{T_1 + 234}\right) = \left(\frac{I}{A}\right)^2 \times \left(\frac{t}{0.0297}\right)$$

For T_1 = 70°F (21°C) (ambient temperature)

$T_{2\ 10AWG}$ = 298°F = $T_{2\ 4/0AWG}$

If T_1 is assumed to be 130°F (ambient temperature that exists typically outside the containment but inside the reactor building), then

$T_{2\ 10AWG}$ = $T_{2\ 4/0AWG}$ = 388°F

It can be seen that the maximum temperature of the LVP cables is around the values for which the cables have been tested.

References:

1. ALCOA Bus Conductor Handbook, Aluminum Company of America. Chapter 6, pp. 75-82

2. ICEA Publication No. P-32-382.

Attachment II (contd.)

Calculation of the secondary seal temperature reached after a fault current for an inboard mounted penetration in a BWR III SAC (400°F inboard, 130°F outboard).

The outboard seal is about 3" long. At its midpoint, its steady state temperature is estimated to be 132°C based on experimental data (i.e., T_1 is 132°C).

Consider a #10AWG cable with an I^2t value of 5.58×10^5:

The cable is attached to a conductor # 8AWG having a circular mil value of 16510.

Using equation 2 from Attachment I:

$$\frac{I^2t}{A^2 (0.0297)} = \log\left(\frac{T_2 + 234}{T_1 + 234}\right)$$

$$\frac{5.58 \times 10^5}{16510^2 (0.0297)} = \log\left(\frac{T_2 + 234}{132 + 234}\right)$$

T_2 equals 195°C at the outboard (Secondary) seal

ATTACHMENT II (Contd.)

Fault current effect during SAC based on a worst case scenario:

Assumptions:

1. The fault current will increase the seal temperature by 160°C above the severe ambient. (Reference 2)
2. The seal material loses all elasticity so that once expanded by the solid copper conductor, it does not return to its original position leaving a leakage path.
3. Consider the largest seal so as to produce the largest leak. (#4/OAWG, .460" dia.).

Calculation:

Coefficient of expansion of copper: 9.12×10^{-6} per deg. F

Change in dia. due to 160°C (288°F) in .460" dia. bar:

$$.46 \times 288 \times 9.12 \times 10^{-6} = 0.0012"$$

Area of doughnut shaped gap:

$$.46 \times 3.14 \times .00012/2 = 0.0000866 \text{ sq. inches}$$

Diameter of pipe having this cross sectional area:

$$.785\ D^2 = 0.0000866\ \ IN^2$$

$$D = 0.01"$$

Length of leak path:

Westinghouse penetrations are 5" long.

Conclusion:

A three phase fault current would produce 3 leakage paths each 0.01" dia. by 5 inches long.

Note: The seal will not blow out if this event occurs because the seals have connectors on the ends larger in diameter than the seal diameter.

FAULT CURRENT ASSESSMENT - ELECTRIC PENETRATIONS

CONTAINMENT	TEMPERATURE, °F		PRESSURE, PSIA		PENETRATION TYPE			PENETRATION CONTAINMENT
	INSIDE DRYWELL	OUTSIDE DRYWELL	INSIDE DRYWELL	OUTSIDE DRYWELL	(3) INSTRUMENTATION	(4) LOW VOLTAGE	(5) HIGH/MEDIUM VOLTAGE	
PWR	361	SPEC: 130 / QUAL 340	155	SPEC: AMB / QUAL 118	NOT APPLICABLE: THERMOCOUPLE AND DETECTOR CIRCUITS CANNOT EXPERIENCE FAULTED CONDITIONS.	REDUNDANT SEAL IN MILD ENVIRONMENT. QUALIFIED TO OUTSIDE ENVIRONMENT.	REDUNDANT SEAL IN MILD ENVIRONMENT. QUALIFIED TO OUTSIDE ENVIRONMENT	MODULAR CANISTER (2)
BWR MARK I	700	SPEC: 130 / QUAL 340	135	SPEC: AMB / QUAL 118	SAME	SAME	SAME	CANISTER (2)
BWR MARK II	550	SPEC: 130 / QUAL 340	135	SPEC: AMB / QUAL 118	SAME	SAME*	SAME*	MODULAR (1) CANISTER (2)
BWR MARK III	[illegible]	SPEC: 130 / QUAL 340	75	SPEC: AMB / QUAL 118	SAME	SAME	SAME	MODULAR

NOTES ON TABLE 1

Background

For the severe environmental accident conditions beyond DBE, there is a concern that the inboard penetration seal which is exposed to the containment environment will not maintain its leak tight integrity. It is assumed for this postulated event that no electrical operability is required. Hence, the only concern is containment integrity. All electrical penetrations are gen- erally of two types: Canister and modular. The canister type has one seal at the inboard end that is exposed to a hostile environment within the containment and a second seal that is at
the outboard end in a milder environment outside the containment. Sufficient distance between the two seals ensures that the con- duction of heat to the second seal is relatively low and hence, its failure is also probably low. The modular penetration type has two seals which may be very close to one another.

