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An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables

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U.S. Nuclear Regulatory Commission

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ABSTRACT

This report documents the findings of an experimental investigation of the effects of thermal aging on the fire damageability of electric cables. Two popular types of nuclear qualified cables were evaluated. The two cables tested were (1) a neoprene jacketed, cross-linked polyethylene (XPE) insulated, three conductor, 12AWG, 600V light power or control cable produced by the Rockbestos Corporation and marketed under the trade name Firewall III, and (2) an ethylene-propylene rubber (EPR) insulated, chlorosulfonated polyethylene (CSPE or Hypalon) jacketed, two conductor, 16AWG, twisted shield pair, 600V instrumentation and signal cable produced by BIW Cable Systems, Incorporated, and marketed under the trade name Bostrad 7E. For each cable type, both unaged (i.e., new off the reel) and thermally aged samples were exposed to steady-state elevated temperature environments until conductor-to-conductor electrical shorting was observed. Plots of the time to electrical failure versus the exposure temperature were developed and thermal damage thresholds were determined.

Thermal aging had a different impact on the thermal damageability of each of the two cable types tested. For the Rockbestos cable, the thermally aged cables were less vulnerable to thermal damage than were the unaged samples. This conclusion is supported by (1) an increase in the thermal damage threshold for the aged samples, and (2) an increase in the time to thermal damage for the aged cables at exposure temperatures above the damage threshold. For the BIW cable, a mixed result was obtained. The threshold of thermal damage was lowered somewhat by the aging process, an indication of an increased vulnerability to thermal damage due to aging. However, for the higher temperature exposures, no statistical difference between the damage times for aged and unaged cable samples was noted. For both cable types, the changes in the thermal damage threshold observed were not considered large enough to result in a significant impact on fire risk estimates because the changes in damage threshold observed were not significant in comparison to other analysis uncertainties including uncertainty in the current models used to assess thermal damage times and uncertainties associated with other fire risk assessment input values.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The objective of the Fire Vulnerability of Aged Electrical Equipment Program is to identify and investigate fire safety issues for which plant aging might lead to an increased level of risk. This report describes the results of a series of tests performed to assess one fire aging issue, that is, the effects of thermal aging on the vulnerability of cables to fire induced thermal damage.

In the consideration of fire safety, cables represent the single most important class of electrical equipment in a nuclear power plant. This results from a number of factors. First, virtually every plant system includes power, control, and/or instrumentation cables. Second, cable "pinch" points (that is, locations where redundant train separation is reduced by the merging of cable routings) often represent dominant contributors to plant fire risk as determined by probabilistic risk assessment (PRA) analyses. Third, cables represent the dominant combustible fuel loading for most plant areas.

In the tests described here, the thermal damageability of two commonly used types of IEEE-383 nuclear qualified, low-flame-spread electric cables was examined. The two cable types tested were:

(1) A Neoprene jacketed, cross-linked polyethylene (XPE) insulated, three conductor, 12AWG, 600V light power or control cable produced by the Rockbestos Corporation and marketed under the trade name Firewall III, and

(2) An ethylene-propylene rubber (EPR) insulated, chlorosulfonated polyethylene (CSPE or Hypalon) jacketed, two conductor, 16AWG, plus shield and drain, 600V instrumentation or signal cable produced by BIW Cable Systems Incorporated and marketed under the trade name Bostrad 7E.

For each of the two cable types tested, both unaged (i.e. new from the cable reel) and thermally aged samples were tested. (No radiation aging was employed in these tests.)

The exposure conditions simulated during testing were considered typical of that expected during an enclosure fire when the subject cables are not involved in the fire itself. The test exposure consisted of immersion of the cable samples into a spatially uniform and optically thick environment such as that which would be expected in the non-flaming region of the fire plume, ceiling jet, or hot upper layer. The most significant difference between the test exposures and anticipated actual exposures was that the tests involved exposure at an elevated steady-state temperature while in actual exposures equipment would experience a transient time/temperature exposure.

The test chamber used in these tests is the Severe Combined Environment Test Chamber (SCETCH). This chamber was originally developed for use in equipment fire environment vulnerability assessments under the USNRC-

sponsored Fire Protection Research Program. SCETCH has also been used in the performance of realistic hydrogen burn environment simulations.

In these cable exposure tests, both the walls of and air within SCETCH were maintained at a uniform steady-state exposure temperature. Circulation of air through the chamber provided for a high level of air movement and mixing within the chamber. Two energized cable samples were exposed in each of the tests performed. The chamber was preheated to the desired exposure temperature, and the cable samples then quickly inserted through a small door in the cover of the chamber. This approach provided a near step change in environment temperature for the cable samples.

In each test, two cable samples were energized using a three-phase, 208 volt power source. In the case of the Rockbestos cable, each of the three conductors was connected to one phase of the power source. In the case of the BIW cable, each of the two conductors and the drain conductor were connected to one phase of the power source. Leakage currents between power phases were monitored continuously. The time to ultimate cable failure, as determined by the failure of a two ampere fuse in any one of the three phase circuits, was also recorded. Two measures of thermal damageability can be made based on these tests.

One measure of fire damageability is the thermal damage threshold. In the context of these tests, the thermal damage threshold is defined as a derived temperature range. The upper limit of this temperature range is defined by the lowest experimental exposure temperature at which electrical failure was observed following exposures of up to 80 minutes. The lower limit of the range was defined by the highest experimental exposure temperature for which no electrical failures were noted following exposures of no less than 80 minutes. These values were determined directly for each cable type in both the aged and unaged condition. (In three of the four cases the threshold temperature range was narrowed to within 5°C. In the case of the aged Rockbestos cable, a shortage of aged samples allowed for narrowing of the threshold range to 15°C only.)

For the Rockbestos cable, the failure threshold of the unaged cable was determined to be 325-330°C, whereas the thermal damage threshold for the aged samples was 350-365°C. For the BIW cable, the unaged cable thermal damage threshold is estimated at 365-370°C, while that of the aged samples was estimated at 345-350°C. Thus, the aging process resulted in the opposite effect on the thermal damage threshold for the two cable products. For the Rockbestos cable, the damage threshold <u>increased</u> by approximately 25-35°C due to aging, while for the BIW cable the threshold <u>decreased</u> by approximately 20°C due to aging.

A second measure of thermal damageability is the relative time to failure for exposure temperatures above the damage threshold. In the case of the Rockbestos cables, the aged samples consistently displayed longer times to failure at a given temperature than did the unaged samples, indicating less vulnerability to thermal damage for the aged samples. In the case of the BIW cable, the time to failure for the aged and unaged samples was not significantly different for exposure temperatures at which failure was observed in both aged and unaged samples. Thus, in the case of the BIW cable, aging had no effect on thermal vulnerability when the exposure temperature was above the threshold of unaged cable thermal damage. (As was described above, aging did reduce the BIW failure threshold.)

It was also noted that in virtually every case, the failure of the cables through conductor to conductor shorting resulted in the initiation of intense, sustained, open flaming in the cable samples. As the cables shorted, sparks ignited the gases being evolved from the cables. Thus, the failure temperatures noted above are clearly above the piloted ignition threshold of the cable samples. In no case was spontaneous ignition of the cables observed prior to electrical failure. These results also indicate that in the modeling of cable fire growth it would be appropriate to include the failure of energized cables as a mechanism for fire spread.

These tests have explored the effects of thermal aging on two of the most common nuclear qualified cables in use in the U. S. nuclear industry today. For these two cable types, thermal aging did affect the thermal damageability of the cables. In one case, aging increased the susceptibility to thermal damage, while in the other case, the susceptibility was reduced.

The thermal damage threshold changes observed in these tests are not considered of a sufficient magnitude to significantly alter risk estimates for scenarios involving cable thermal damage. The fact that the thermal damage thresholds were altered by the aging process implies the introduction of uncertainty in this fire risk assessment input factor. However, the magnitude of the changes observed will not significantly alter the risk perspective because fire risk assessments typically include large uncertainties associated with fire modeling and the estimation of equipment damage times, the inherent uncertainty in fire behavior, and the uncertainty associated with other risk assessment input values, particularly those associated with the use of engineering judgment. These other sources of uncertainty will continue to dominate overall fire risk estimate uncertainty.

It should also be noted that these tests have not explored the impact of other fire environmental effects, such as suppressant application and high humidity, on cable survival. The failure thresholds given above indicate the threshold of gross electrical failure. In most cases, significant levels of current leakage were noted prior to gross failure. Specific applications must be examined to determine whether such leakage could constitute the failure of a circuit to perform its design function. Also, because a mixed result was obtained for the two cable types tested, it can be assumed that for other cable types, the impact of thermal aging on thermal damageability would display similar mixed results. Thus, no direct conclusion regarding the impact of thermal aging on the fire vulnerability of any other cable type can be drawn based on the results of these tests.

1.0 INTRODUCTION

The tests described here were performed as a part of the USNRC-sponsored Fire Vulnerability of Aged Electrical Components Program. It is the objective of this program to identify and investigate fire safety issues that might lead to an increased plant risk as a result of plant aging. The tests described in this report investigated one of the identified fire aging issues, namely, the potential that cable thermal aging might result in an increased vulnerability to fire-induced thermal damage.

The issue of cable aging and fire vulnerability was chosen as the focus of initial investigation under this program for a number of reasons.[1] First, cables represent the single most prevalent class of electrical equipment in a nuclear power plant. Virtually every plant system includes power, control, and instrumentation cables. Second, in the analysis of fire risk, postulated cable damage scenarios often represent dominant contributors to fire-induced core damage frequency estimates, and often to overall plant core damage frequencies as well. In particular, cable "pinch" points, that is points where the cabling for multiple safety and support systems converge, are often identified as risk important. Finally, cables represent the dominant combustible fuel loading for most plant areas.

In the evaluation of fire risk, estimation of the thermal damageability of electrical cables can play a critical role. Should the aging of cables be determined to significantly change the vulnerability of cables to fire-induced damage, then a significant change in fire risk estimates for scenarios involving cable failure would result. It is this question which the tests described here address. In these tests, the effects of aging on the vulnerability of cables to thermal heating was investigated. Two types of qualified nuclear grade cables were tested in these tests. These two cable types represent two of the most commonly used nuclear grade cables currently installed in U.S. commercial reactors [1]. The two cable types tested were:

(1) A Neoprene jacketed, cross-linked polyethylene (XPE) insulated, three conductor, 12AWG, 600V light power or control cable produced by the Rockbestos Corporation and marketed under the trade name Firewall III, and

(2) An ethylene-propylene rubber (EPR) insulated, chlorosulfonated polyethylene (CSPE or Hypalon) jacketed, two conductor, 16AWG, plus shield and drain, 600V instrumentation or signal cable produced by BIW Cable Systems Incorporated and marketed under the trade name Bostrad 7E.

As will be shown below, mixed results were obtained for the two cable types tested. In one case aging reduced the vulnerability of the cables to thermal damage while in the second case aging resulted in an increased thermal damageability. However, in neither case were the differences considered large enough to result in a significant change in fire risk estimates. It should also be noted that these tests have not addressed other damaging aspects of the fire environment such as suppressant application and high humidity.

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1. The identification and prioritization of issues is discussed further in a draft NUREG/CR report currently under review (NUREG/CR-5464).

2.0 OVERVIEW OF TEST APPARATUS AND PROCEDURES

2.1 Accelerated Thermal Aging

The accelerated thermal aging protocol was based on use of the Arrhenius theory of accelerated aging. For each of the two cable batches, a thermal oven was used to provide a constant elevated temperature environment for a period of approximately one month. The two cable types were aged separately. No deviations from the anticipated aging protocol were experienced for either of the two cable types utilized. For the Rockbestos cables, an aging temperature of 150°C was utilized. For the BIW cables, an aging temperature of 125°C was utilized. In the case of thermal damageability, it was decided that the cable insulation, rather than the jacket, would play the critical role. Therefore, the aging conditions were aimed primarily at aging of the insulation to a conservative end of life condition, and aging of the jackets was not a primary consideration. Using the Arrhenius theory, these artificial aging conditions correspond to normal life exposure conditions as described in Table 2.1.

Table 2.1: Equivalent Normal Life Exposure Conditions Corresponding to the Accelerated Aging Conditions Imposed Upon the Aged Cable Test Specimens

Cable/Material:	Accel. Aging Conditions:	Equivalent 40 Year Life:
Rockbestos FIREWALL III:		
Neoprene Jacket[1]	28 days @ 150°C	59°C
XPE Insulator[2]	28 days @ 150°C	82°C
BIW BOSTRAD 7E:		
Hypalon Jacket[3]	28 days @ 125°C	52°C
EPR Insulator[4]	28 days @ 125°C	60°C

1. Assumes an activation energy of 0.83 Electron Volts
2. Assumes an activation energy of 1.2 Electron Volts
3. Assumes an activation energy of 0.95 Electron Volts
4. Assumes an activation energy of 1.1 Electron Volts

Note that the Rockbestos cable product was aged to somewhat more severe conditions than was the BIW cable product. The reason for this difference is that the Rockbestos cable is utilized as a light power or control cable whereas the BIW cable is primarily an instrumentation or signal cable. Therefor, because the light power cable would be subject to higher levels of self-heating, it was considered appropriate to utilize a more severe aging end condition for the Rockbestos cable.

For the purpose of aging, cable sections were cut from the cable reel to the desired length of 36 inches. The protective jacketing at each end of these cable segments was trimmed back in anticipation of electrical termination of the cables prior to the thermal damageability testing. The cable specimens were then placed horizontally on metal mesh shelves in the aging oven following pre-heating of the oven itself. The environment at various points inside the aging oven was monitored continuously.

2.2 Thermal Exposure Testing

For the performance of thermal exposure tests, the Severe Combined Environment Test Chamber (SCETCH) was used. This chamber was originally developed as a part of the USNRC-sponsored Fire Protection Research Program (reference USNRC FIN A1010) for use in the evaluation of the vulnerability of equipment to fire induced damage. SCETCH has also been used for the performance of single and multiple pulse hydrogen burn survival tests for electrical equipment [2].

SCETCH is comprised of a pressure vessel, designed to ASTM standards, surrounded by quartz heating lamps. The power to these quartz lamps is automatically controlled through a data logger and minicomputer monitoring system. The chamber itself is a cylinder measuring approximately 18 inches in diameter by 24 inches long. A small window was installed in the front face of the test chamber so that direct observation of the cables during exposure was possible. In a transient mode the chamber temperature can be ramped at a rate of up to 600°F/min. For the purposes of hydrogen burn simulations, an additional heat flux simulation module capable of transients up to 2000°F/sec is also available. This additional heat flux module was not utilized in the tests described here.

For the purposes of these tests, lamp power was controlled to provide a constant inner chamber wall temperature consistent with the desired thermal exposure temperature. In addition, air was circulated through the chamber in a flow-through system. The incoming air was heated by circulation heaters. The power to these circulation heaters was also automatically controlled to maintain a specified general chamber air temperature. Because both the wall temperature and air temperature were maintained at the same value, the environment simulated was that of a spatially uniform and optically thick hot gas layer exposure. Because of the rate and configuration of the air circulation within the chamber, a highly convective environment resulted (i.e., the air inside the chamber was very well mixed on a continuous basis). Figure 2.1 provides a general view of the SCETCH facility as configured for these tests.

In the actual performance of testing, the cable samples were laid out, two per test, on a cable support system outside the chamber. In each test, both of the cable samples would be essentially the same (i.e., both the same cable type, and either both aged or both unaged). The chamber system was preheated to the desired temperature (both walls and air at the same temperature) and the controller set to maintain that temperature. The cable support mechanism was constructed such that very fast insertion (on the order of 1-2 seconds) of the cable samples into the exposure environment was possible. This quick insertion after oven preheating resulted in a near step change in the cable thermal environment from ambient to immersion in a uniform radiative and convective environment at the desired temperature.

Once inserted, one end of each cable sample projected out of the chamber for connection to the power source. The other end of the cable was located inside the chamber. Special precautions were taken to insure that the end of the cable inside the chamber was protected from direct exposure in order to insure that cable end effects observed in other tests [3] would not affect the test results. Figure 2.2 provides a view of the cable insertion mechanism and general configuration of the cables prior to insertion.

Each of the two cable samples was energized during testing. A three-phase 208VAC power source was used. No base current load was imposed on the cables. When testing the Rockbestos cable, each of the three conductors was connected to one phase of the power source. When testing the BIW cable, each of the two conductors, and the shield/drain conductor were connected to one phase of the power source. For each conductor of each cable, current limiting resistors were provided to limit fault currents. Figure 2.3 provides a schematic representation of the cable energizing circuit. Ultimate cable failure was determined by the failure of 2 ampere fuses in a series/parallel circuit with the current limiting resistors. Leakage currents were monitored continuously by monitoring the voltage drop across each of the current limiting resistors.

The detection level of the leakage current measurement system is estimated at approximately 3 mA. This estimate is based on the observation of poor AC voltage measurement accuracy at equivalent leakage current levels of less than 3 mA. In the design of the AC voltage measurement system, a compromise was required between the speed of the measurements and the accuracy of the measurements at very low values. Thus, a certain minimum detection level corresponding to this low voltage inaccuracy was accepted as the price of higher measurement speed.

In each test, the time to initial electrical failure, as indicated by the failure of any one of the three 2 ampere fuses for each cable sample, was noted. Also noted was the time to ignition of the cable samples based on visual observations. In order to determine the thermal failure threshold, all tests were continued until either electrical failure was observed or no less than 80 minutes of elapsed exposure time. (In some cases, exposure times exceeded 90 minutes with no observed failures.) Thus, the reported failure thresholds are generally for exposures of up to 80 minutes.

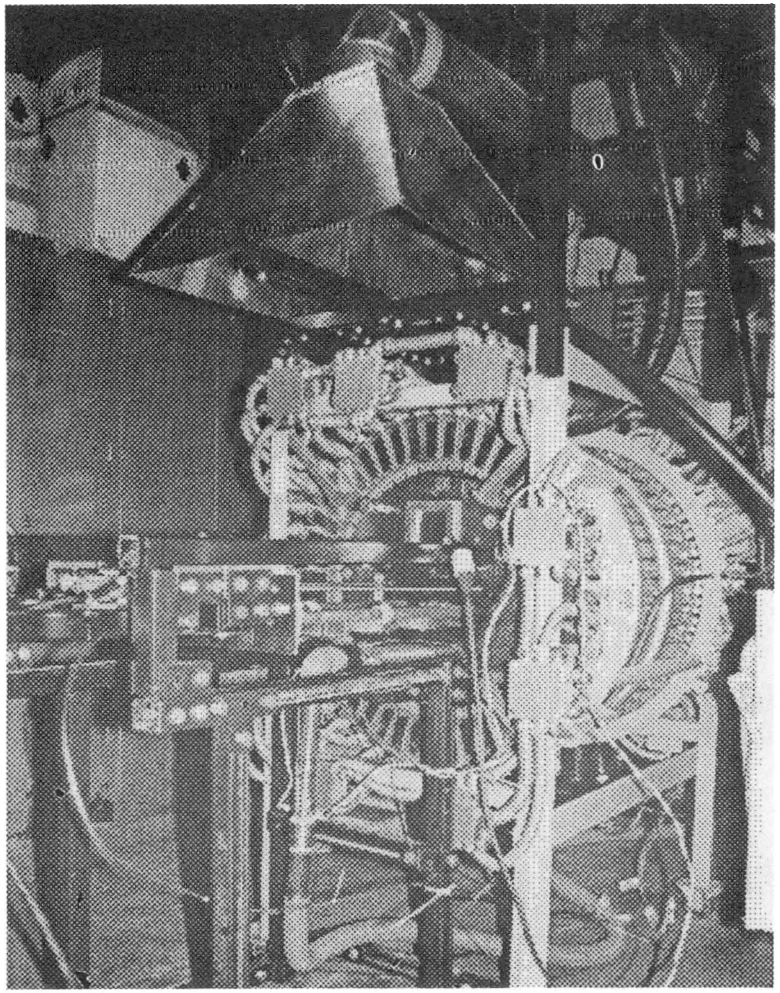


Figure 2.1: General View of the SCETCH Facility as Configured for Use in These Tests.

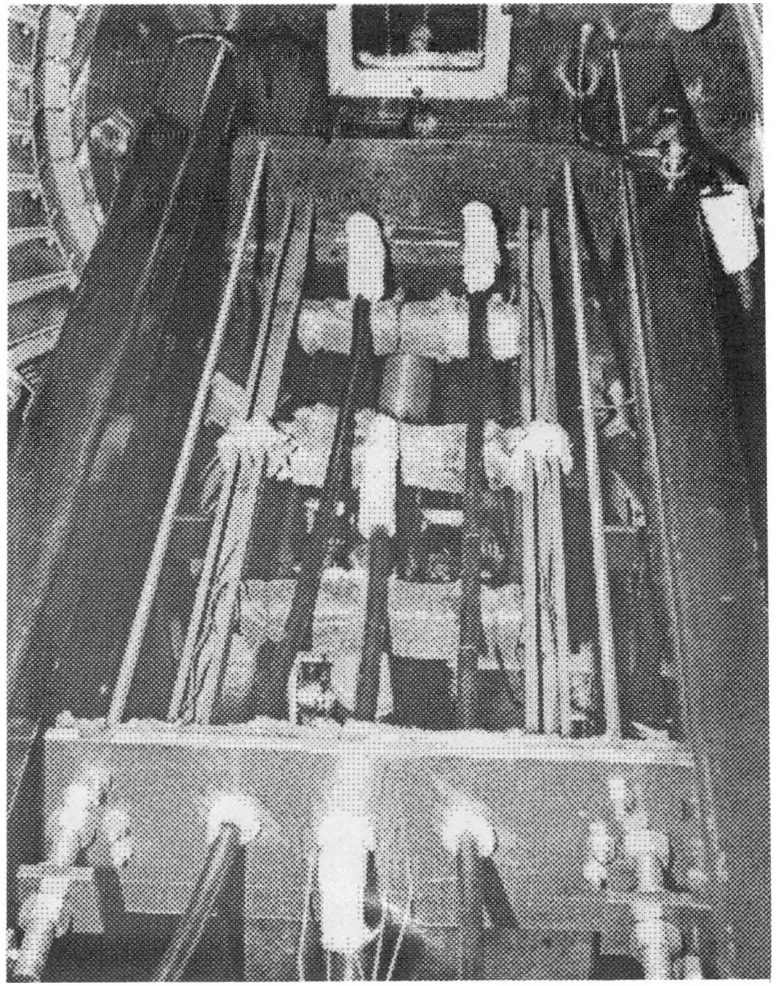


Figure 2.2: View of the Cable Support and Insertion Mechanism Prior to Insertion of the Cable Samples.

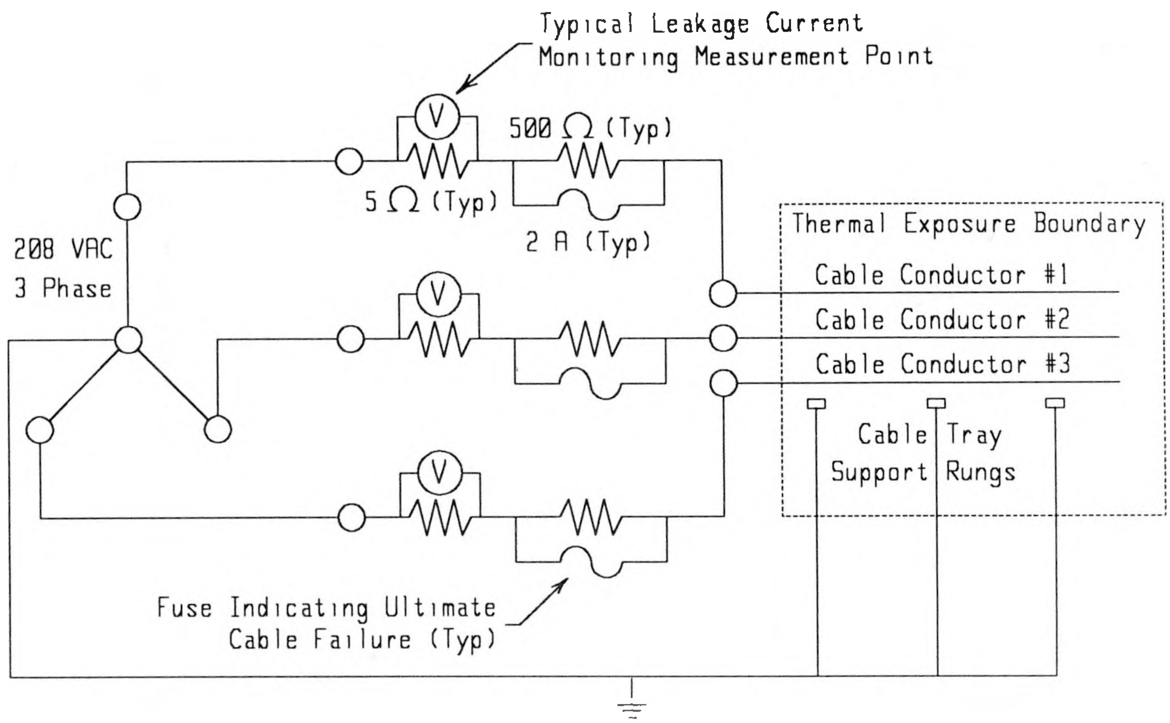


Figure 2.3: Schematic Representation of the Cable Energizing and Integrity Monitoring Circuitry.

3.0 EXPERIMENTAL RESULTS FOR ROCKBESTOS FIREWALL III

3.1 Description of the Cable Product

The Rockbestos cable tested was a 3-conductor, 12 AWG, light power or control cable. (Other sizes and configurations of this cable are also available for higher power or instrumentation applications.) The insulation was cross-linked polyethylene (XPE), and the jacket was neoprene. (Rockbestos also markets this product with a chlorosulfonated polyethylene (CSPE) jacket.) This cable is an IEEE-383 qualified nuclear grade cable, and is marketed under the trade name Firewall III. This cable was selected for use in these tests because it represents one of the most commonly utilized cables in the commercial U.S. nuclear power industry [1].

The Rockbestos cable product is a multi-conductor cable which is made up of a number of individual constituents. The constituents of the composite cable can be itemized as follows:

Constituent:	Material:	Weight per Length of Cable (g/m)
Conductors	Copper	87.9
Insulator	XPE	36.1
Jacketing	Neoprene	71.3
Interstitial Material	(Assumed Nylon, Paper, and Cellophane)	8.4
Total Cable Weight (grams/meter):		203.7

The final item, interstitial material, is made up of three separate materials. The first, assumed to be a nylon-like material, is a thin, rolled, expandable (i.e., extensively slitted) material which fills the gaps between the individual insulated conductors below the jacketing. The second is a paper material which is assumed to be a wrapping used to bind the other materials together while the jacketing is applied. The third is a cellophane-like material in a small, thin, clear strip which identifies the manufacturer.

3.2 Physical Effects of Accelerated Thermal Aging

Artificial aging of the Rockbestos Firewall III cables was performed at a temperature of 150°C. The cable samples were aged at this temperature for a total of 28 days. Assuming an activation energy of 1.2 eV, and assuming Arrhenius behavior, the artificial aging would correspond to an equivalent life of 40 years at 82°C.

Following the removal of the cable samples from the aging chamber it was noted that the neoprene jacket had developed extensive cracks and had become quite brittle. In several cases handling of the aged cable samples resulted in small sections of the jacket falling away from the cables. Visual inspection of the cable insulation revealed no such cracking. Continuity and insulation resistance testing of the aged samples prior to thermal exposure testing revealed no faults.

The cracking of the jacket observed following aging raised a concern that the increased exposure of the inner insulation might result in more efficient heat transfer directly to the insulation, and hence, might reduce failure times. As will be discussed below, this turned out not to be the case.

3.3 Measured Cable Response to Thermal Environment

In certain tests on unaged cable samples, short sections of non-energized "dummy" cable were included in the exposure. These dummy samples were instrumented with two thermocouples; one located just below the jacket, and one in the center of the cable between the three individual insulated conductors. (Thermocouples could not be inserted into the aged samples because the aging process sealed the small openings that were used to feed thermocouples into the cable.) None of the energized cable samples were instrumented in this way.

Figure 3.1 illustrates the typical response of the dummy cable samples to thermal exposure. This figure also provides an illustration of the consistency of the exposure environment and the impact of cable insertion on that exposure. Note that as the cables were inserted, at time=0 seconds on this figure, a drop in the exposure environment temperature is experienced. This drop is caused by the insertion of cold thermal mass and a limited amount of ambient air into the test chamber. The automatic temperature control system would quickly compensate for this effect and typically within approximately 2 minutes the exposure environment had fully recovered.

In many cases the thermocouple readings from these dummy samples indicated that combustion of some parts of the cable was taking place prior to failure. This is indicated by the fact that the measured internal cable temperatures often exceeded the exposure chamber temperature. In Figure 3.1, this behavior is noted at approximately 650 seconds. An exothermic reaction, such as smoldering combustion, is the only reasonable explanation for this behavior. It is assumed that this reaction involved the interstitial materials used in the production of the cables. It is also likely that smoldering of the jacketing material occurred since cable samples removed after as much as 90 minutes of exposure at temperatures just below the electrical damage threshold were found to have severely charred jacketing. In these cases, the insulator was intact, rather soft, and showed no signs of charring.

3.4 Thermal Damageability Observations

For the Rockbestos cable samples, the leakage current behavior observed in each test sample followed a definite pattern. This pattern was essentially the same for both the unaged and the aged samples. Figure 3.2 is typical of the leakage current data. Upon insertion into the test chamber (time=0 in this plot) the cables experience an initial short-term rise in conductor-to-conductor current leakage which falls off to near zero leakage after approximately 120-200 seconds. This behavior is attributed to thermal shock effects. The magnitude of the leakage current during this period typically peaked at 5-10 mA. Beginning after approximately 300-600 seconds of exposure, the cables would experience a second increase in leakage current. Within an additional 300 seconds, the leakage current would typically reach a level of approximately 15 mA. This leakage rate would then remain essentially constant until the time of ultimate failure when a precipitous increase in leakage would be experienced.

Users of the failure/time data presented here should be careful to note this behavior. The criteria used as the basis for the failure times (presented in Tables 3.1-3.3) was a leakage current in excess of 2 amperes, as demonstrated by failure of a 2 ampere fuse. The test data indicate that short sections of the cable can experience a long term leakage rate on the order of 15 mA under elevated temperature conditions before experiencing a precipitous short circuit. In some circuits, this level of leakage may be unacceptable, and hence, may represent circuit failure. One must also consider that exposure of longer sections of cable to these elevated temperatures would increase the overall current leakage. Each individual case must be examined for leakage current sensitivity and the data applied accordingly.

3.5 Thermal Damage Test Results

One measure of thermal damageability is the threshold at which gross electrical failure can be expected. Tables 3.1 and 3.2 provide the time to electrical failure (based on failure of the two ampere current limiting fuse) as a function of exposure temperature for each individual test of the unaged and aged Rockbestos cable samples, respectively. Table 3.3 provides the average failure time for each of the exposure temperatures for both the aged and unaged samples. Figure 3.3 provides a graphic presentation of the data presented in these tables. Each of the individual data points is shown, as well as simple linear splines connecting the applicable average failure times as given in Table 3.3. The actual leakage current data for each of the individual test samples is presented in Appendix A.

For the unaged Rockbestos cable samples, the threshold of thermal damage is estimated at approximately 325-330°C. For the aged samples the threshold for thermal damage is estimated at 350-365°C. (Note that a shortage of available cable samples prevented us from further narrowing the failure threshold range for the aged samples.) In each case, these failure ranges may be interpreted as follows:

- Cable failures were observed during exposure tests at the temperature corresponding to the upper limit of the stated range (i.e., 330°C and 365°C for the unaged and aged cables, respectively).

- At a temperature corresponding to the lower limit of each range, no failures were observed following cable exposures of no less that 80 minutes in duration (i.e., 325°C and 350°C for the aged and unaged cables, respectively).

These results indicate that for this cable type, extensive thermal aging did not adversely impact the thermal damage threshold, and in fact, raised the thermal damage limit.

A second measure of damageability is the relative time to gross electrical failure at exposure temperatures above the threshold value. As seen in Figure 3.3, at each of the temperatures at or above 365°C, the lowest experimental temperature at which damage was observed in the aged samples, the average time to failure, and in fact, the times to failure for each of the individual samples, are greater for the aged cables than for the unaged cables. This result again indicates that the aged cables are less vulnerable to fire-induced thermal damage.

In observing the data one should also note the behavior of the time to damage data, particularly at or near the estimated threshold temperature. For temperatures on the order of 10°C or more above the threshold, the failure times are very consistent and well grouped. However, at or near the damage threshold, the variation in failure times becomes quite large. This can be attributed to two factors. First, slight variations in the cable samples themselves are to be expected. Given the observed behavior, even a small change in the actual damage threshold for a given sample would result in a large change in the damage time when the exposure is very near that threshold. Second, very slight variations in the exposure environment could also result in significant changes in the time to damage.

3.6 Summary of Rockbestos Thermal Damage Results

For each of the two measures of thermal damageability discussed, failure threshold and failure time at temperature, the aged cables performed better (i.e., displayed a lower damage vulnerability) than did the unaged cables. However, the differences noted are not considered large enough to result in a significant change in the estimation of fire risk for scenarios involving fire-induced cable failure. The failure threshold was raised by only 25-35°C, and "life expectancy" was generally extended by only a few minutes. What is important, is that the aging process clearly did not result in an increased fire vulnerability, the potential concern being investigated here.

It was interesting to note that a possible concern raised upon observation of the aged cable samples turned out to be unfounded. Following thermal aging, the cable jacketing was observed to be extensively cracked, and in some cases, small sections of the jacket had fallen away. This was thought to represent a potential for increased exposure of the inner insulation to heating, and thus, a potential mechanism by which aged cables might be more vulnerable to thermal damage than the unaged cables. However, in thermal exposure testing it was found that with the unaged cable samples, the jacket would split open almost immediately upon insertion, directly exposing the inner insulated conductors. Thus, the cracking of the jacket through thermal aging appeared to have no effect on the damageability of the cables.

It was also noted that during thermal exposure testing, in every case in which failure of the energized cables was observed, the sparks which resulted caused the ignition of intense, sustained, open flaming in the cable sample. This observation indicates three things:

(1) the temperature threshold for piloted ignition of the cable samples is lower than the damage thresholds identified here,

(2) in the modeling of cable fire growth, the failure of energized cables should be considered as a mechanism for fire spread as well, and

(3) in no case was spontaneous ignition of open flaming in the cables prior to electrical failure observed indicating that the spontaneous ignition (or non-piloted ignition, or auto-ignition) temperature is above the lower limit of thermal damage for this cable.

The data presented provides an indication of the thermal damageability of this cable product in a fire environment. Caution should be exercised in the extrapolation of this data to other cable types and other cable products utilizing similar materials.

Table 3.1: Thermal Damageability Data for Unaged Rockbestos Firewall III Cable Samples.

Test No.	Cable No.	Exposure Temp. (°C)	Failure Time* (min:sec)
9	1	325	NF
9	2	325	NF
21	1	330	34:01
21	2	330	33:31
45	1	330	73:56
45	2	330	78:32
10	1	335	17:00
10	2	335	19:00
20	1	335	16:30
20	2	335	29:35
4	1	350	11:40
4	2	350	12:28
19	1	350	12:15
19	2	350	12:15
6	1	375	7:14
6	2	375	6:50
18	1	375	7:48
18	2	375	7:48
12	1	400	5:50
12	2	400	5:55
17	1	400	5:58
17	2	400	6:18

* NF indicates no failure observed following an exposure of no less than 80 minutes.

Table 3.2: Thermal Damageability Data for Aged** Rockbestos Firewall III Cable Samples.

Test No.	Cable No.	Exposure Temp. (°C)	Failure Time* (min:sec)
7	1	350	NF
7	2	350	NF
8	1	365	87:20
8	2	365	67:30
26	1	365	39:30
26	2	365	58:55
43	1	365	19:29
43	2	365	18:57
25	1	370	50:00
25	2	370	57:30
42	1	370	16:48
42	2	370	18:03
5	1	375	22:35
5	1	375	19:15
24	1	375	17:07
24	2	375	17:40
11	1	400	10:35
11	2	400	11:05
13	1	400	10:10
13	2	400	10:30
23	1	400	9:30
23	2	400	9:24
22	1	425	7:15
22	2	425	7:25

* NF indicates no failure observed following an exposure of no less than 80 minutes.

** Cables aged to equivalent of 40 years at 82°C for the insulator.

Table 3.3: Average Failure Time Data for Rockbestos Firewall III Cable Samples.

Exposure Temp. (°C)	Average Failure Time* (min)
Unaged Samples:	
325	NF
330	55.00
335	20.25
350	12.16
375	7.42
400	6.00
Aged Samples:	
350	NF
365	48.61
370	35.59
375	19.15
400	10.21
425	7.33

* NF indicates no failure observed following an exposure of no less than 80 minutes.

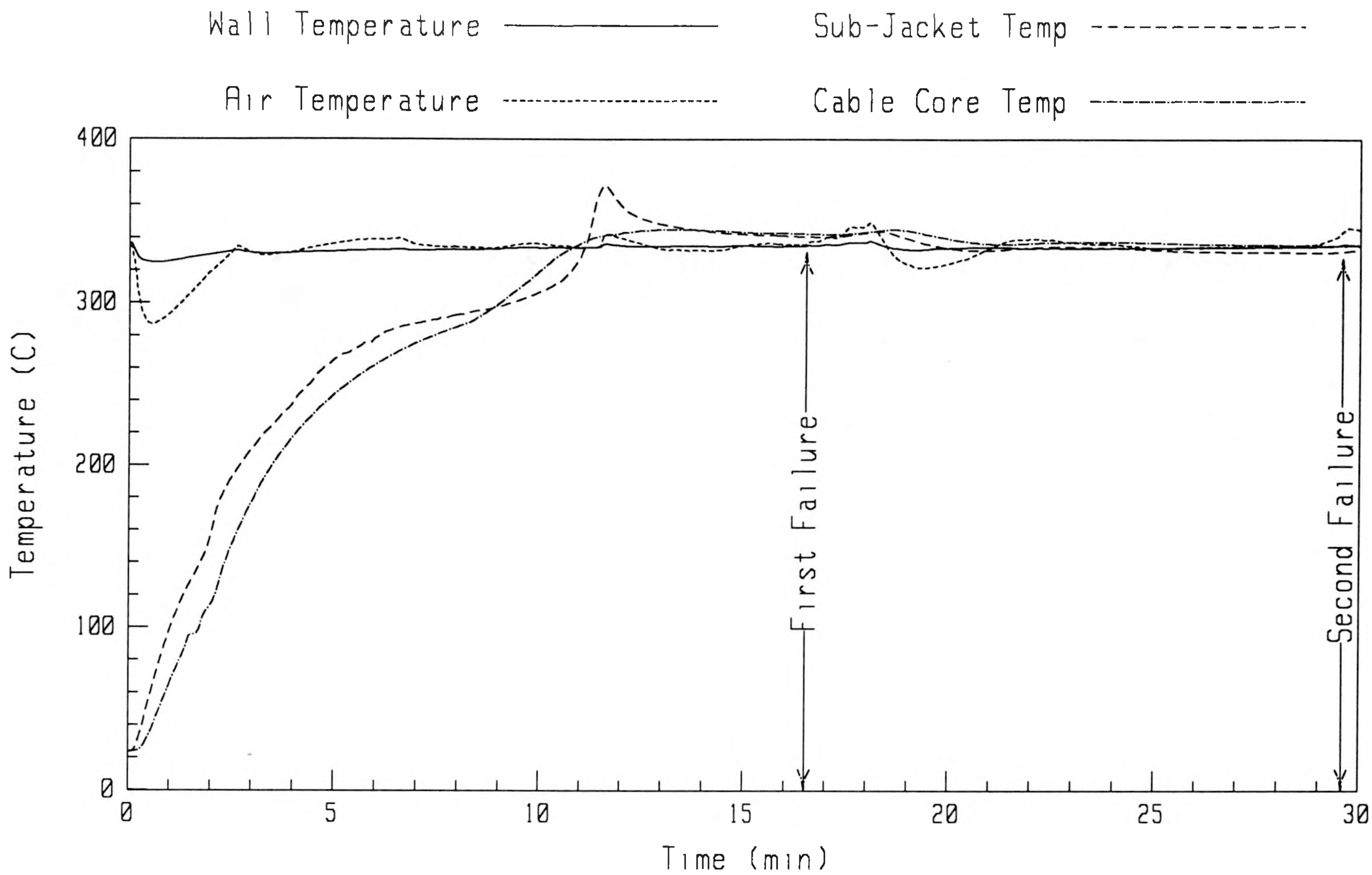
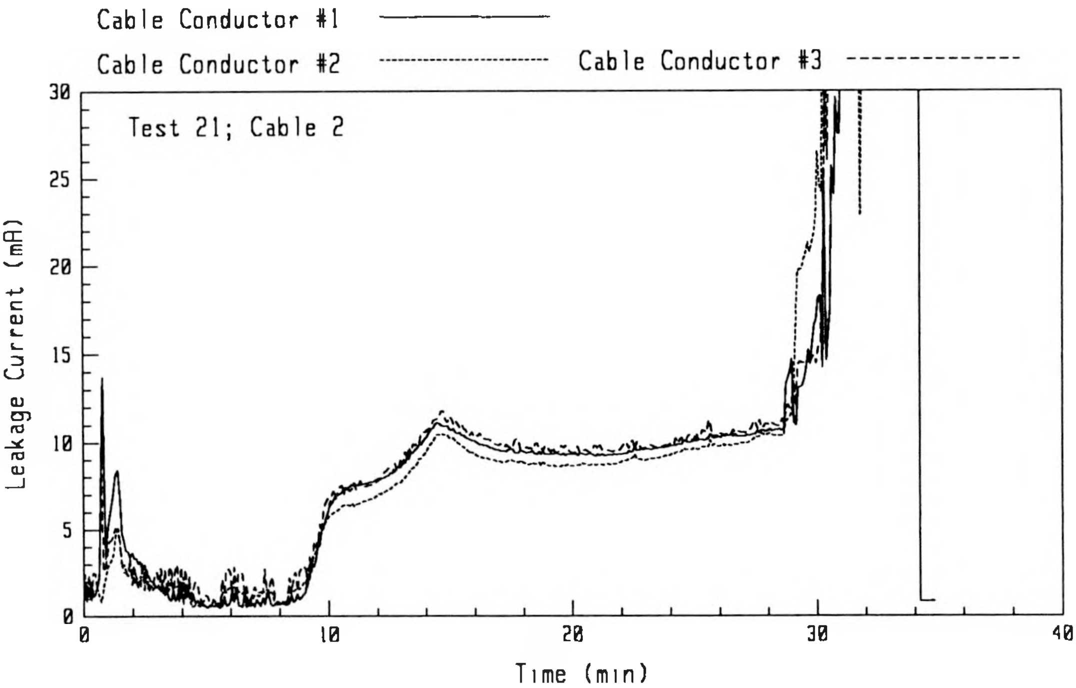
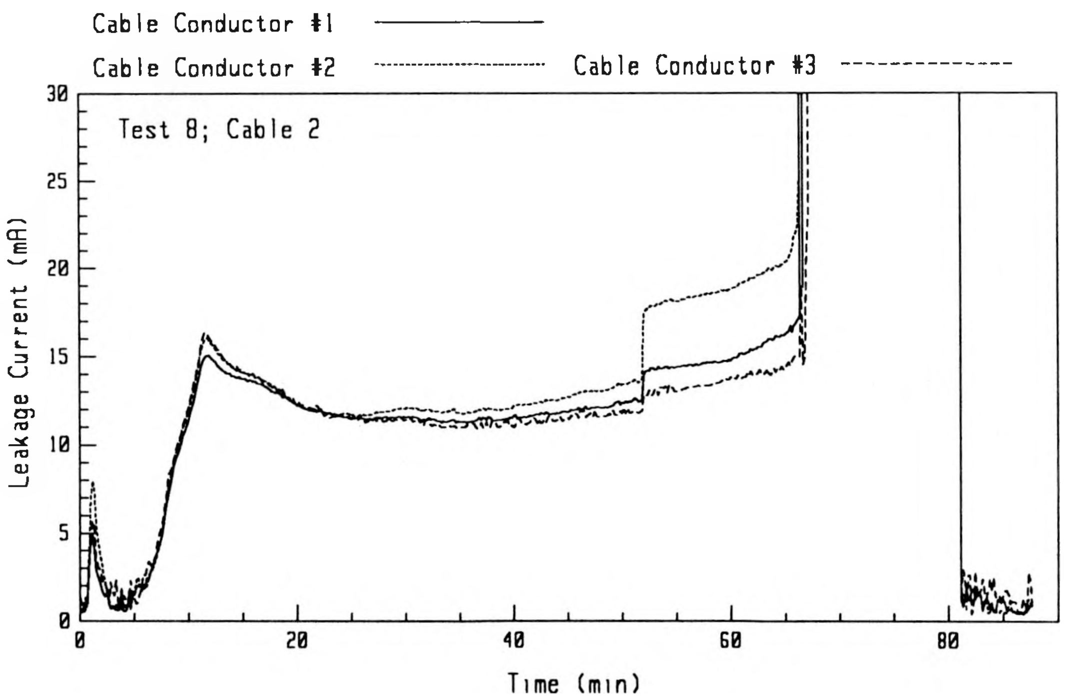


Figure 3.1: Typical Cable Internal Temperature Response for an Unaged Sample of the Rockbestos Cable. This Plot was Taken from Test 20, and Also Illustrates the Consistency of the Exposure Environment. Note that Cable Insertion Occurred at (Time = 0) in this Plot.



(a) Unaged Rockbestos Cable



(b) Aged Rockbestos Cable

Figure 3.2: Typical Leakage Current Data for (a) an Unaged and (b) an Aged Rockbestos Cable Sample. Note that Cable Insertion Occurred at (Time = 0) in these Plots.