The effects of fault current on the penetration assembly is two fold - thermal and mechanical. In the thermal effect, the fault current causes an increase in temperature of the wire which heats the interface with the surrounding sealing compound. Penetra- tions are generally designed to limit the temperature in the attached cable to 250°C starting at 90°C due to short circuit currents. The fault current therefore produces a temperature increase of 160°C. However, most manufacturers attach a larger than required cable to the penetration. As a result, the seal temperature increases by only 69°C. Hence, if the seal were at an accident environment of 340°F (171°C), the fault current would add 69°C for a total seal temperature of 240°C. Actual fault currents produce lower temperature increases because the length of the cable between the circuit breaker and the penetration will reduce the fault current below the design values.

The mechanical effect due to fault current will result in mechanical forces on the cables in a direction normal to the cable axis with very little force in a direction parallel to the cable axis. The magnitude of the force will depend on the size of the cable under consideration. However, it has been noted that the failure due to these forces occurs usually in the cable splices. The intermediate supports of the cable wires are designed to resist these forces, so that these failures can be minimized.

NOTE 1

For the BWR II containment, all known penetration modules are mounted to the outside end of the containment nozzle. Therefore, one of the redundant seals will not be subjected to the extreme drywell temperatures. Under this condition, the penetrations have been qualified to fault currents per IEEE 317-1971 worst case.

NOTE 2

Canister construction provides for the penetration to extend the full length of the containment nozzle. Therefore, one of the redundant seals is not exposed to the extreme temperatures of the drywell and note one is also applicable.

NOTE 3

Instrument circuits include thermocouple wires and coaxial cables. These conductors are high resistance paths carrying small currents and thus do not experience fault current heating.

NOTE 4

For low voltage circuits, wire size range from #18 AWG through #4/0AWG. All have been qualified to fault currents. The calculated force and the rise in temperature for these wires due to a short circuit is not large enough to be of any concern (see Attachment II).

NOTE 5

(a) The General Electric (GE) high voltage penetration utilizes an epoxy bushing typical of other manufacturers high/medium voltage modules. In the qualification test program by General Electric, the penetration was jacketed by heater cables and internally pressurized to 300°F and 100 psig respectively under relative humidity conditions of 790%. The penetration was then subjected to a fault current of 80000 amps. asymmetrical and 63000 amps. symmetrical for an 8 cycle duration. Following the test, the penetration remained leak tight to 1×10^{-6} cc (He)/sec. Further, the penetration was pre-aged to 5×10^{7} R (gamma) at a dose rate of 3.7×10^{6} R/hr prior to the test described above.

In the GE test configuration, the penetration was located within 10 feet of the transformer. Thus, the resistance of the circuit is small compared to the installed condition where the circuit breaker is well over that length. Thus the test is conservative in that it produced a greater force than would normally be expected.

(b) A flame applied for 20 minutes to one end of a module burned off all the cable insulation and about 0.5 in. of the penetration potting material without damage to the seal of a Westinghouse module.

(c) A test sample of potting material 8 in. long subjected to a temperature of 950° - 1070°C for 3 hours experienced a temperature rise at the outside end of only 9°C above the ambient at 25°C.

(d) As a part of the qualification effort for the Clinch River Breeder Reactor, a Conax penetration was exposed during a test to 1200°F on the inboard side. The temperature destroyed the inboard seal. In 1969, Conax penetrations were over-tested to fault currents of 62000 amps. for 3 seconds and did not exhibit leakage until after the penetration cooled down. The penetration survived 41000 amps. for 100 cycles without any leakage.

The secondary seal temperature in all cases under consideration. seems to be in a sufficiently mild environment to survive the added temperature of fault currents which could occur during a severe accident. Hence, it is our judgement that a fault current during the early stages of a severe accident would not cause a leak to develop.