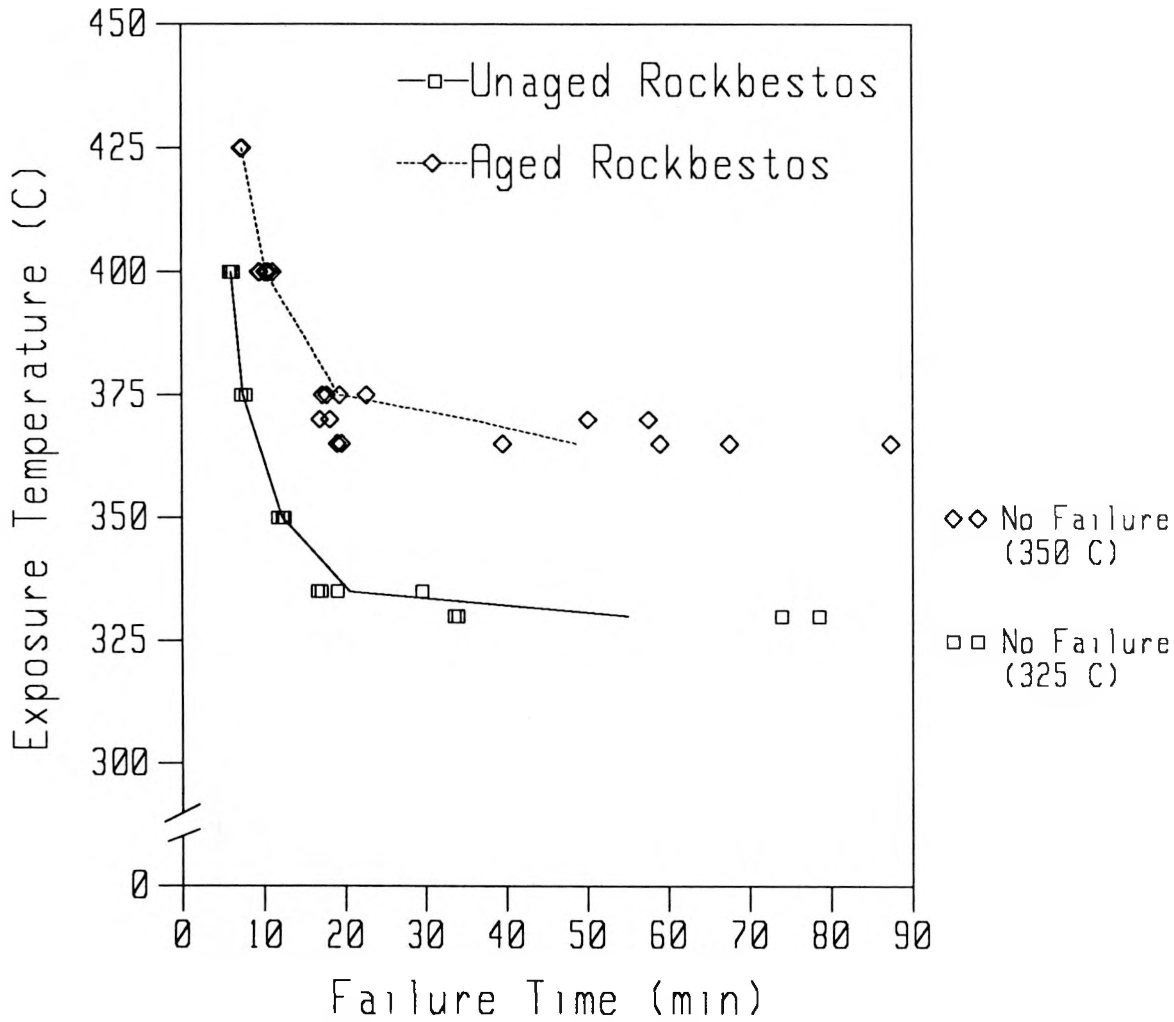


Figure 3.3: Cable Thermal Damage Data for Both the Aged and Unaged Samples of the Rockbestos Firewall III Neoprene/XPE Cables.

4.0 EXPERIMENTAL RESULTS FOR BIW BOSTRAD 7E

4.1 Description of the Cable Product

The second cable tested in this effort was a Boston Insulated Wire (BIW), 2-conductor, 16 AWG cable with shield and drain. This cable is marketed by BIW under the trade name BOSTRAD 7E. The cable has a chlorosulfonated polyethylene (CSPE or Hypalon) jacket, and an ethylene-propylene rubber (EPR) insulator. The individual constituents of the cable can be itemized as follows:

Constituent:	Material:	Weight per Length of Cable (g/m)
Conductors	Copper	31.8
Insulator	EPR	30.8
Jacket	Hypalon	76.3
Interstitial Material	(Foil, and Cellophane Plastic)	4.3
Total Cable Weight (grams/meter):		143.2

The materials identified above as interstitial materials included two different materials. First, a metal foil material was wrapped around the individual conductors to act as the cable shield. The second material was a thin clear plastic wrapping material, suspected to be cellophane, used to identify the manufacturer and, presumably, to bind the constituents while the jacket was applied. It should also be noted that the weight of the conductors given above included the weight of the drain wire and the two insulated conductors.

4.2 Physical Effects of Accelerated Thermal Aging

Artificial aging of the BIW Bostrad 7E cables was performed at a temperature of 125°C. The cable samples were aged at this temperature for a total of 28 days. For the EPR insulating material, assuming an activation energy of 1.1 eV, and assuming Arrhenius behavior, the accelerated aging protocol would correspond to an equivalent life of 40 years at 60°C.

Following the removal of the cable samples from the aging chamber it was noted that the Hypalon jacket had changed in color from the original bright orange, to a dull tan color. However, the Hypalon jacket retained some flexibility and no cracking was observed. Visual inspection of the cable insulation also revealed no cracking. Continuity and insulation resistance testing of the aged samples prior to thermal exposure testing revealed no faults.

4.3 Measured Cable Response to Thermal Environment

In certain tests of the unaged cable samples, non-energized "dummy" samples were included in the exposure. These dummys were instrumented with a single thermocouple located just below the jacket and below the foil shield wrapping material. Figure 4.1 illustrates the typical response of the dummy cable samples to thermal exposure.

As noted above, it was observed that during exposure testing of the unaged BIW cable samples, the jacketing material would swell significantly. Thus the exact placement of the thermocouples during exposure is uncertain. Because the thermocouples were located below the foil shield wrap and because this foil material would typically be found in essentially its original condition and location following testing, it is assumed that the thermocouple remained in close contact with the individual conductors during testing.

The thermocouple readings from these dummy samples did not indicate that any combustion was taking place prior to electrical failure and the resulting ignition. This may be due to the swelling which displaced the jacket material from contact with the thermocouple. It was found that the jacketing of cables removed from the oven with no observed failure or flaming were heavily charred. Thus it is suspected that smoldering combustion of the jacket did, in fact, occur, even though not indicated directly by the temperature readings.

Note that this figure also provides an indication of the consistency of the exposure environment. After insertion of the cable samples, a drop in chamber temperature would be experienced (on the order of 50°C). Within approximately 2 minutes, this drop in temperature would have been compensated for, and the desired exposure temperature reestablished.

4.4 Thermal Damageability Observation

Figure 4.2 illustrates the typical leakage current response data for both an aged and unaged BIW cable sample. For full presentation of the cable leakage current data for each sample in each test, refer to Appendix A. Note that the aged and unaged cables performed quite differently. Leakage currents for the unaged cable samples would typically remain below the threshold of instrumentation detection (estimated at 3 mA as discussed in Chapter 2 above) until shortly before ultimate failure when a precipitous rise in current leakage was experienced. For the aged cable samples, the leakage currents would rise to a level of approximately 10 mA within 2-3 minutes of insertion. Leakage currents would remain relatively constant until within 2-4 minutes of ultimate failure when the leakage current would again begin rising. Leakage currents were observed to reach a level of 15-25 mA before a precipitous jump and ultimate failure was observed. In some circuits, this level of leakage current could represent the failure of the circuit to perform its function [4]. (The reported damage times described below are all based on the failure of a 2 ampere fuse in any one current leg.) Each application should be examined for sensitivity to leakage currents.

One other significant visual difference in the behavior of the aged and unaged cable samples was noted during exposure testing. For the unaged samples, the jacketing material was observed to swell significantly upon heating. This swelling gave the cable the appearance of a string of blackened popcorn. For the aged cable samples, no such swelling was observed. Upon heating, the aged samples would discolor further and split open at various locations along the cable. This difference in jacket behavior may be a result of the higher flexibility of the unaged material. As the cables are heated, off-gassing takes place in the materials below the jacket. In the case of the unaged cables, the jacket is assumed to stretch and allow for expansion of these gases. In the case of the aged cables, it is assumed that two factors reduce the likelihood that such swelling would be observed. First, during the aging process, certain of these early release products would already have been removed. Second, for the aged cable the jacket retains insufficient flexibility to support such expansion, and hence, the jacket splits open in order to relieve the buildup in pressure.

It was also noted that in every case in which failure of the energized cables was observed, the sparks which resulted caused the ignition of intense, sustained, open flaming in the cable sample. This observation indicates that in the modeling of cable fire growth, the failure of energized cables through heating should be considered a mechanism for fire spread as well. It also indicates that the temperature threshold for piloted ignition of the cable materials is lower than the observed threshold of thermal damage. In no case was spontaneous ignition of the cables prior to failure observed.

4.5 Thermal Damage Test Results

Tables 4.1 and 4.2 provide the time to electrical failure (based on failure of the two ampere current limiting fuse) and exposure temperature for each individual test of the unaged and aged BIW cable samples respectively. Table 4.3 provides the average failure time for each of the exposure temperatures for both the aged and unaged samples. Figure 4.3 provides graphic presentation of the data presented in these tables. Each of the individual data points is shown, as well as simple linear splines connecting the applicable average failure times as given in Table 4.3.

For the unaged cable samples the threshold of thermal damage was determined to be 365-370°C. For the aged samples the threshold for thermal damage was determined to be 345-350°C. In each case these threshold values may be interpreted as follows:

- Cable failures were observed during exposure tests at the temperature corresponding to the upper limit of the stated range (i.e., 370°C and 350°C for the unaged and aged cables, respectively).

- At a temperature corresponding to the lower limit of each range, no failures were observed following cable exposures of no less that 80 minutes in duration (i.e., 365°C and 345°C for the aged and unaged cables, respectively).

These results indicate that thermal aging resulted in a reduction in the thermal damage threshold of approximately 20°C. This change is relatively modest, and will not result in a significant change in estimates of fire risk.

In observing the data, one should also note the relative time to damage for the aged and unaged cables. For exposure temperatures at which both the aged and unaged cable samples were observed to fail, that is exposures greater than or equal to 370°C, the times to electrical failure are essentially the same for the aged and unaged samples. This behavior is quite different than that of the Rockbestos cable.

4.6 Summary of BIW Thermal Damage Results

For the BIW cable product tested, it was found that thermal aging reduced the thermal damage threshold of the cable by approximately 20°C. This result indicates an increased vulnerability to thermal damage due to aging. However, the change is considered relatively modest, and is not expected to result in a significant change in fire risk estimates. It was also noted that for higher temperature exposures, no statistically significant difference between the aged and unaged cables were noted.

One final insight gained was that in every case in which electrical shorting of the cable samples was observed, an intense, self-sustaining fire was initiated. In no case was spontaneous ignition of the cables observed prior to cable failure. This indicates that:

(1) the temperature threshold for piloted ignition of the cable samples is lower than the damage thresholds identified here,

(2) in the modeling of cable fire growth, the failure of energized cables should be considered as a mechanism for fire spread, and

(3) the spontaneous ignition (or non-piloted ignition, or auto-ignition) temperature is above the lower limit of thermal damage for this cable.

The data presented provides an indication of the thermal damageability of this cable product in a fire environment. Caution should be exercised in the extrapolation of this data to other cable types and other cable products utilizing similar materials.

Table 4.1: Thermal Damageability Data for Unaged BIW Bostrad 7E Cable Samples.

Test No.	Cable No.	Exposure Temp. (°C)	Failure Time* (min:sec)
30	1	365	NF
30	2	365	NF
31	1	370	17:48
31	2	370	16:08
44	1	370	20:01
44	2	370	18:36
29	1	375	17:30
29	2	375	16:45
41	1	375	16:05
41	2	375	14:26
28	1	400	8:42
28	2	400	6:40
40	1	400	7:00
40	2	400	6:25
27	1	425	5:05
27	2	425	4:20

* NF indicates no failure observed following an exposure of no less than 80 minutes.

Table 4.2: Thermal Damageability Data for Aged** BIW Bostrad 7E Cable Samples.

Test No.	Cable No.	Exposure Temp. (°C)	Failure Time* (min:sec)
49	1	345	NF
49	2	345	NF
48	1	350	59:12
48	2	350	47:11
50	1	350	72:59***
50	2	350	49:32
47	1	355	31:09
47	2	355	20:41
46	1	360	31:35
46	2	360	24:28
51	1	360	23:52
51	2	360	21:20
37	1	365	19:04
37	2	365	19:50
38	1	365	15:10
38	2	365	16:12
36	1	375	10:50
36	2	375	11:52
39	1	375	12:42
39	2	375	14:47
33	1	400	9:08
33	2	400	8:38
34	1	400	9:25
34	2	400	7:45
32	1	425	6:28
32	2	425	6:08
35	1	425	6:26
35	2	425	6:26

* NF indicates no failure observed following an exposure of no less than 80 minutes.

** Cables aged to equivalent of 40 years at 60°C for the insulator.

***Loss of computer control resulted in drop in chamber temperature to 330°C for period of 2 minutes at time equal to 68 minutes into the exposure. Cable #2 was not affected as cable failure occurred prior to control failure.

Table 4.3: Average Failure Time Data for the BIW Bostrad 7E Cable Samples

Exposure Temp. (°C)	Average Failure Time* (min)
Unaged Samples:	
365	NF
370	17.98
375	16.11
400	7.20
425	4.70
Aged Samples:	
345	NF
350	57.22
355	25.92
360	25.31
365	17.57
375	12.55
400	8.73
425	6.36

* NF indicates no failure observed in at least two samples exposed for no less than 80 minutes.

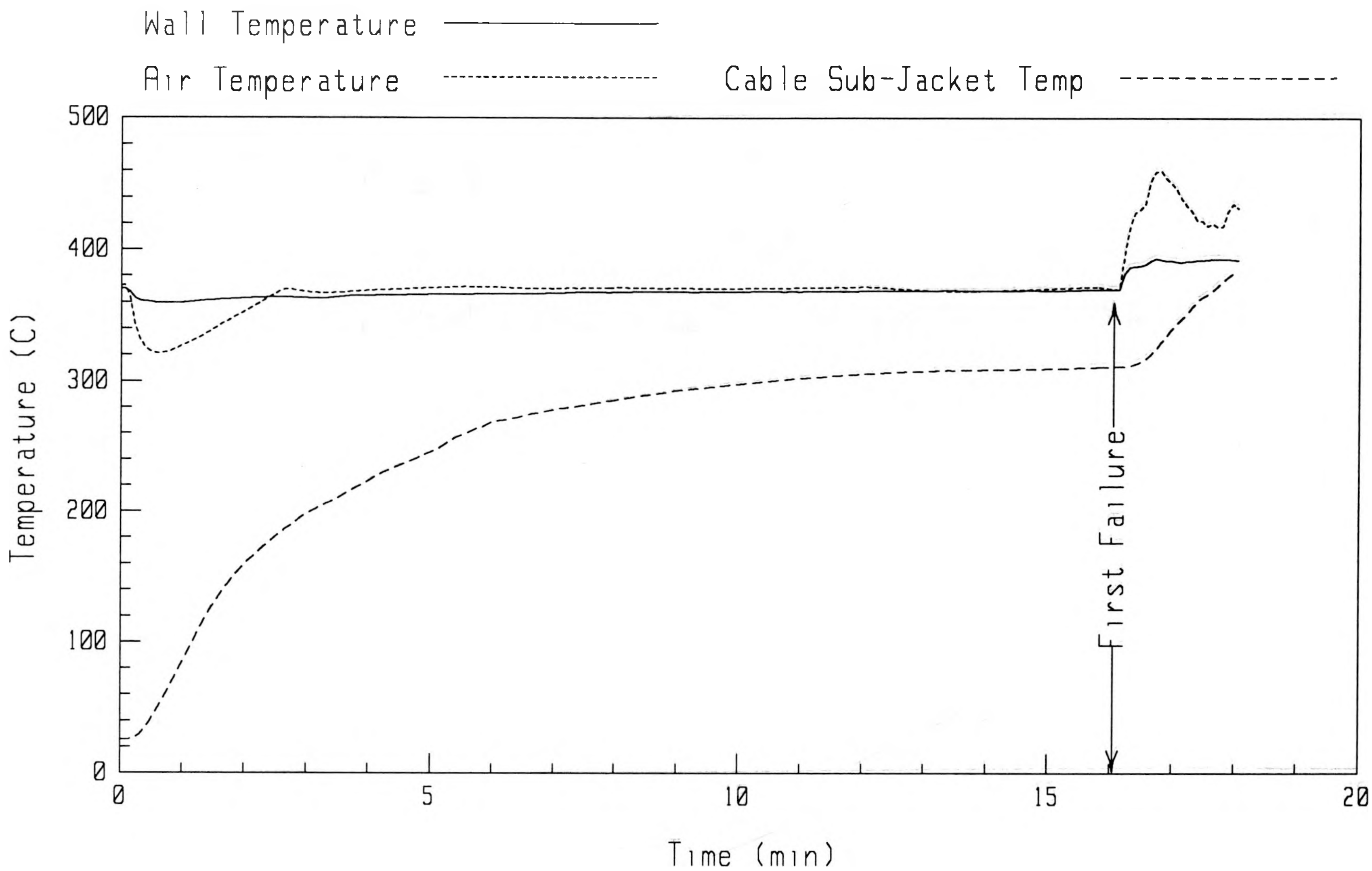
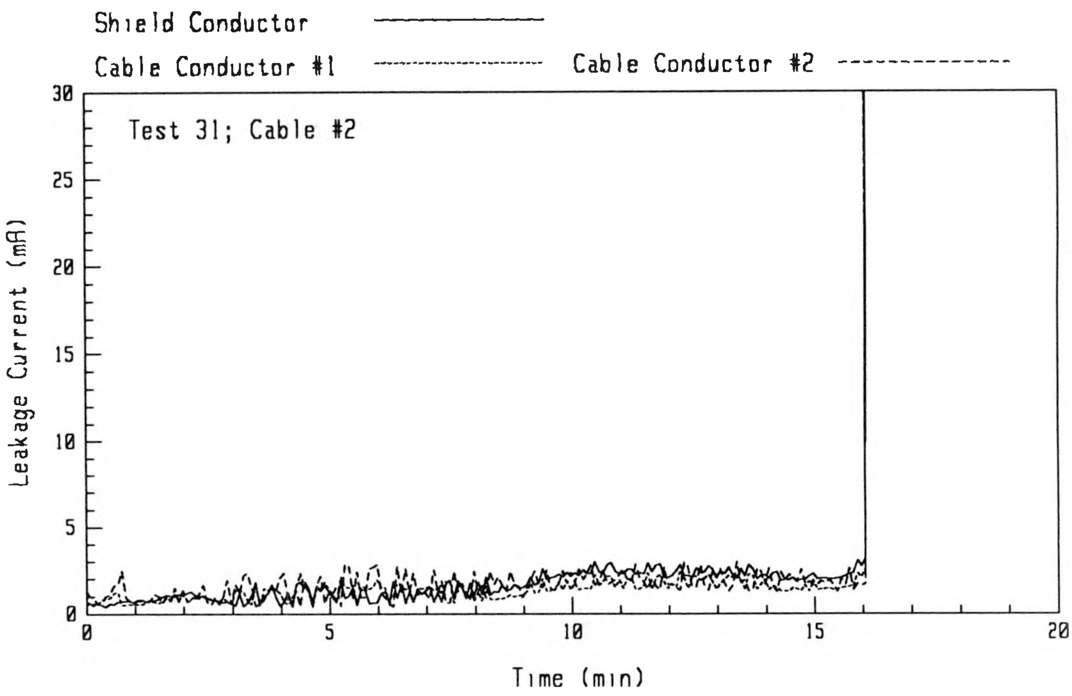
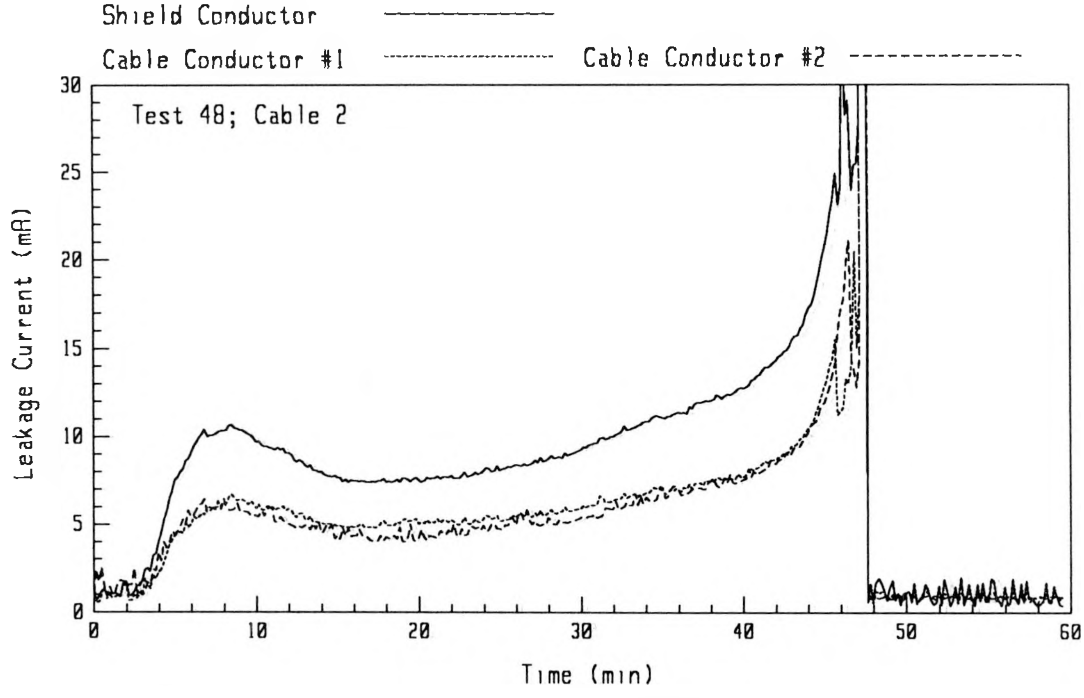


Figure 4.1: Typical Cable Internal Temperature Response for an Unaged Sample of the BIW Cable. This Plot was Taken from Test 31, and Also Illustrates the Consistency of the Exposure Environment. Note that Cable Insertion Occurred at (Time = 0) in this Plot.



(a) Unaged BIW Cable



(b) Aged BIW Cable

Figure 4.2: Typical Leakage Current Data for (a) an Unaged and (b) an Aged BIW Cable Sample. Note that Cable Insertion Occurred at (Time = 0) in these Plots.

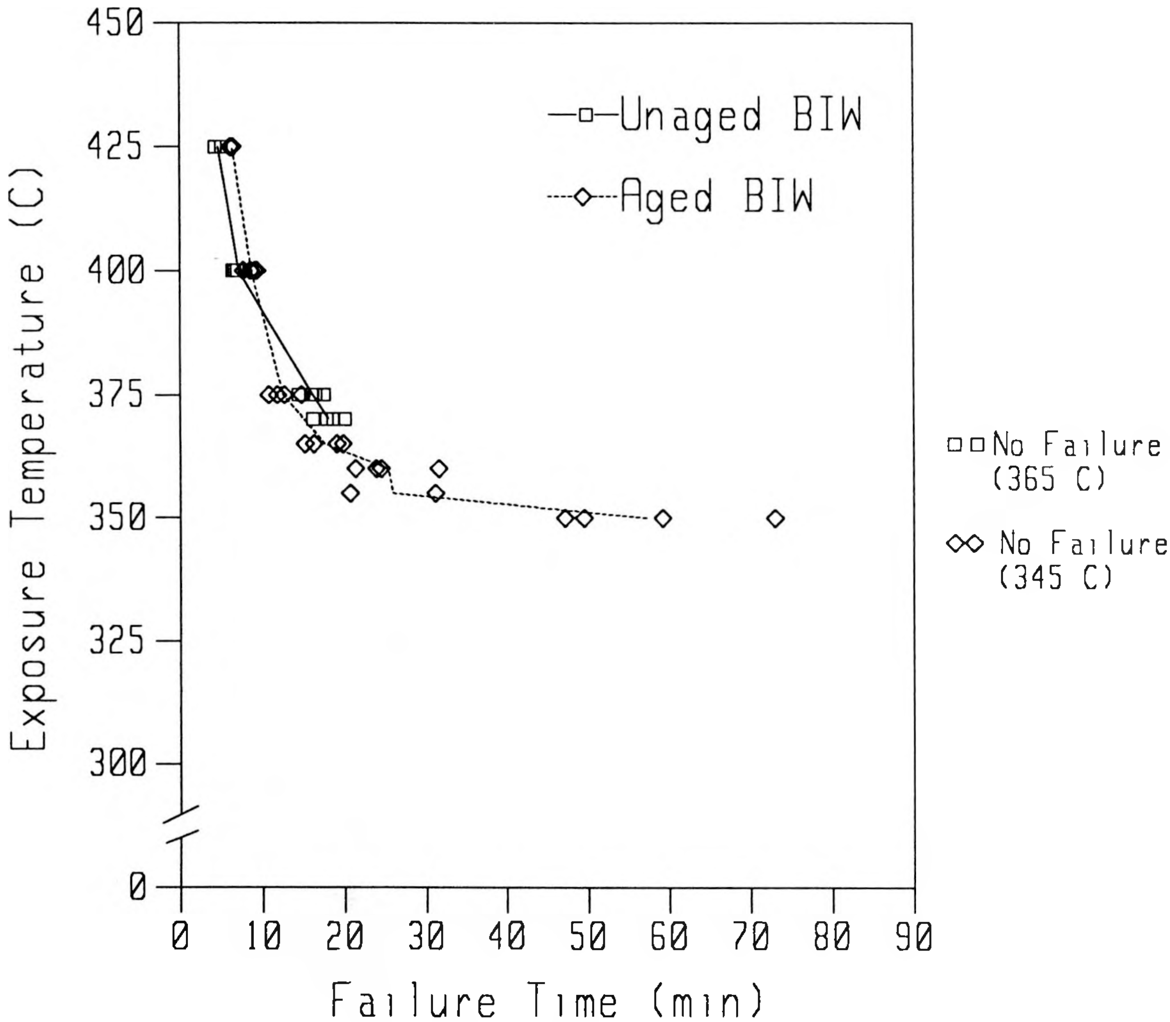


Figure 4.3: Cable Thermal Damage Data for both the Aged and Unaged Samples of the BIW Bostrad 7E EPR/Hypalon Cables.

5.0 CONCLUSIONS

In summary, the results of these tests demonstrated that thermal aging can be expected to change the thermal damageability of electrical cables. However, thermal aging had a quite different impact on the two cable types tested. Table 5.1 presents a summary of the thermal damage thresholds determined for both cable types in both the aged and unaged condition.

In the case of the Rockbestos cable, the thermal damage threshold of the aged cables was approximately 25-35°C higher than that of the unaged cables. Also, the time to failure at any given exposure temperature was consistently longer for the aged cables than for the unaged cables (See Figure 3.3). Both of these results are indicative of a reduced vulnerability to thermal damage for aged cables as compared to unaged cables.

In the case of the BIW cable it was found that the threshold of thermal damage for the aged cables was approximately 20°C lower than that of the unaged cables. This result is indicative of an increased vulnerability to thermal damage for the aged cables as compared to the unaged cables. At higher exposure temperatures, no statistical difference between the time to thermal damage for the aged and unaged cables was observed (see Figure 4.3).

Table 5.1: Summary of Aging Effects on Cable Thermal Damage Threshold.

Cable Type	Unaged Cable Damage Threshold* (°C)	Aged Cable Damage Threshold* (°C)
Rockbestos Firewall III Neoprene/XPE	325-330	350-365
BIW Bostrad 7E EPR/Hypalon	365-370	345-350

* Note that in each case, electrical failure was observed during exposures at the upper end of the stated range, while no failure was observed during exposures at the lower limit of the stated range of no less than 80 minutes in duration.

It should be recognized that for both cable types tested, significant levels of leakage current, on the order of 15 mA, were observed prior to the onset of catastrophic failure. The damage thresholds and damage times reported above are all based on the failure of a 2 ampere fuse in any one leg of the energizing circuitry. Specific applications must be examined to determine whether or not current leakage on the order of that observed here could constitute failure of the circuit to perform its function. In certain circuits, a current leakage of 15 mA may be unacceptable. Also, if the length of cable exposed is longer than that tested here, approximately 24 inches of exposed length, then a corresponding increase in total current leakage should be anticipated.

It was also observed that for both cable types, in virtually every case in which electrical failure occurred, the arcing caused the initiation of intense, sustained, open flaming in the cable samples. This observation leads to three conclusions:

- The temperature threshold for piloted ignition of the cable materials is less than the thermal damage thresholds identified in Table 5.1 above.

- The failure of energized cables during a fire should be considered as a mechanism of further fire spread and secondary fuel ignition.

- Because no cases of spontaneous ignition prior to cable failure were noted, the spontaneous ignition temperature of the cable materials is likely higher than the lower limit of thermal damage identified above.

These tests have demonstrated that thermal aging can be expected to affect the vulnerability of cables to thermal damage. The direction and magnitude of that effect will be dependent on the composition of the cable material, and most likely, on the composition of the insulation on the individual conductors rather than the jacket. In the case of the two cable types evaluated in this effort, the changes in thermal damageability are not considered large enough to result in significant changes in the estimated risk due to fire scenarios involving the failure of these two cable types. Rather, the differences can be treated as uncertainties in the cable damage threshold limits. No significant risk impact is expected because the uncertainty in other fire risk assessment input factors is much more significant than the uncertainties identified here.

It should also be noted that these tests have investigated only one damaging aspect of the fire environment, namely, direct thermal heating. In particular, no examination of the vulnerability to fire suppressant induced damage or the impact of aging on such vulnerability has been undertaken.

6.0 REFERENCES

1. A.R. DuCharme and L.D. Bustard, "Characterization of In-Containment Cables for Nuclear Power Plant Life Extension," Presented at the *ASME/JSME Pressure Vessel and Piping Conference*, Honolulu, HI, July 1989.

2. D.B. King, V.F. Nicolette, and V.J. Dandini, *Safety-Related Equipment Survival in Hydrogen Burns in Large Dry PWR Containment Buildings* NUREG/CR-4763, SAND86-2280, Sandia National Laboratories, Albuquerque, NM, March 1988.

3. S.P. Nowlen, *A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1989*, NUREG/CR-5384, SAND89-1359, Sandia National Laboratories, Albuquerque, NM, December 1989.

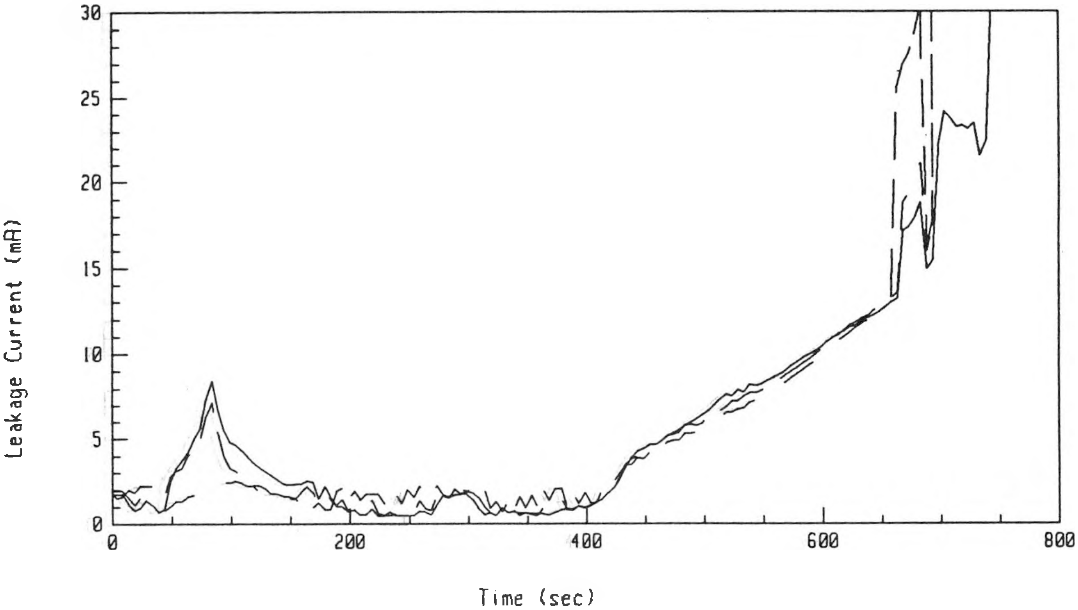
4. C.M. Craft, *Screening Tests of Terminal Block Performance in a Simulated LOCA Environment*, NUREG/CR-3418, SAND83-1617, Sandia National Laboratories, Albuquerque, NM, August 1984.

APPENDIX A

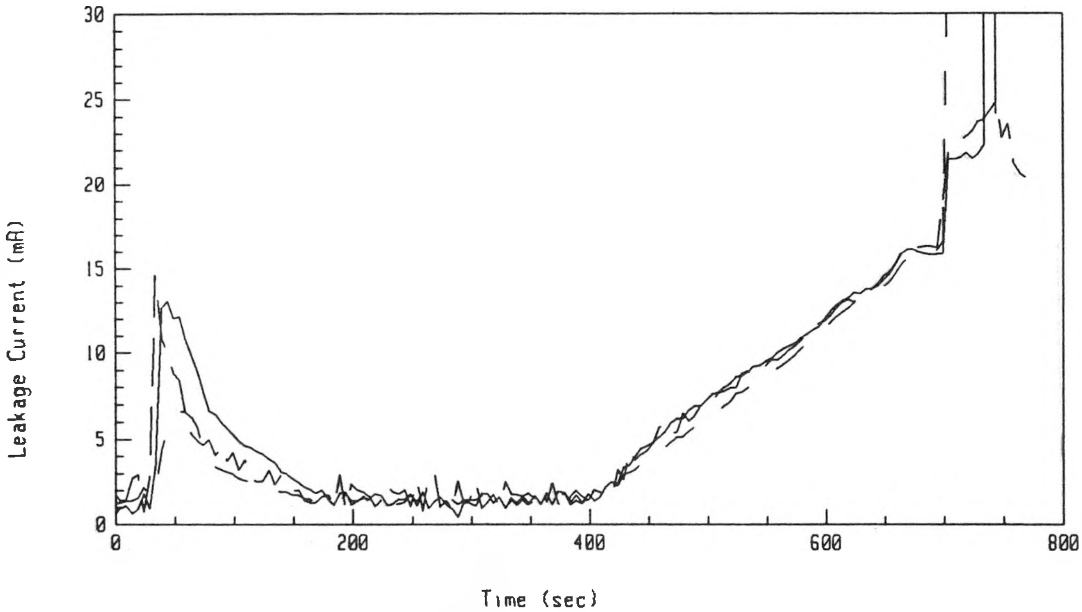
LEAKAGE CURRENT DATA

The following figures provide the actual leakage current data for each of the two cable specimens tested in each of Tests 4-51. (Tests 1-3 were facility shakedown tests and the data is not reported here.) In each plot, the leakage current for each of the individual conductors is given. In the case of the three conductor Rockbestos cable, each of the three conductors was connected to one phase of a 208VAC three-phase power source as shown in Figure 2.3. The cable conductors were identical and connected in random order. In the case of the two conductor BIW cable, the two conductors and the shield drain conductor were each connected to one phase of the power source. For the leakage current plots from the BIW cable tests, the shield leakage current is consistently shown as the solid line in each plot.

Each plot identifies the test number, the cable type, the aging condition, and the exposure temperature. Any anomalous behavior noted during testing (instrumentation or control failures) are also noted. In some cases, leakage currents appear to return to zero following a precipitous jump upwards (failure). This is due to the fact that the power source was isolated to an individual cable after failure occurred. In no cases was cable "healing" observed.

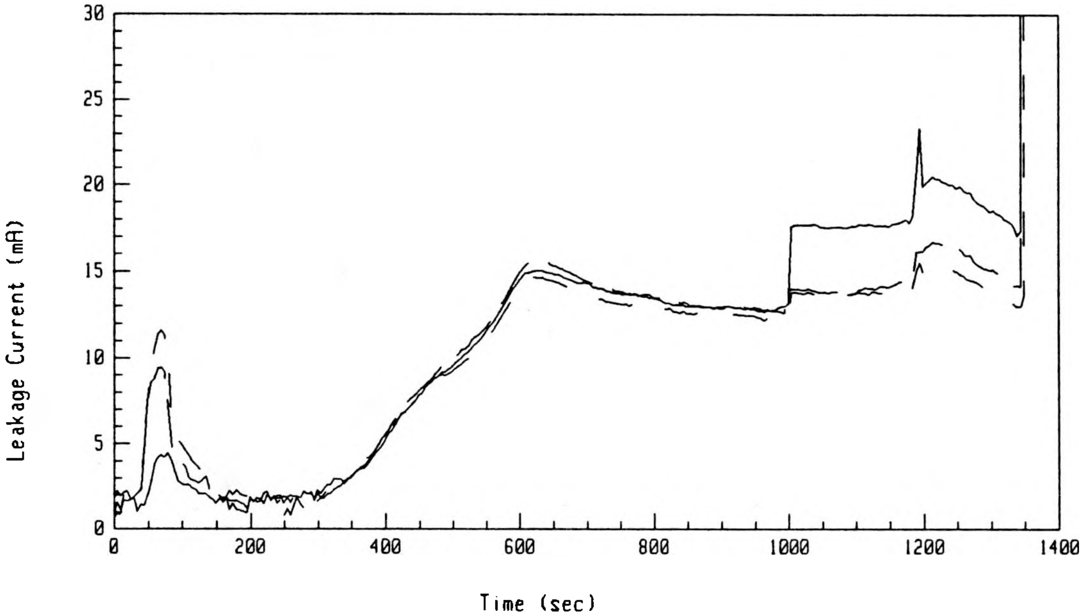


Test 4; Cable 1

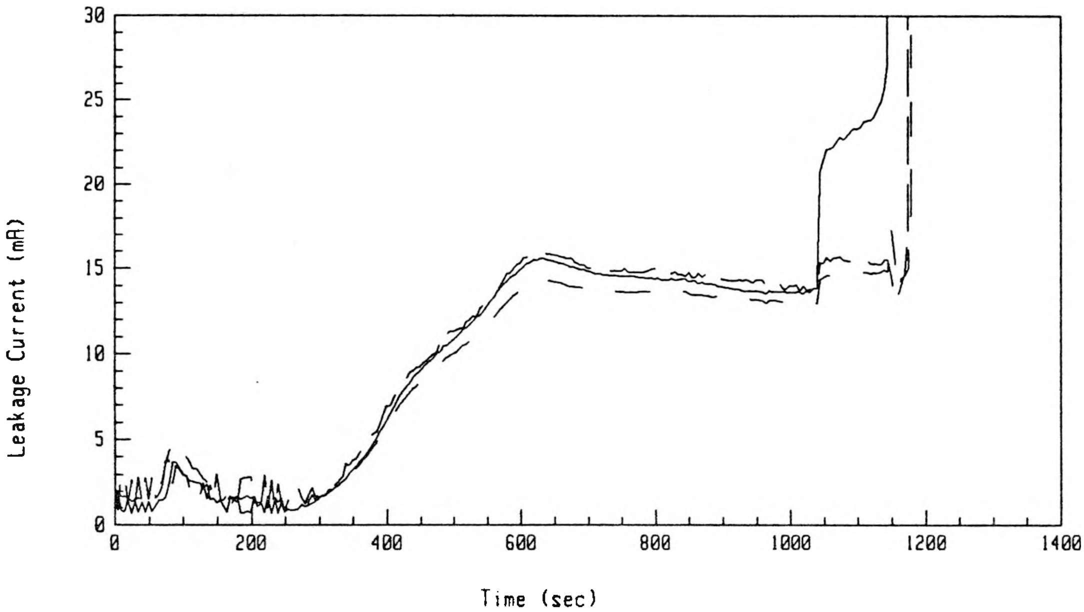


Test 4; Cable 2

Figure A-1: Leakage Current Data For Test 4 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 350°C.

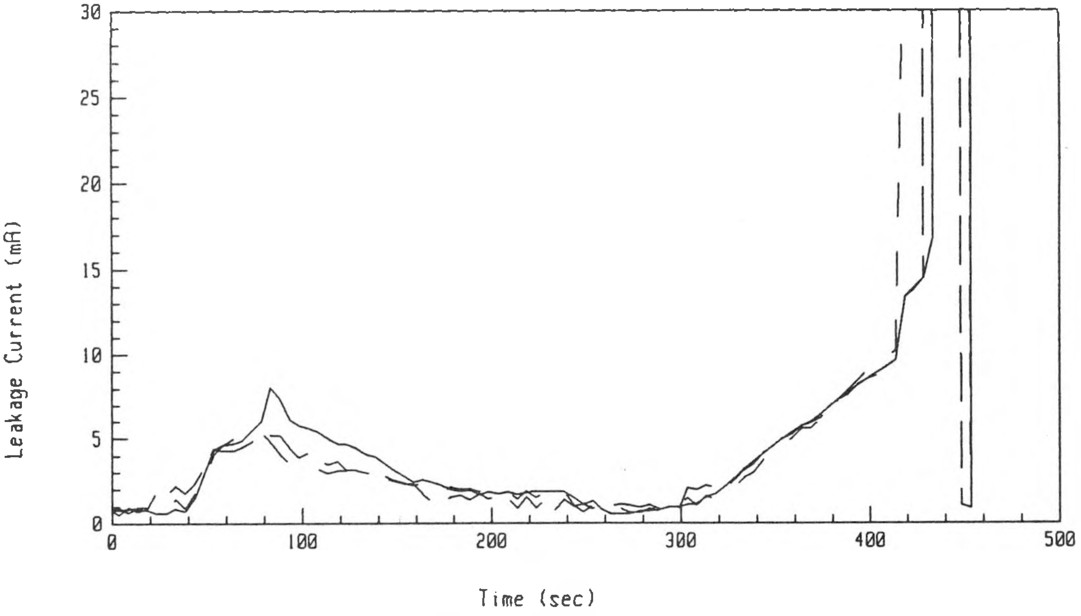


Test 5; Cable 1

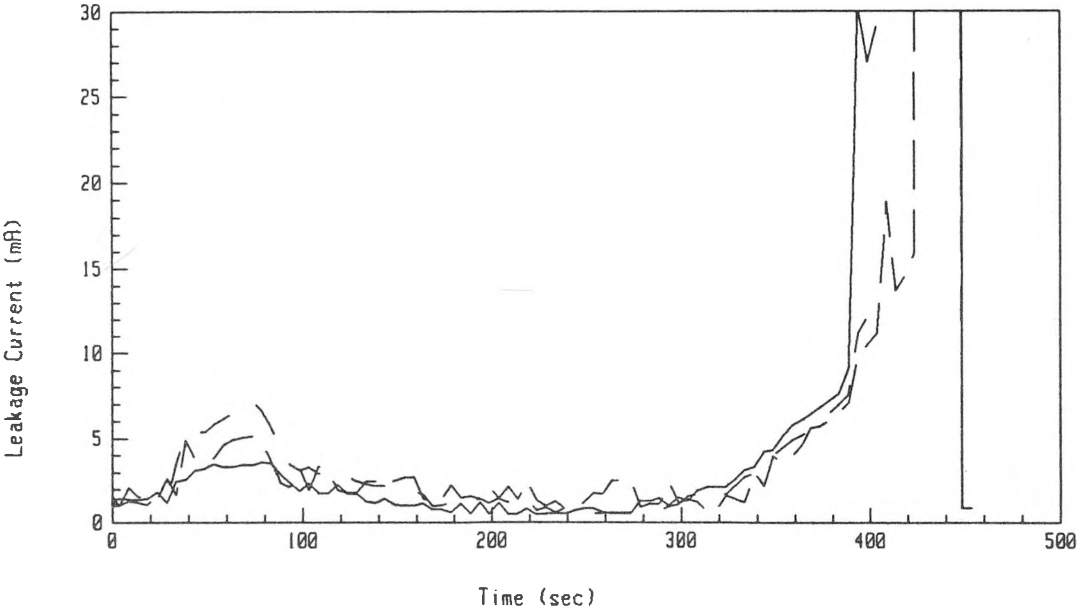


Test 5; Cable 2

Figure A-2: Leakage Current Data For Test 5 Involving an Aged Rockbestos Cable at an Exposure Temperature of 375°C.

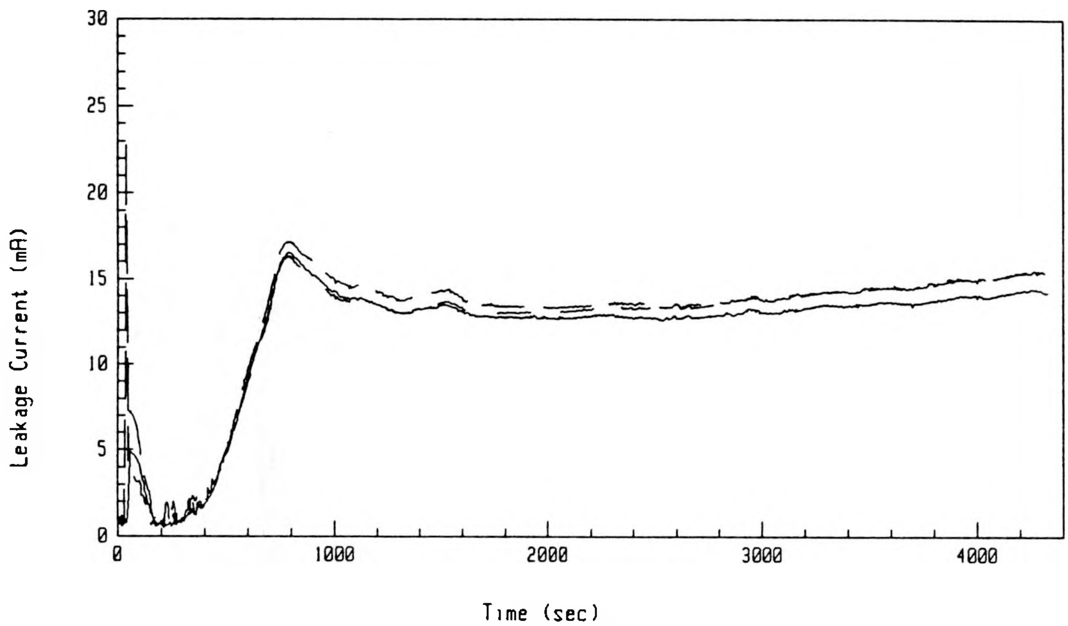


Test 6; Cable 1

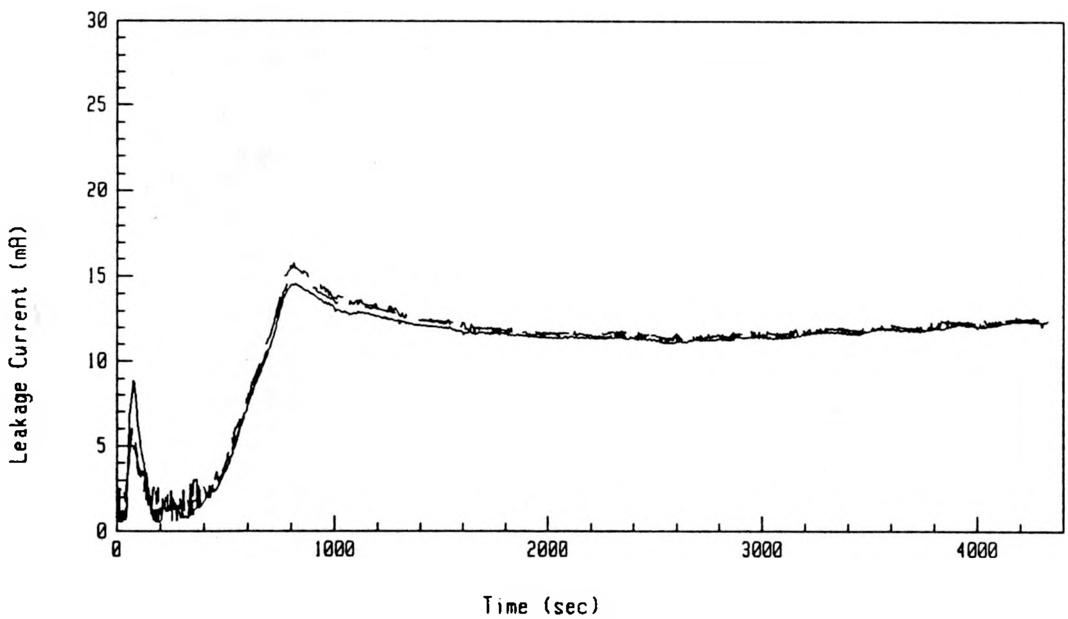


Test 6; Cable 2

Figure A-3: Leakage Current Data For Test 6 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 375°C.