Distribution:

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Mail Stop NL/S-217B
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USNRC/RES
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DeKalb, IL 60115

Institut fur Mechanik
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Attn: Prof. G. I. Schueller
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CANADA

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ITALY

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Via Vitaliano Brancati, 48
I-00144 Roma
ITALY

Nuclear Power Construction Dept.
Tokyo Electric Power Company
Attn: Hideaki Saito
No. 1-3, Uchisaiwa-cho, 1-Chome
Chiyoda-ku
Tokyo, 100
JAPAN

Nuclear Equipment Design Dept.
Hitachi Works, Hitachi, Ltd.
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3-1-1 Saiwai-Cho
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JAPAN

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Koto-Ku
Tokyo 135
JAPAN

Shimizu Construction Co., Ltd.
Attn: Toshiaki Fujimori
No. 18-1, Kyobashi 1-Chome
Chuo-ku
Tokyo 104
JAPAN

Nuclear Power Division
Shimizu Corp.
Attn: Yoichiro Takeuchi
Mita 43, Mori Bldg. 13F
No. 13-16, Mita 3-Chome
Minato-ku
Tokyo, 108
JAPAN

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28020 Madrid
SPAIN

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CH-5303 Wuerlingen
SWITZERLAND

Swiss Federal Nuclear Safety Inspectorate
Federal Office of Energy
Attn: S. Chakraborty
CH-5303 Wuerenlingen
SWITZERLAND

Swiss Federal Institute of Technology
Attn: Prof. F. H. Wittmann
Chemin de Bellerive 32
CH-1007 Lausanne
SWITZERLAND

Elektrowatt Ingenieurunternehmung AG
Attn: John P. Wolf
Bellerivestr. 36
CH-8022 Zurich
SWITZERLAND

Atomic Energy Establishment
Attn: Peter Barr
Winfrith
Dorchester Dorset
DT2 8DH
UNITED KINGDOM

Atomic Energy Authority
Safety and Reliability Directorate
Attn: D. W. Phillips
Wigshaw Lane, Culcheth
Warrington WA3 4NE
UNITED KINGDOM

HM Nuclear Installation Inspectorate
Attn: R. J. Stubbs
St. Peter's House, Stanley Precinct
Bootle L20 3LZ
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Taylor Woodrow Construction Limited
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(2 copies)
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Southall, Middlesex
UB1 2QX
UNITED KINGDOM

Central Electricity Generating Board
Attn: J. Irving
Barnett Way
Barnwood, Gloucester
GL4 7RS
UNITED KINGDOM

Central Electricity Generating Board
Attn: Carl Lomas
Booths Hall
Chelford Road
Knutsford, Cheshire
WA16 8QG
UNITED KINGDOM

HM Nuclear Installations Inspectorate BrC
Attn: Peter Watson
St. Peter's House
Bootle, Mereyside L20 3LZ
UNITED KINGDOM

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

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-5334
SAND89-0327

2. TITLE AND SUBTITLE

Severe Accident Testing of Electrical Penetration Assemblies

3. DATE REPORT PUBLISHED

MONTH	YEAR
November	1989

4. FIN OR GRANT NUMBER

FIN A1364

5. AUTHOR(S)

David B. Clauss

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

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

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

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

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Tests of three different full-size electrical penetration assemblies (EPAs) were conducted to evaluate their behavior under severe accident conditions that were simulated using steam at elevated temperature and pressure. Leakage, temperature, and cable insulation resistance were monitored throughout the tests. Nuclear qualified EPAs were procured from D. G. O'Brien, Westinghouse, and Conax. Severe accident sequence analysis was used to generate the severe accident conditions (SAC) for a large dry pressurized water reactor (PWR), a boiling water reactor (BWR) Mark I drywell, and a BWR Mark III wetwell. Based on a survey conducted by Sandia, the D. G. O'Brien EPA was chosen for the PWR SAC test, the Westinghouse for the Mark III test, and the Conax for the Mark I test. The EPAs were radiation and thermal aged to simulate the effects of a 40-year service life and loss-of-coolant accident (LOCA) before the SAC tests were conducted. The design, test preparations, conduct of the severe accident test, experimental results, posttest observations, and conclusions about the integrity and electrical performance of each EPA tested in this program are described in this report. The leak integrity of the EPAs tested in this program was not compromised by severe accident loads. There was significant degradation in the insulation resistance of the cables, which could affect the electrical performance of equipment and devices inside containment during the progression of a severe accident.

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

severe accidents
electrical penetrations
electrical equipment qualification
equipment survival

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)
Unclassified

(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)

☆U. S. GOVERNMENT PRINTING OFFICE:1989-262-436:00339

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

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