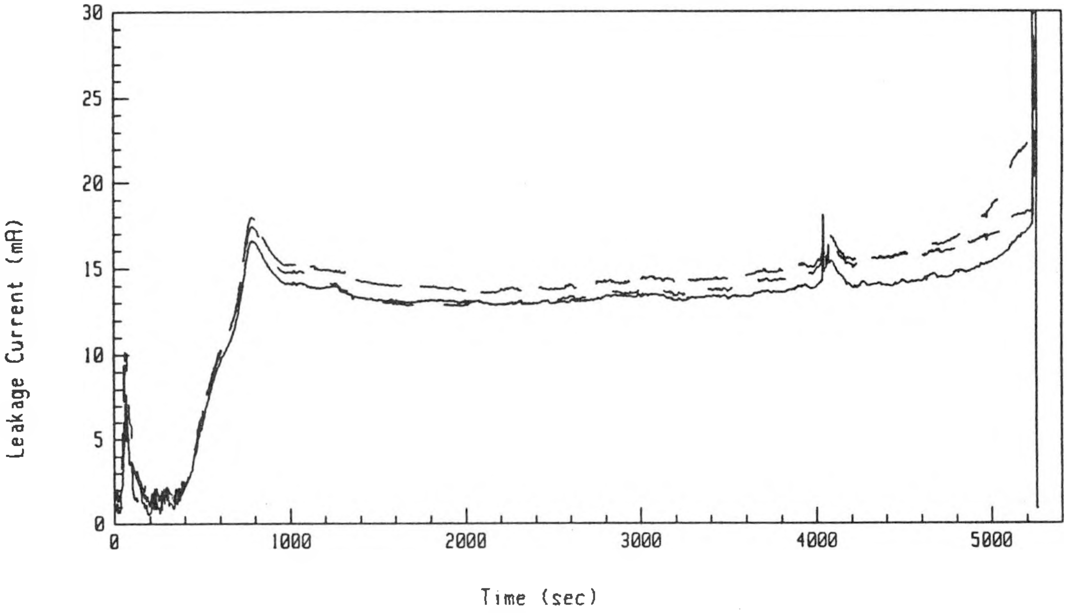


Test 7; Cable 1

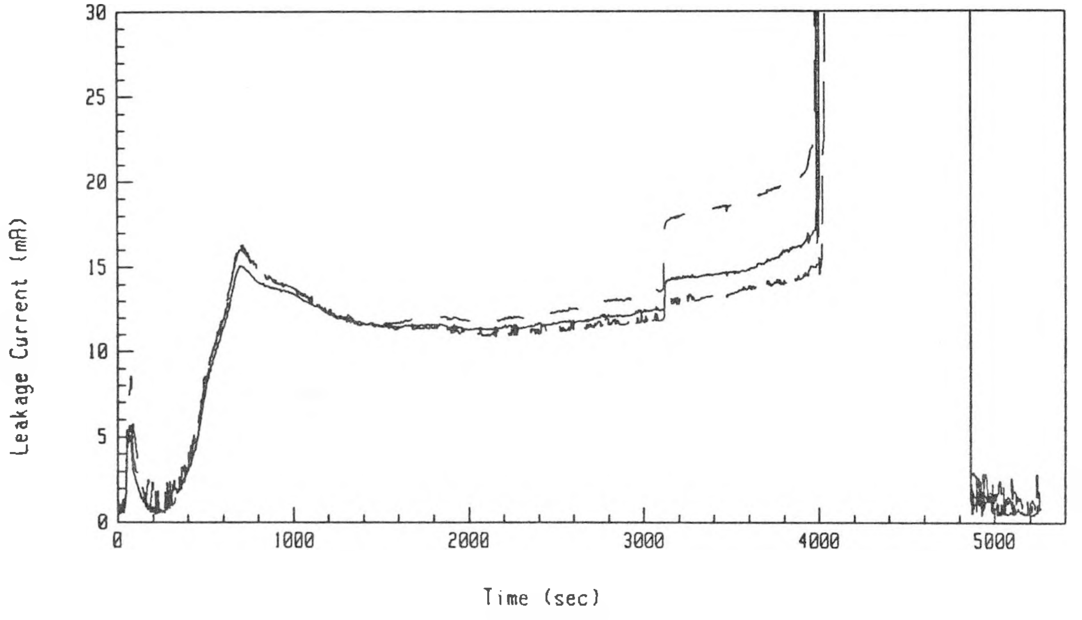


Test 7; Cable 2

Figure A-4: Leakage Current Data For Test 7 Involving an Aged Rockbestos Cable at an Exposure Temperature of 350°C.

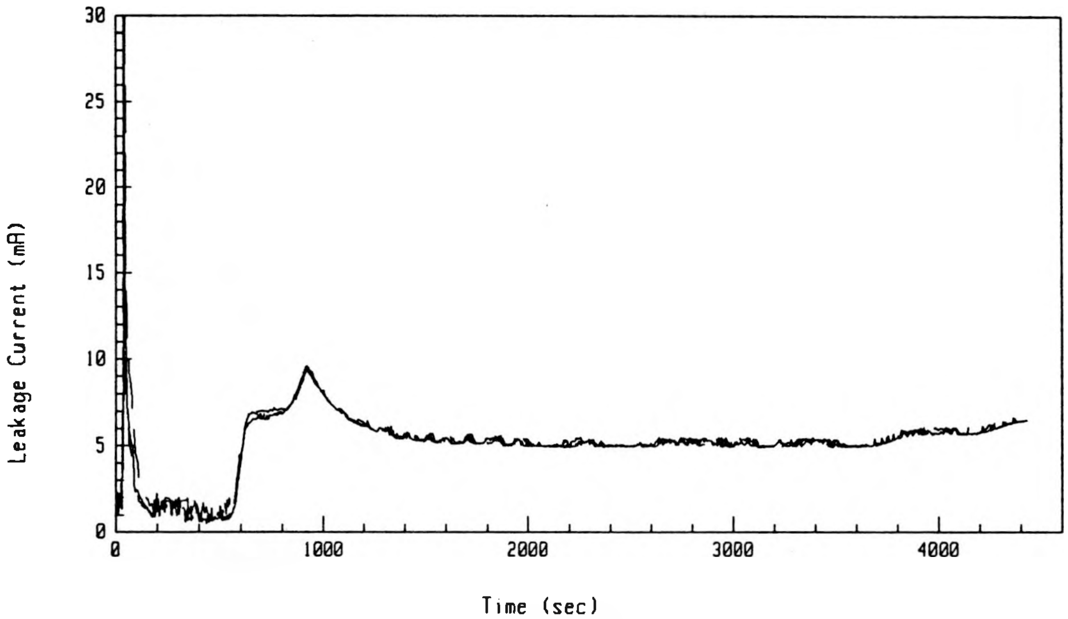


Test 8; Cable 1

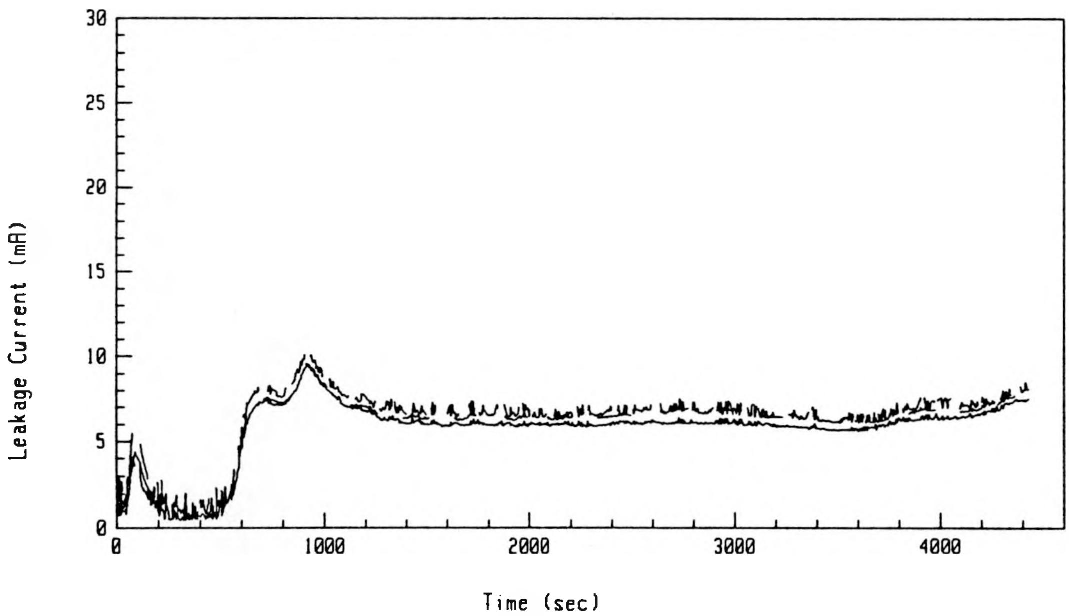


Test 8; Cable 2

Figure A-5: Leakage Current Data For Test 8 Involving an Aged Rockbestos Cable at an Exposure Temperature of 365°C.

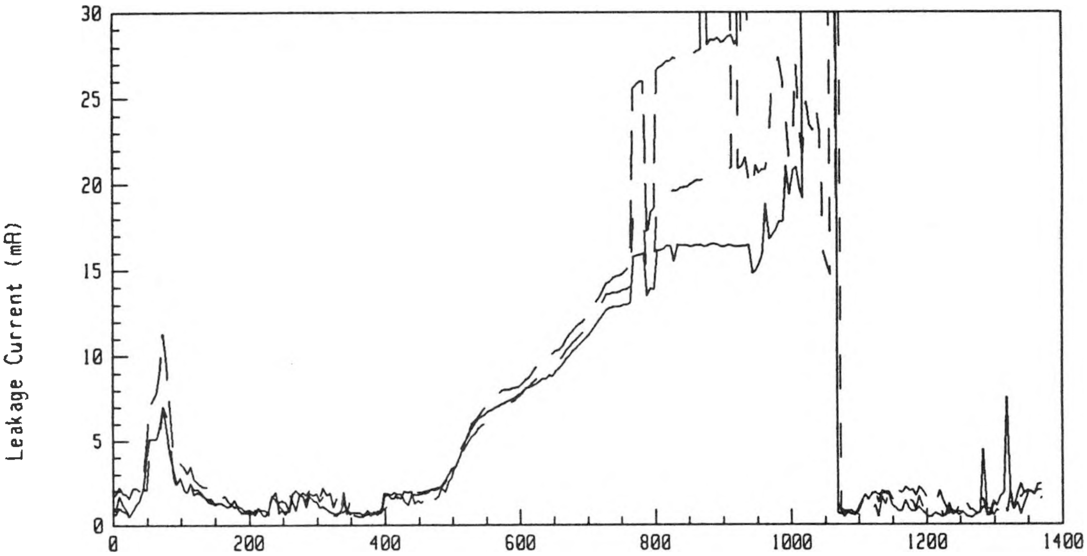


Test 9; Cable 1

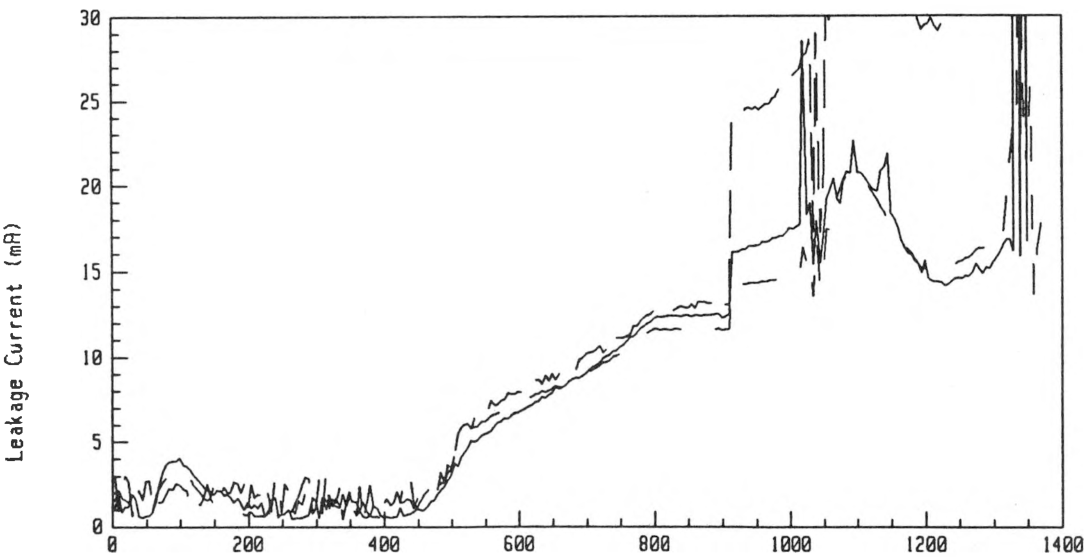


Test 9; Cable 2

Figure A-6: Leakage Current Data For Test 9 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 325°C.

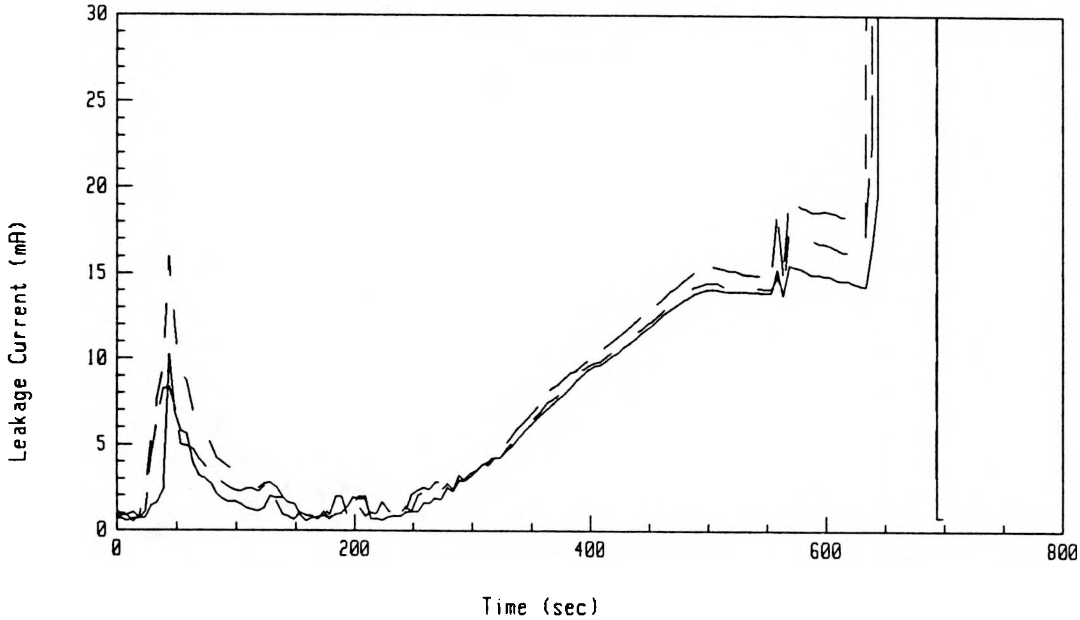


Test 10; Cable 1

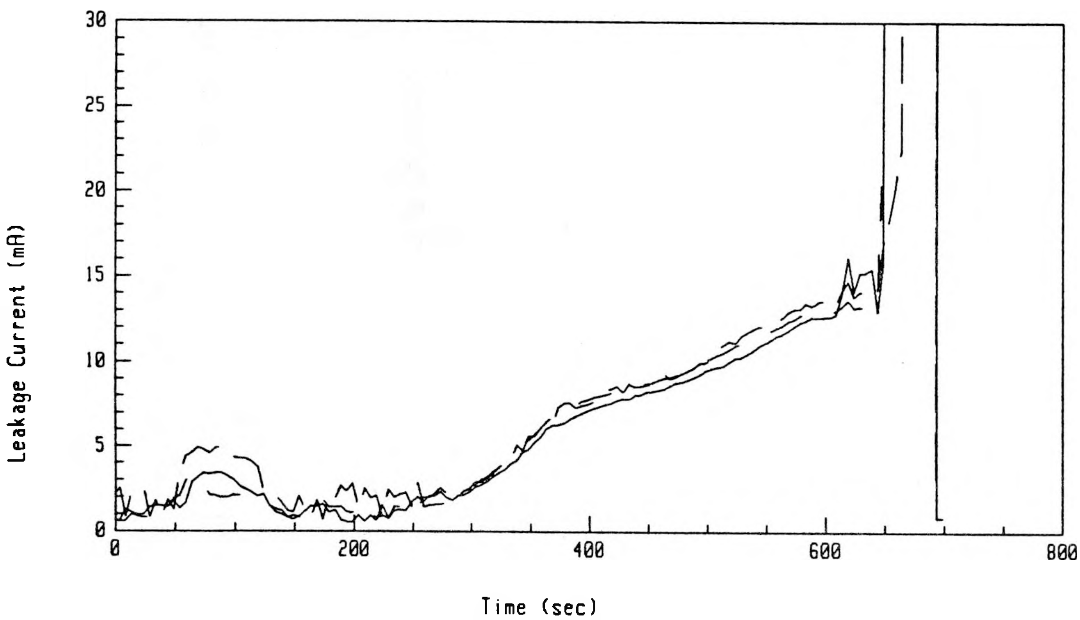


Test 10; Cable 2

Figure A-7: Leakage Current Data For Test 10 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 335°C.

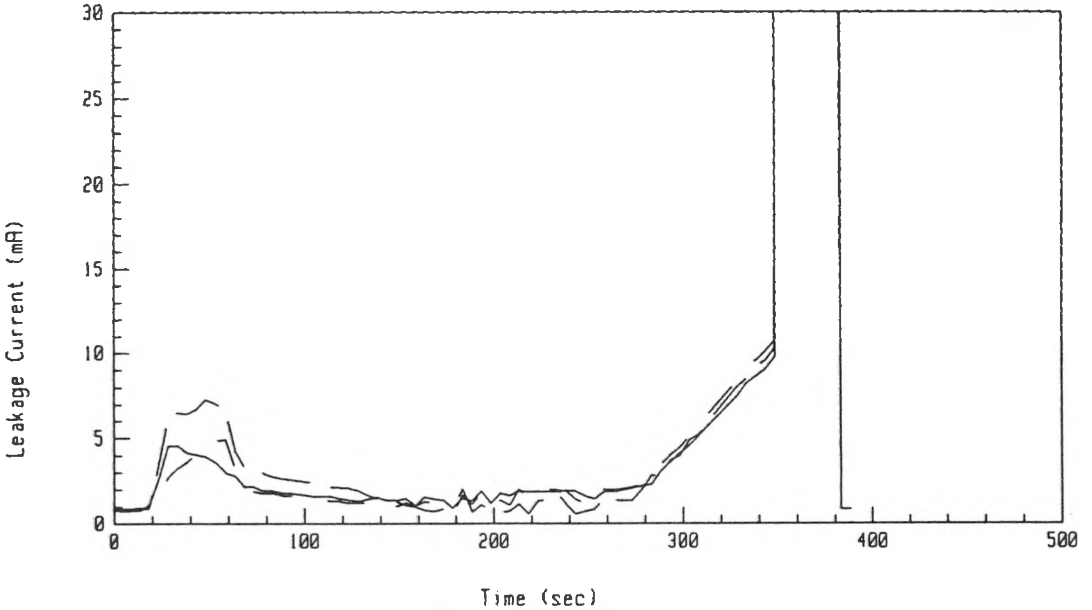


Test 11; Cable 1

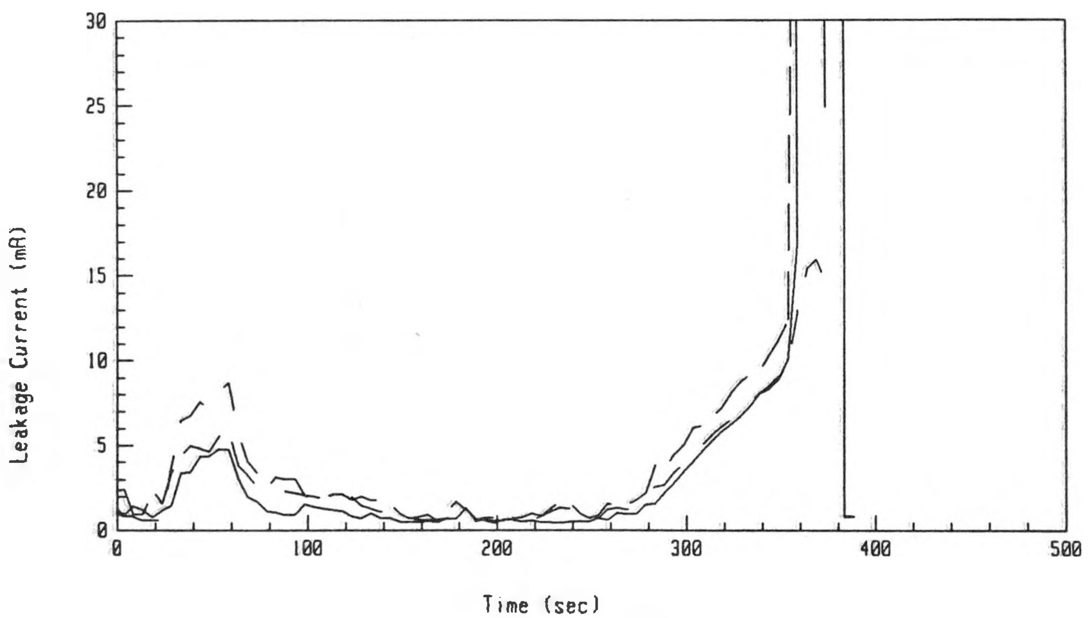


Test 11; Cable 2

Figure A-8: Leakage Current Data For Test 11 Involving an Aged Rockbestos Cable at an Exposure Temperature of 400°C.

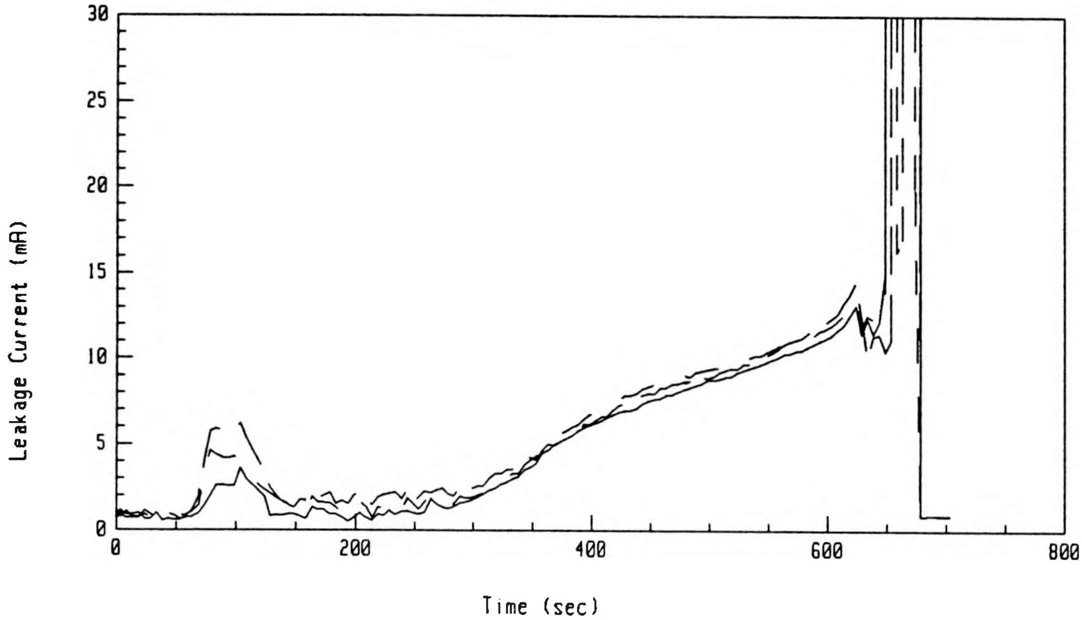


Test 12; Cable 1

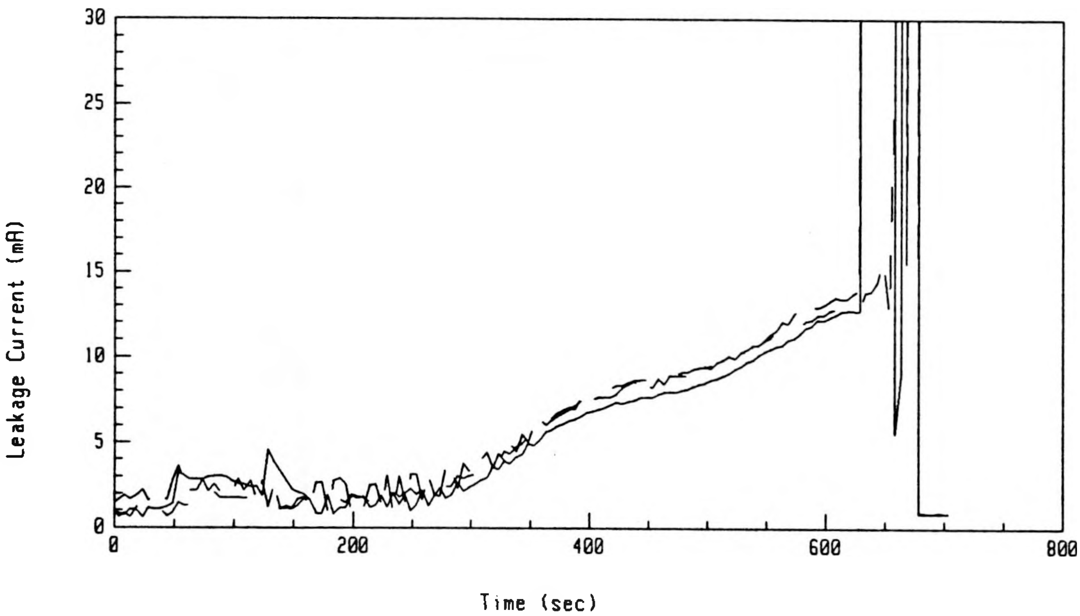


Test 12; Cable 2

Figure A-9: Leakage Current Data For Test 12 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 400°C.

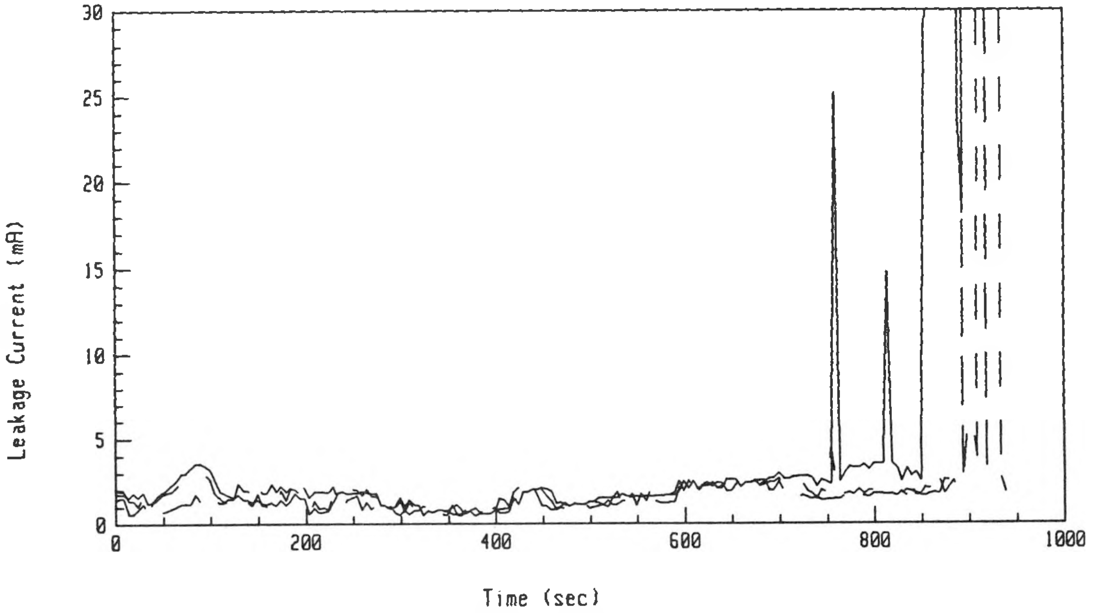


Test 13; Cable 1

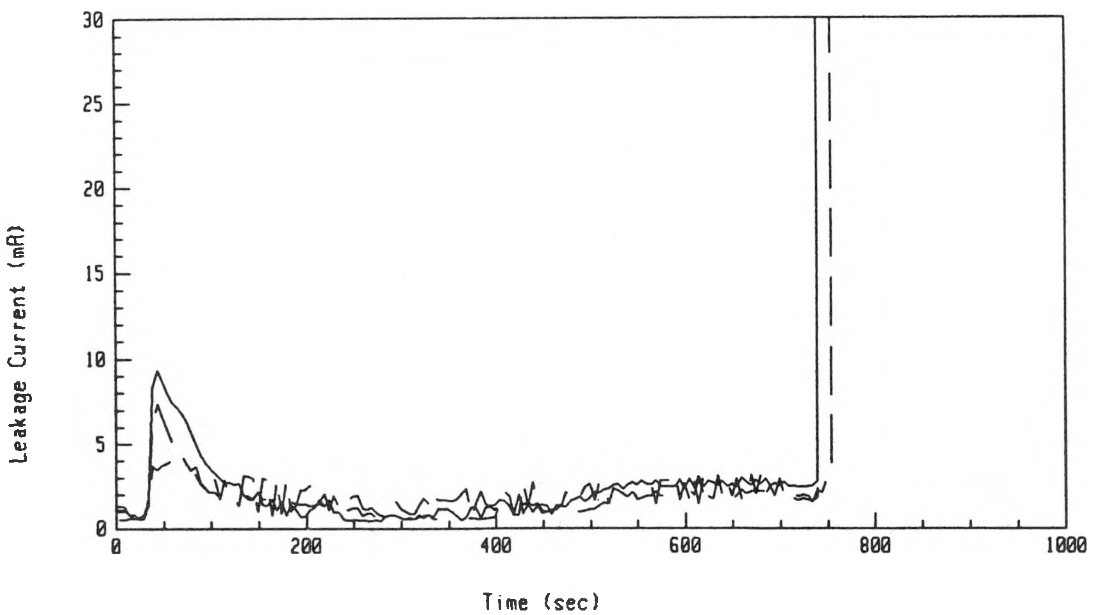


Test 13; Cable 2

Figure A-10: Leakage Current Data For Test 13 Involving an Aged Rockbestos Cable at an Exposure Temperature of 400°C.

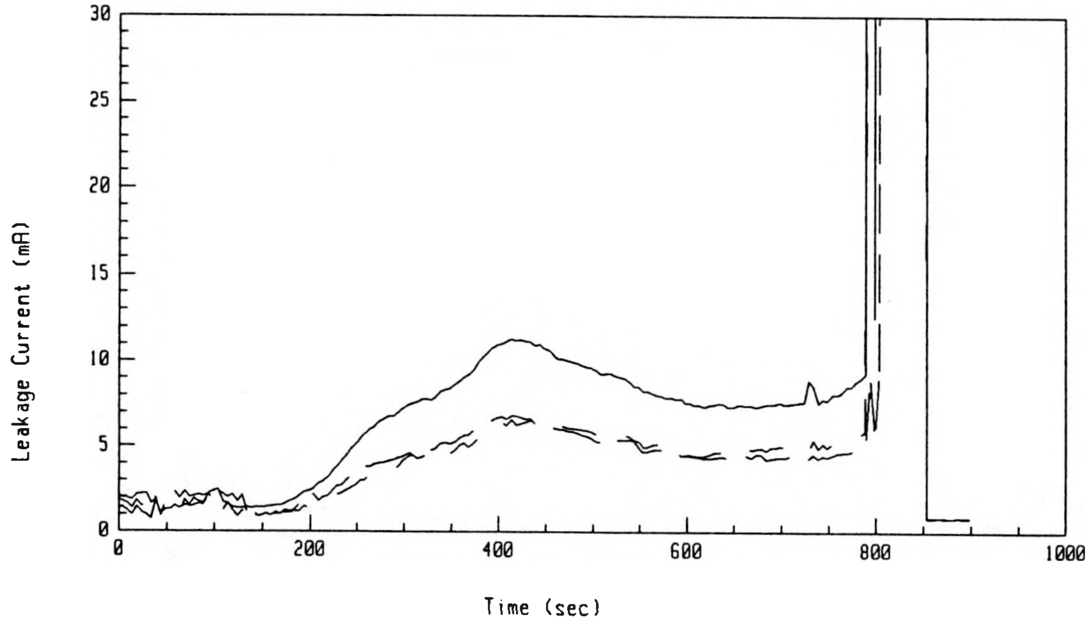


Test 14; Cable 1

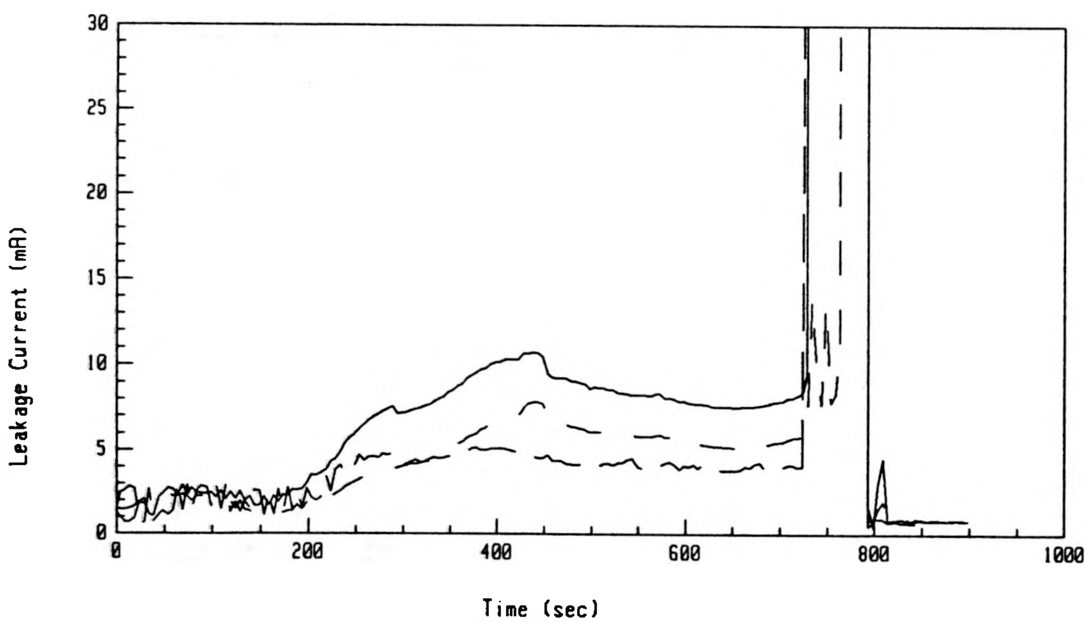


Test 14; Cable 2

Figure A-11: Leakage Current Data For Test 14 Involving an Unaged BIW Cable at an Exposure Temperature of 375°C.

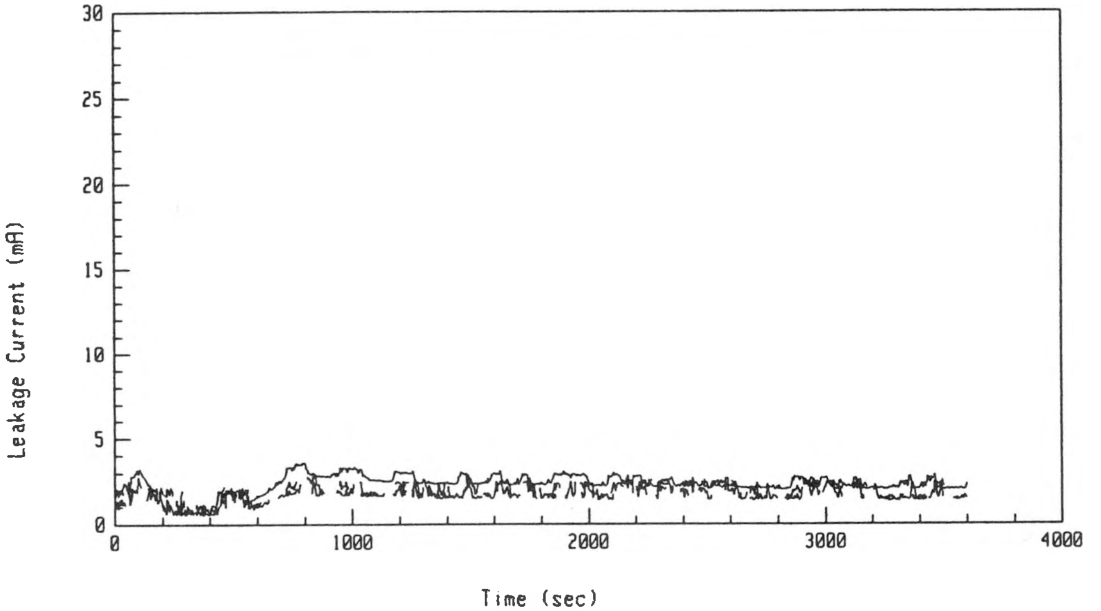


Test 15; Cable 1

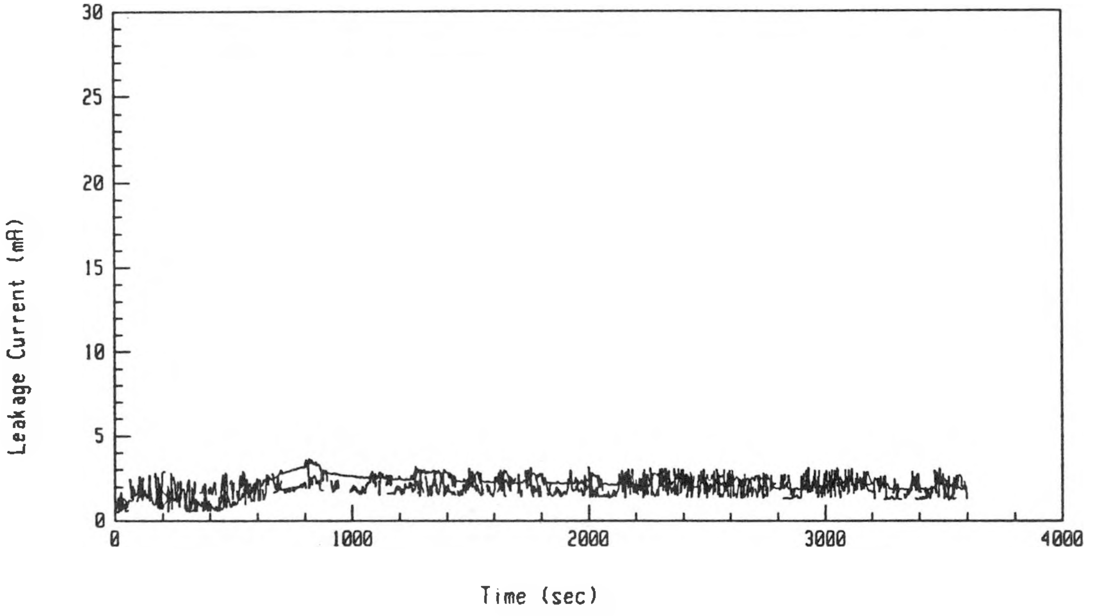


Test 15; Cable 2

Figure A-12: Leakage Current Data For Test 15 Involving an Aged BIW Cable at an Exposure Temperature of 375°C.

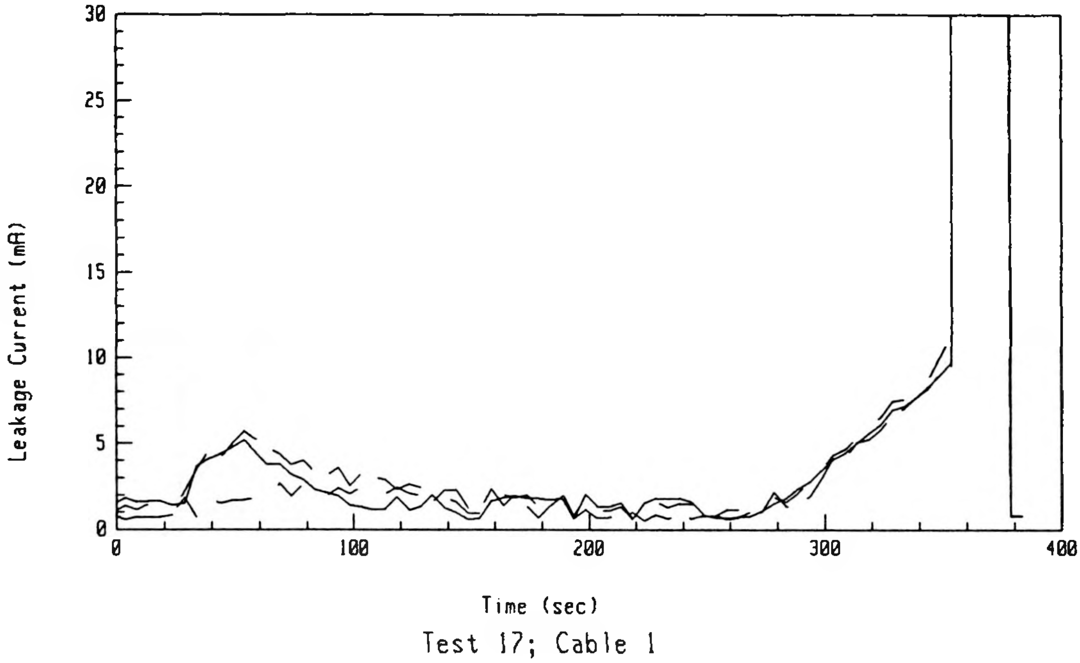


Test 16; Cable 1



Test 16; Cable 2

Figure A-13: Leakage Current Data For Test 16 Involving an Unaged BIW Cable at an Exposure Temperature of 350°C.



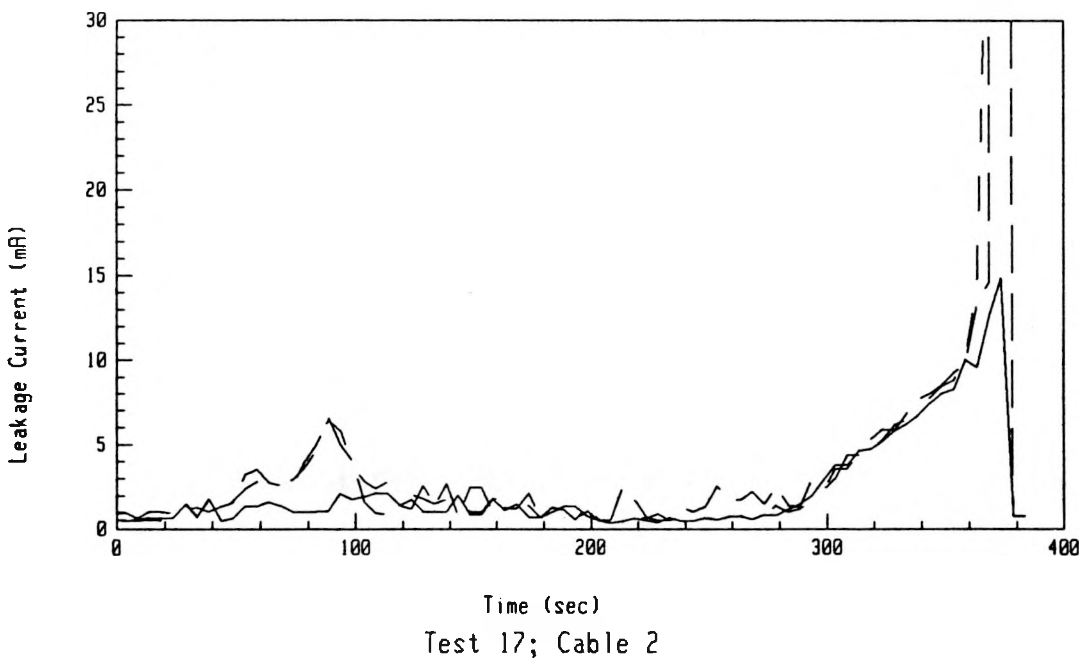
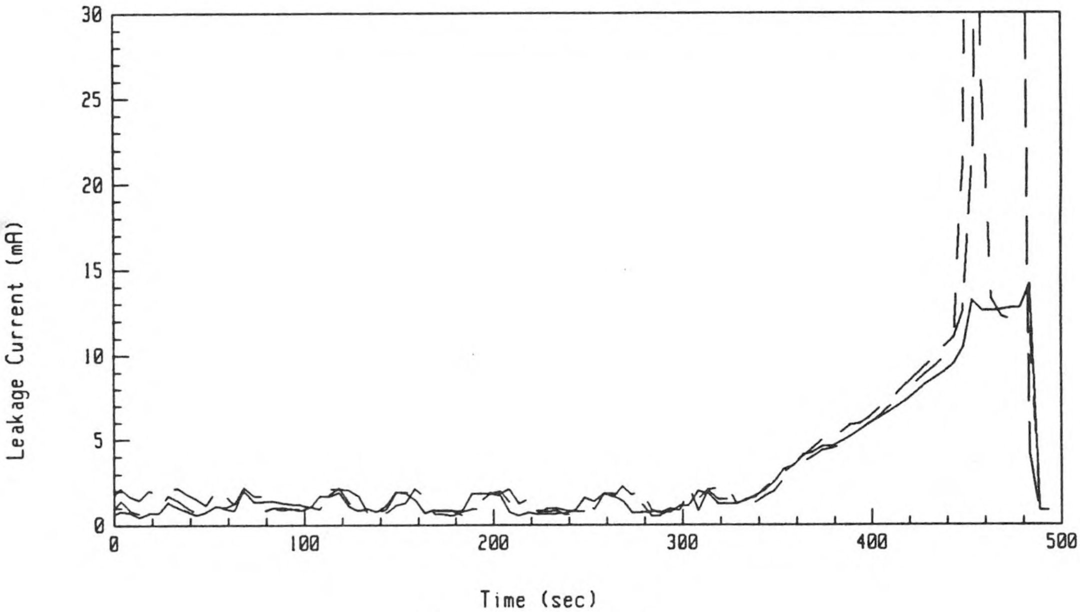
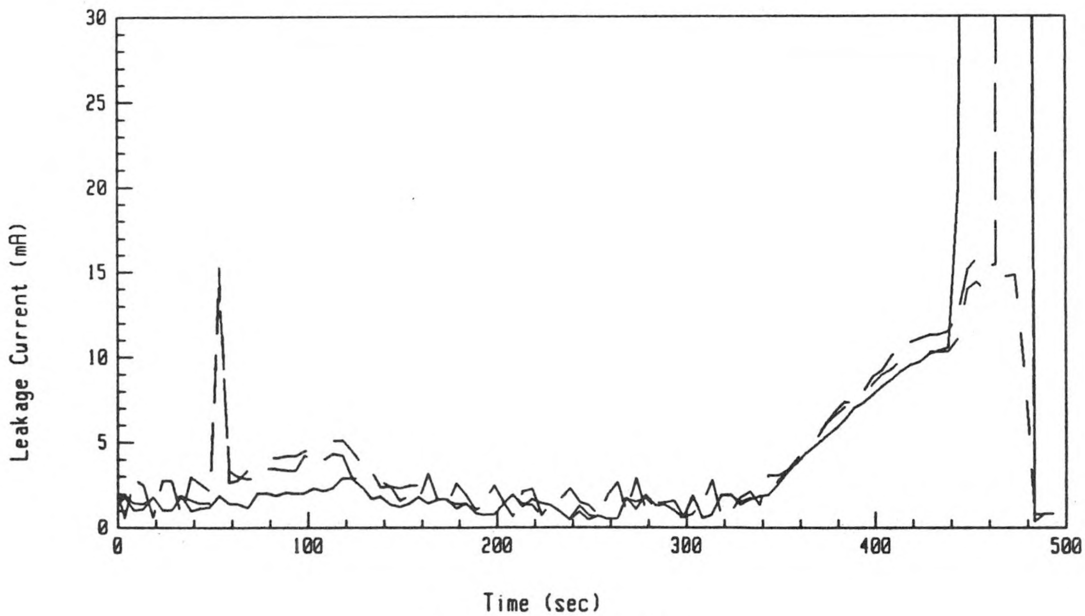


Figure A-14: Leakage Current Data For Test 17 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 400°C.

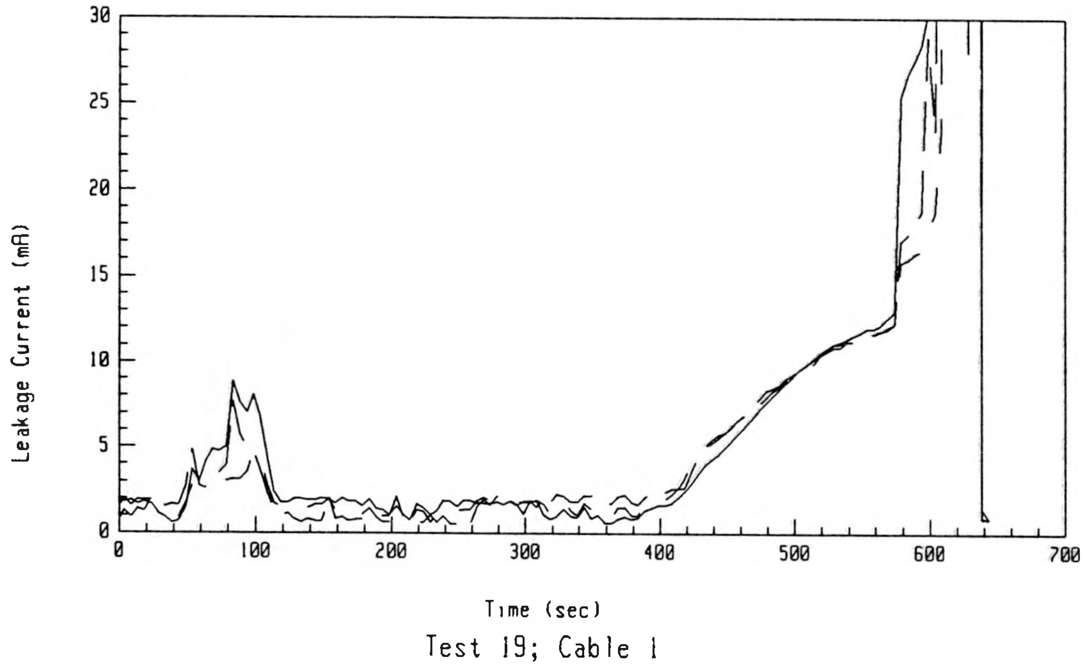


Test 18; Cable 1



Test 18; Cable 2

Figure A-15: Leakage Current Data For Test 18 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 375°C.



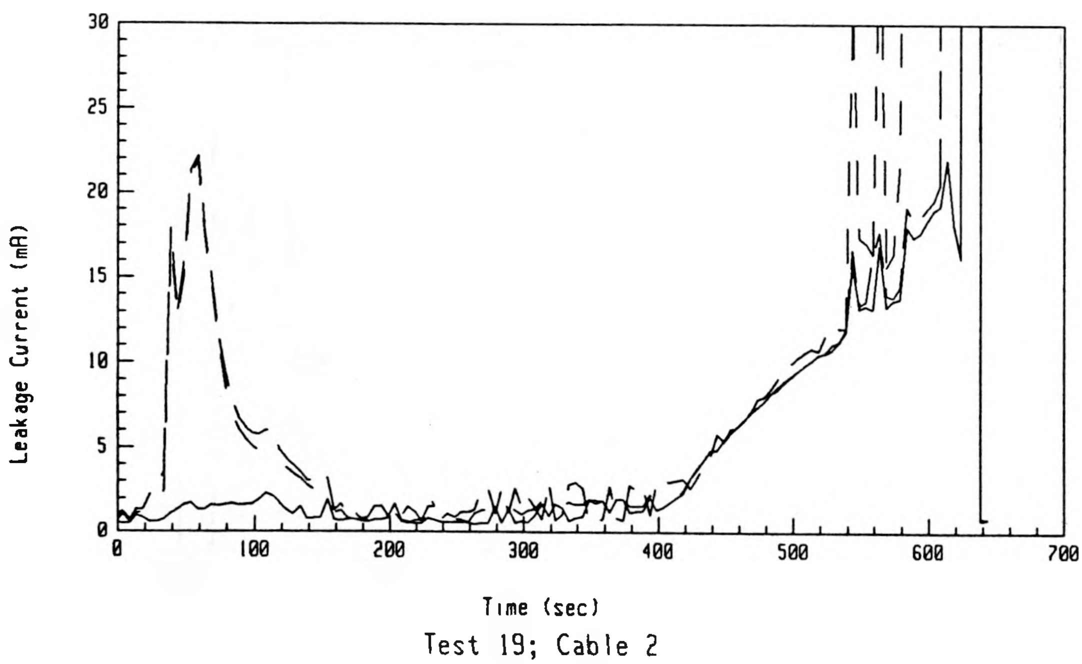
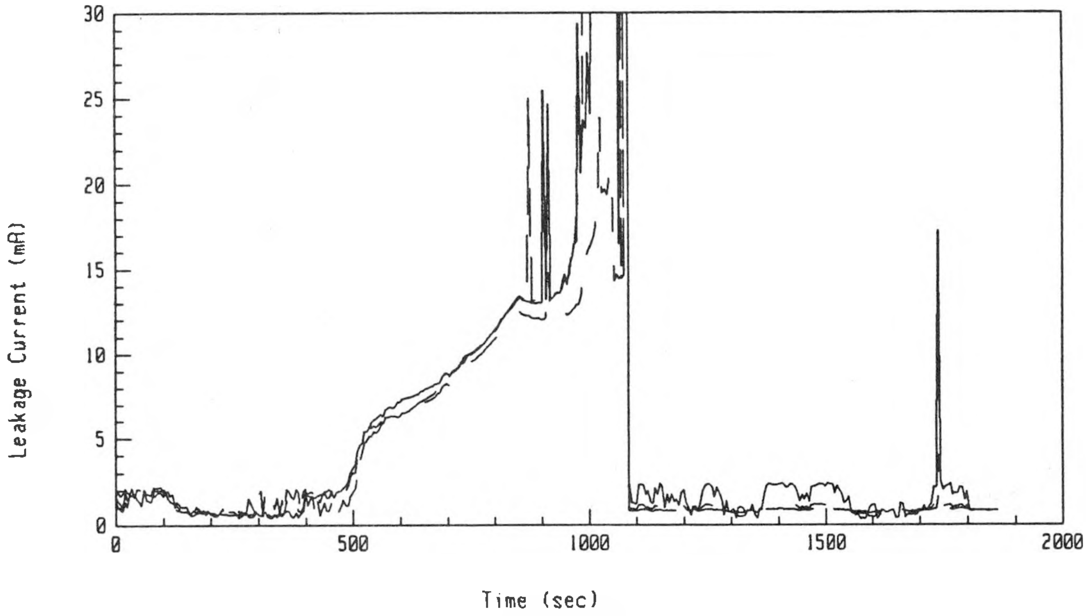
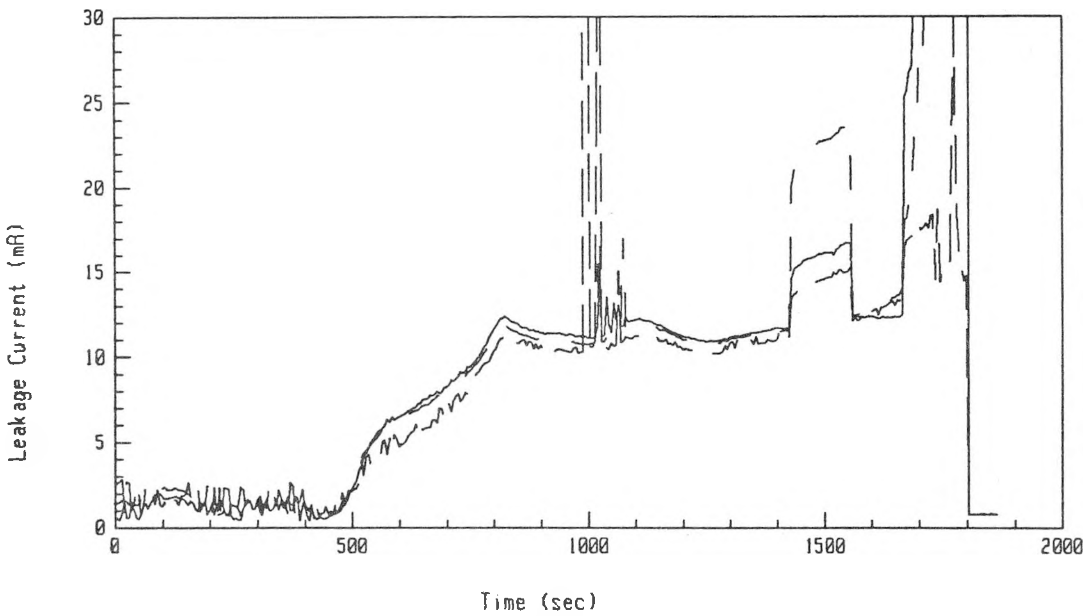


Figure A-16: Leakage Current Data For Test 19 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 350°C.

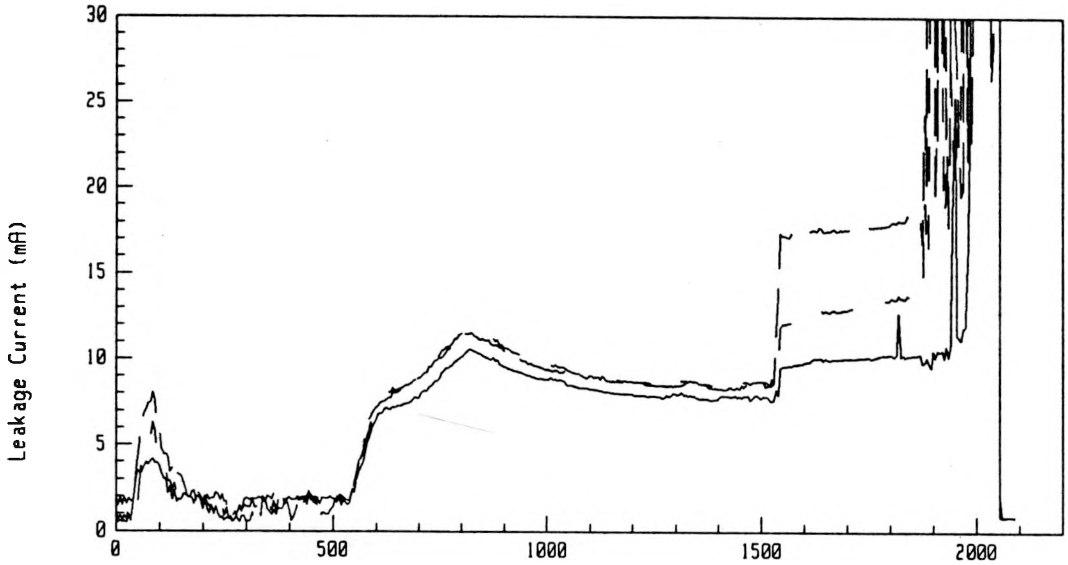


Test 20; Cable 1

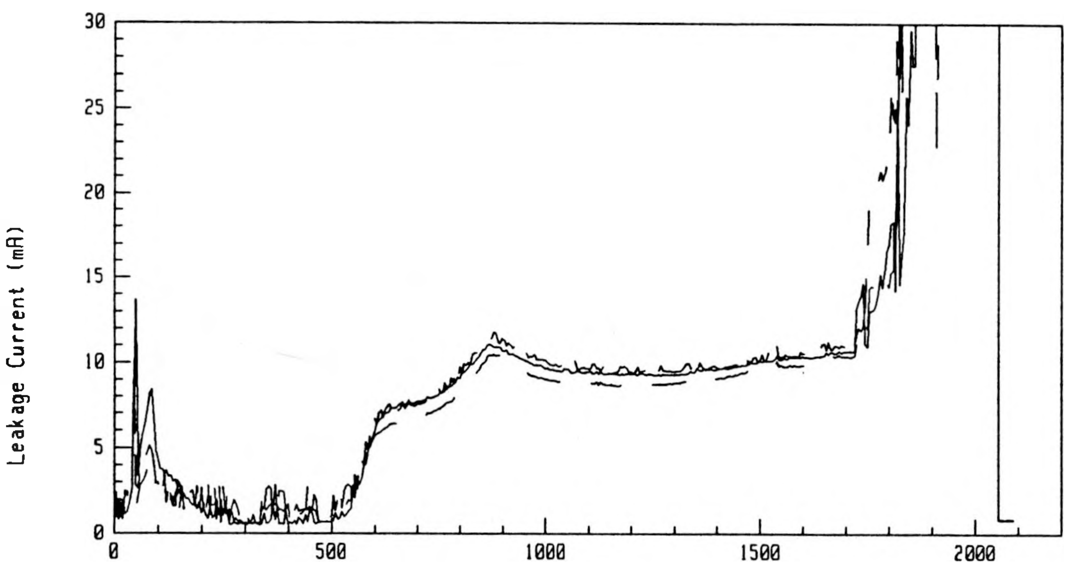


Test 20; Cable 2

Figure A-17: Leakage Current Data For Test 20 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 335°C.

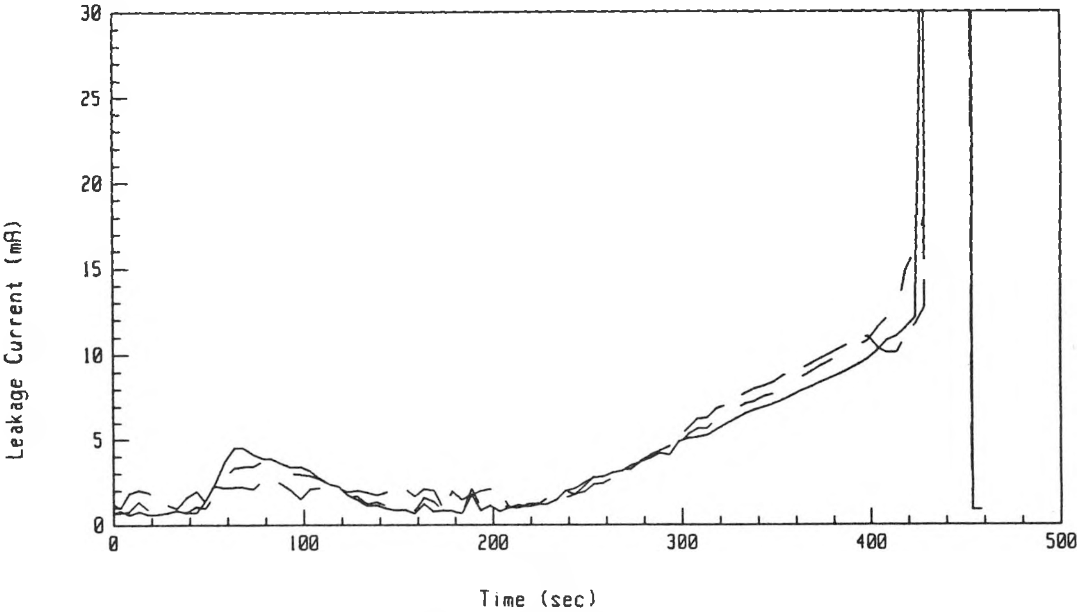


Time (sec)
Test 21; Cable 1

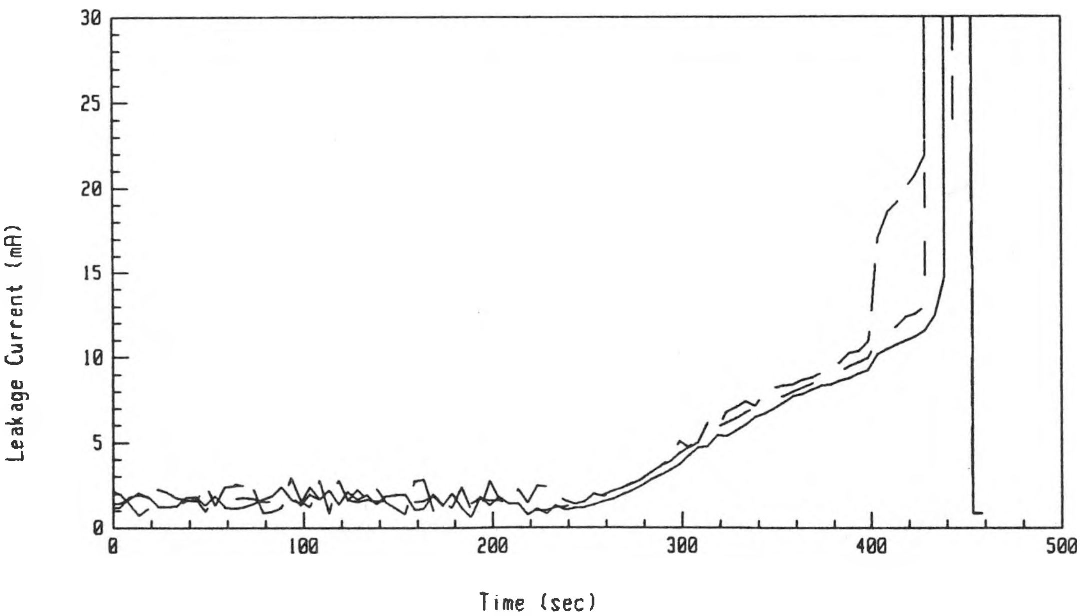


Time (sec)
Test 21; Cable 2

Figure A-18: Leakage Current Data For Test 21 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 330°C.

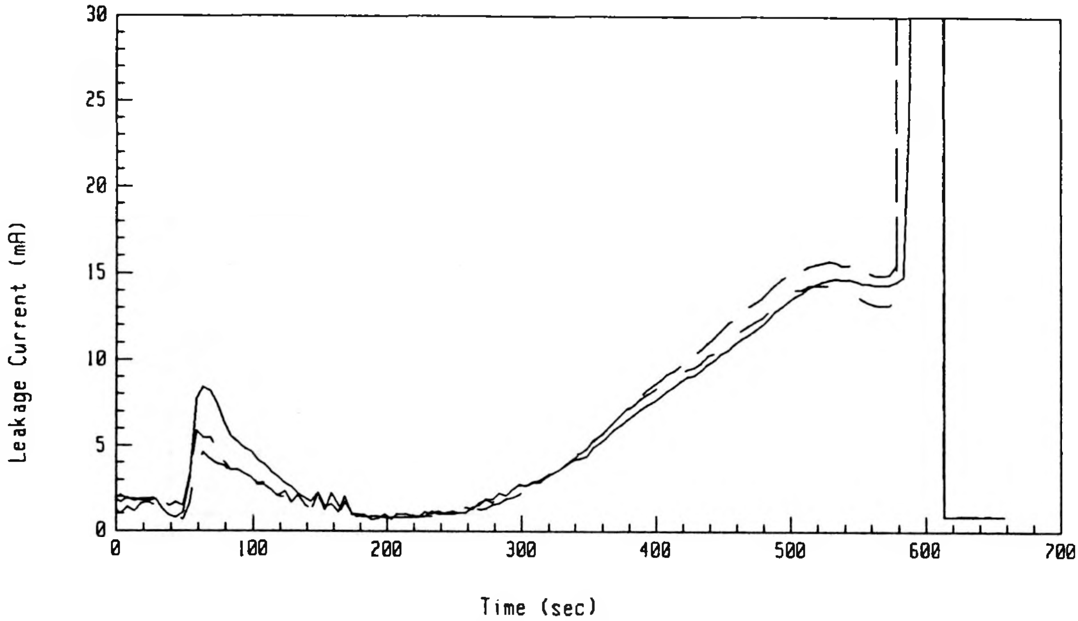


Test 22; Cable 1

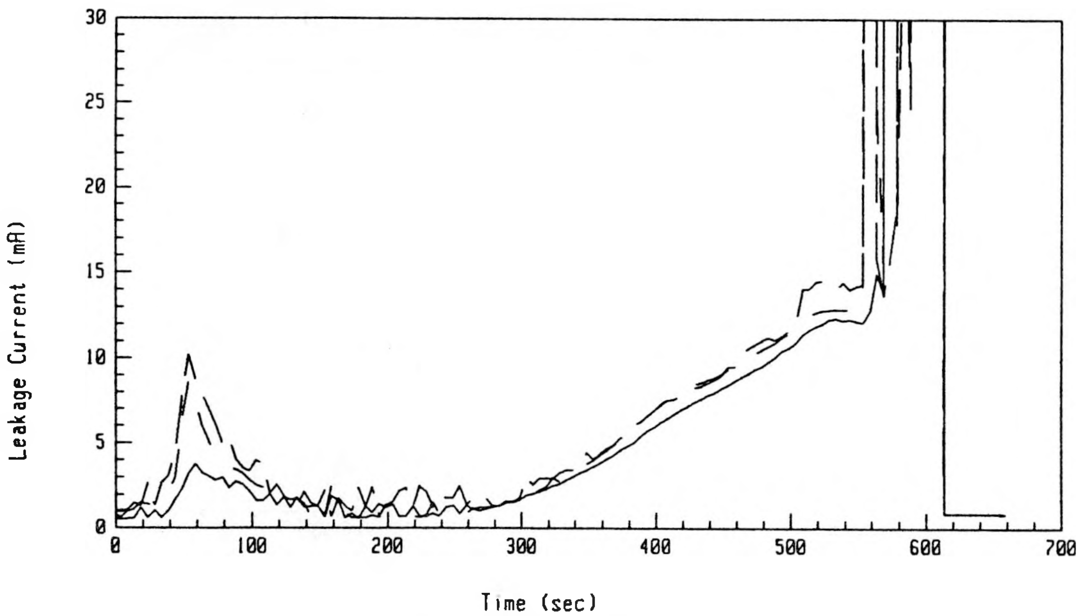


Test 22; Cable 2

Figure A-19: Leakage Current Data For Test 22 Involving an Aged Rockbestos Cable at an Exposure Temperature of 425°C.

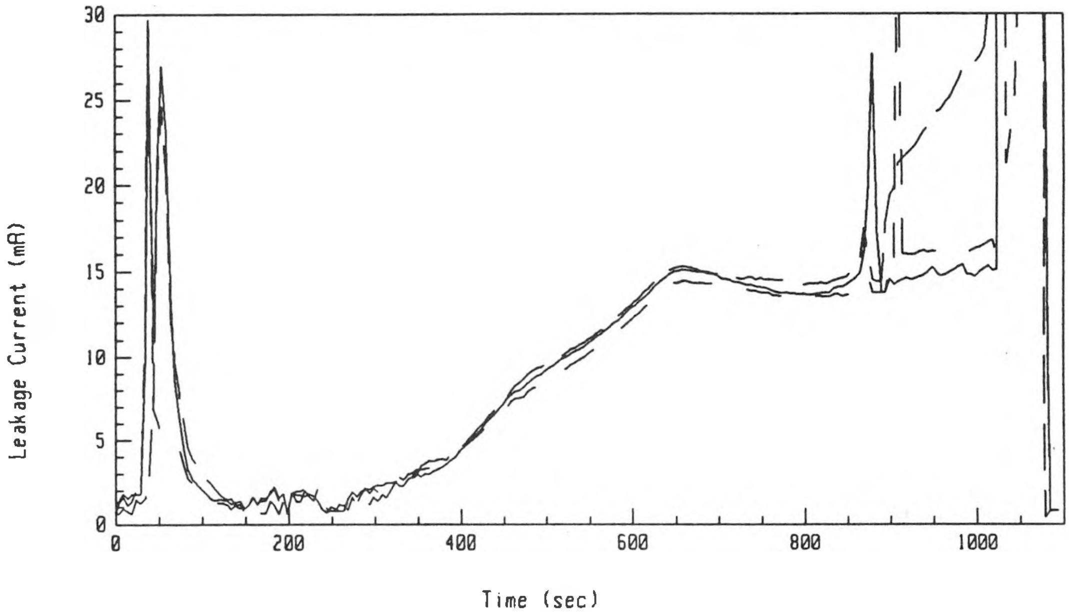


Test 23; Cable 1

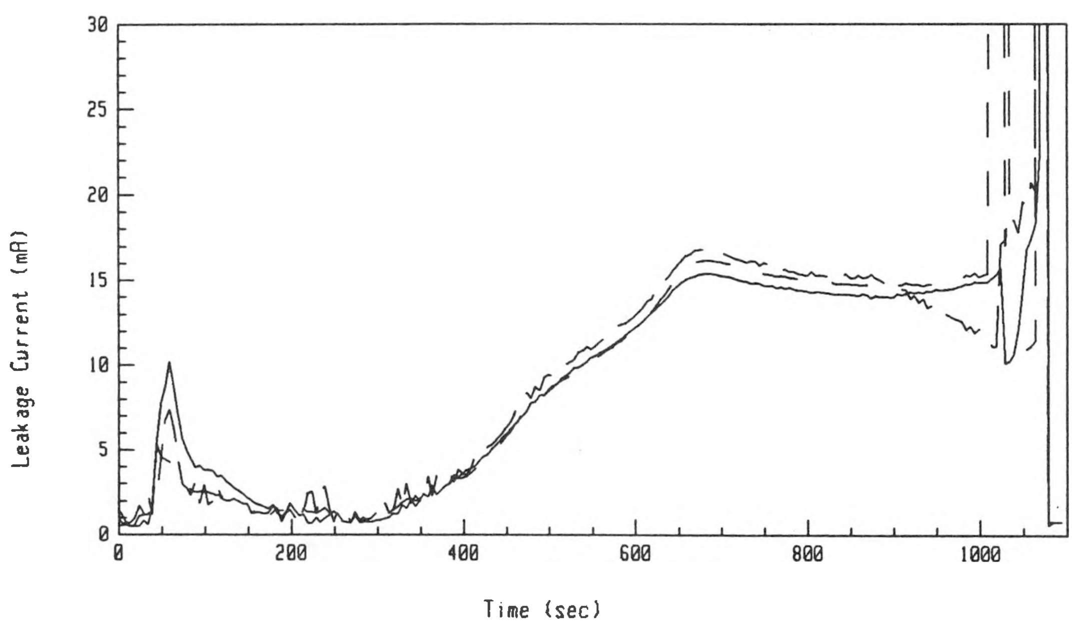


Test 23; Cable 2

Figure A-20: Leakage Current Data For Test 23 Involving an Aged Rockbestos Cable at an Exposure Temperature of 400°C.

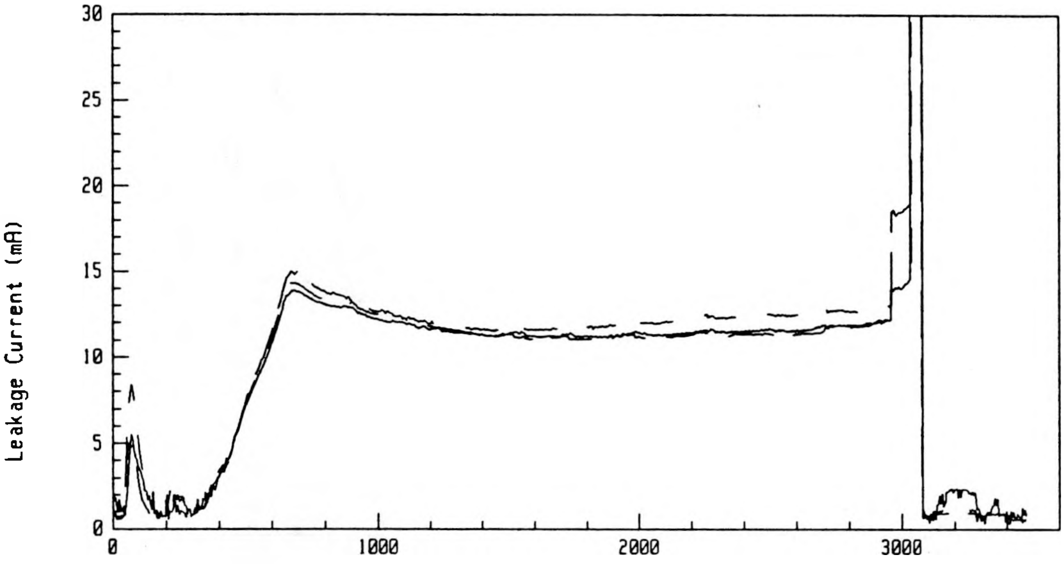


Test 24; Cable 1

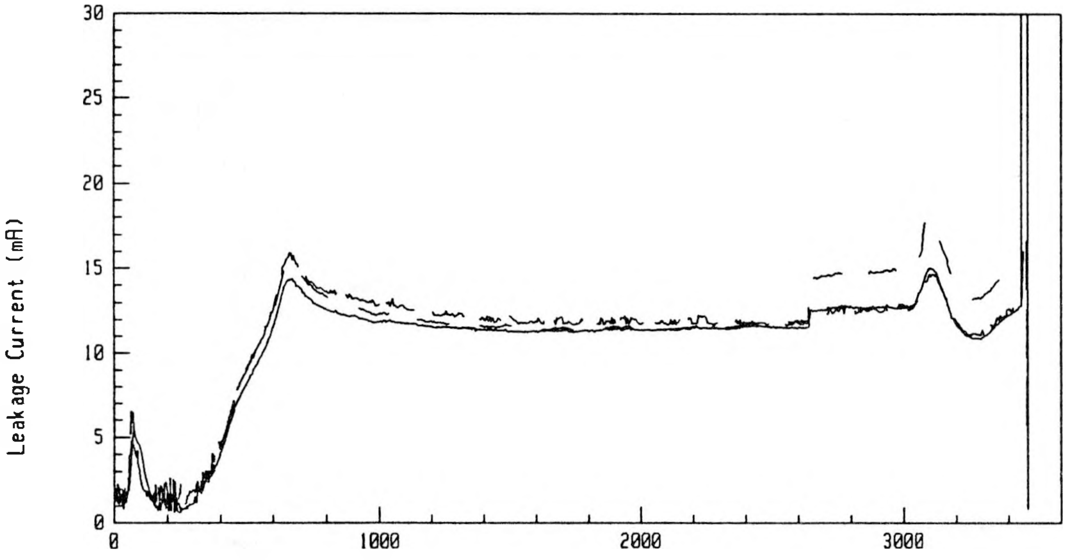


Test 24; Cable 2

Figure A-21: Leakage Current Data For Test 24 Involving an Aged Rockbestos Cable at an Exposure Temperature of 375°C.

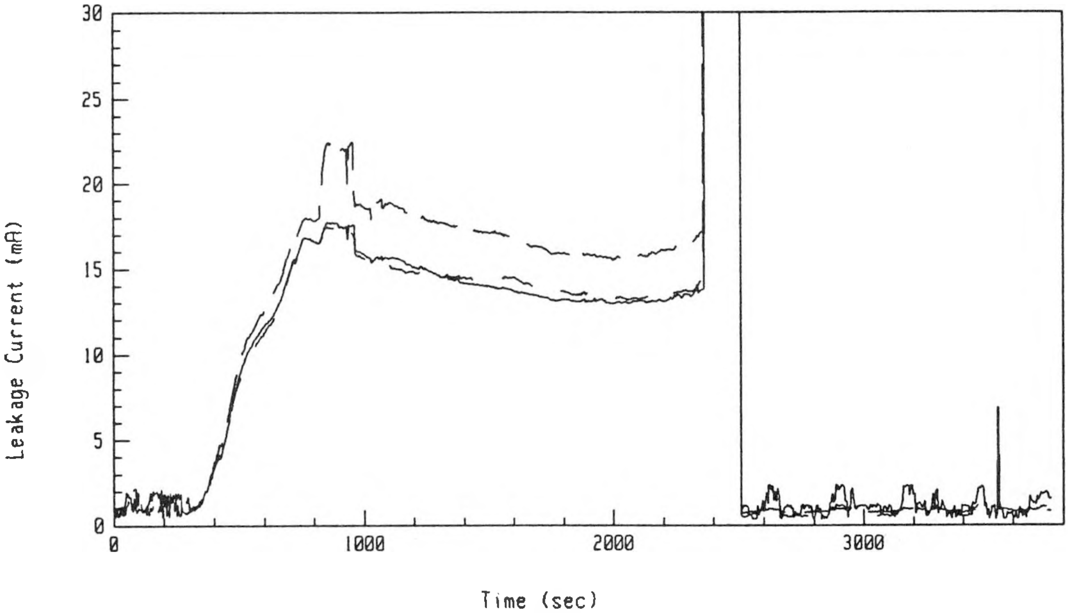


Test 25; Cable 1

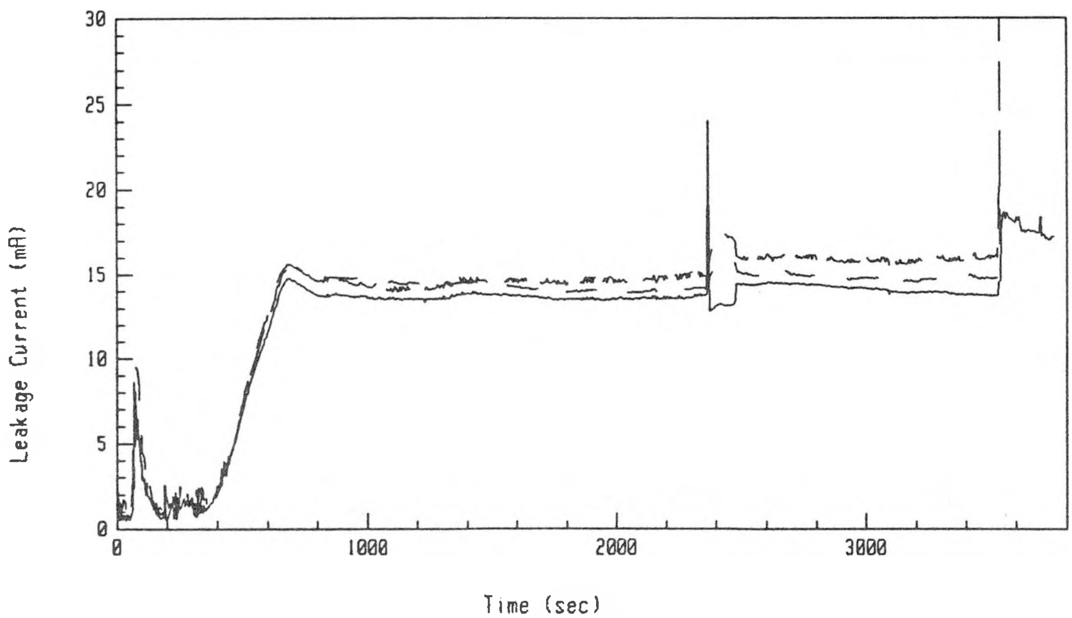


Test 25; Cable 2

Figure A-22: Leakage Current Data For Test 25 Involving an Aged Rockbestos Cable at an Exposure Temperature of 370°C.

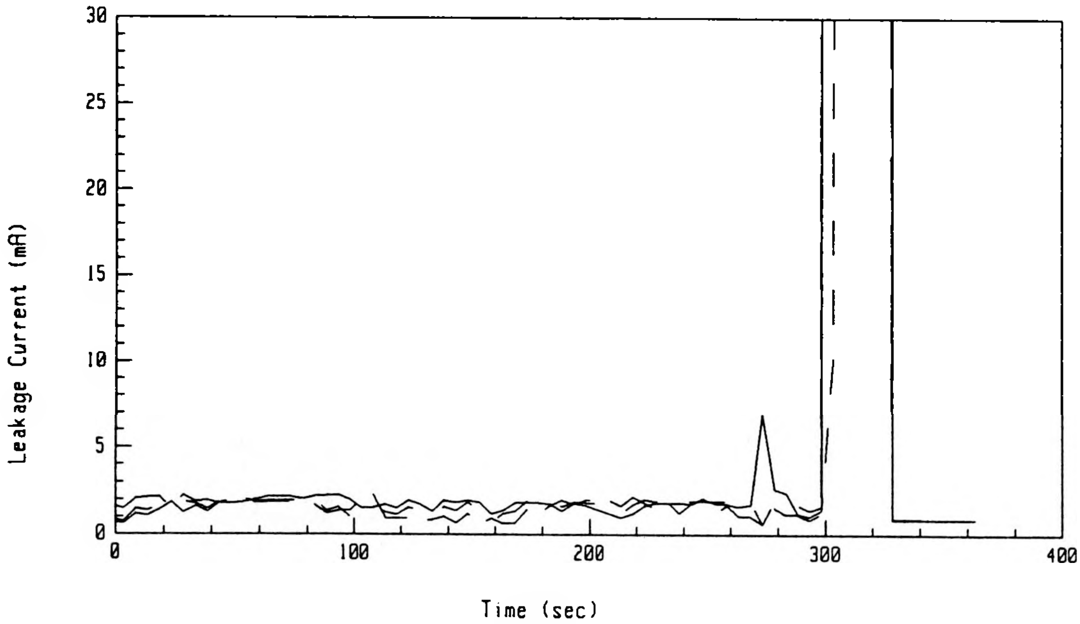


Test 26; Cable 1

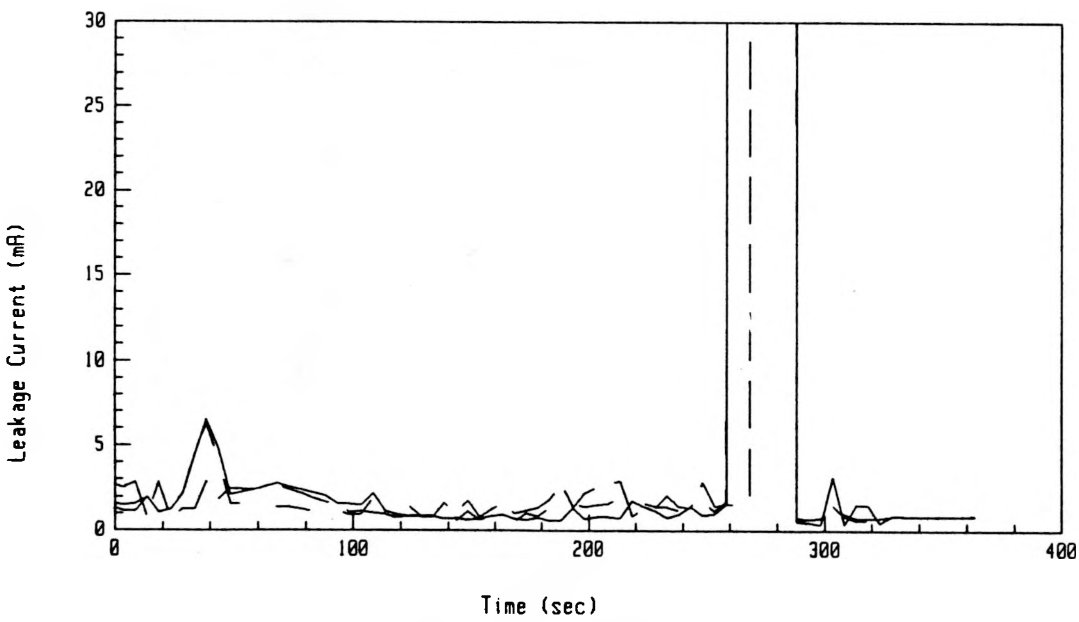


Test 26; Cable 2

Figure A-23: Leakage Current Data For Test 26 Involving an Aged Rockbestos Cable at an Exposure Temperature of 365°C.

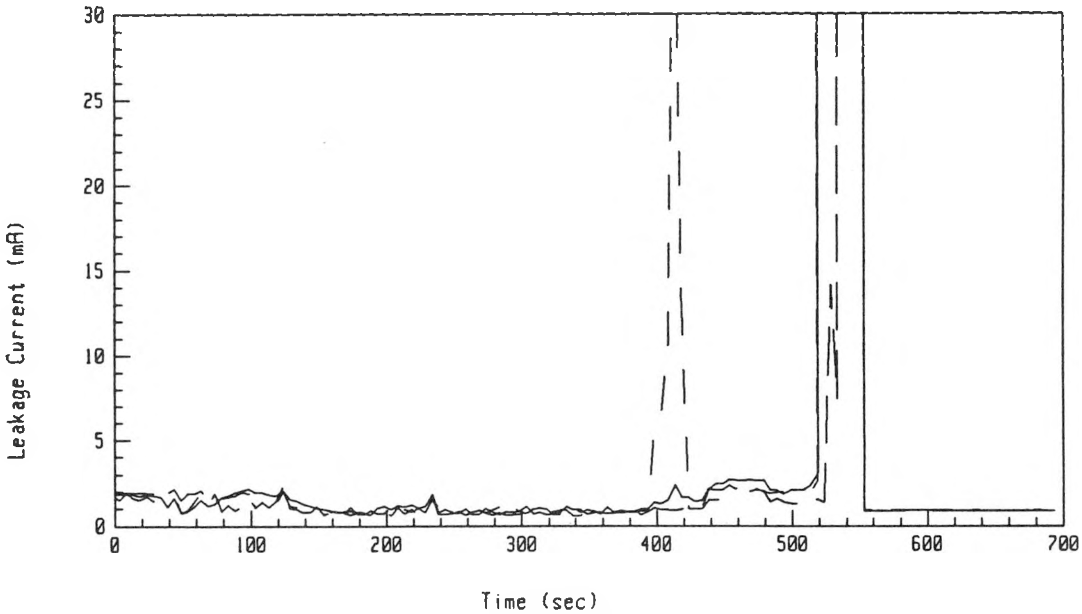


Test 27; Cable 1

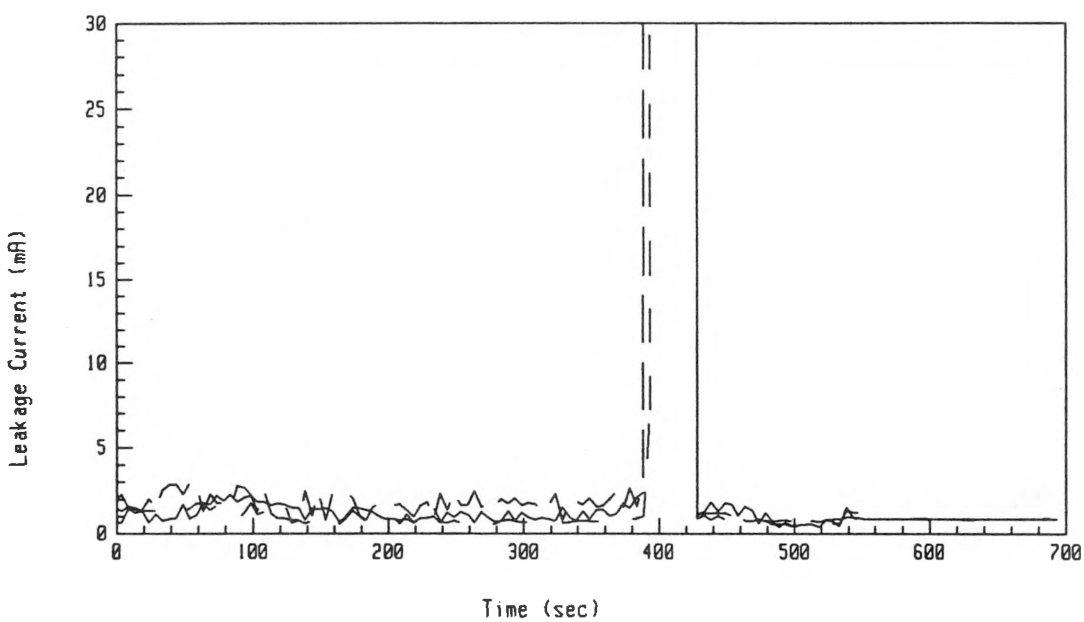


Test 27; Cable 2

Figure A-24: Leakage Current Data For Test 27 Involving an Unaged BIW Cable at an Exposure Temperature of 425°C.

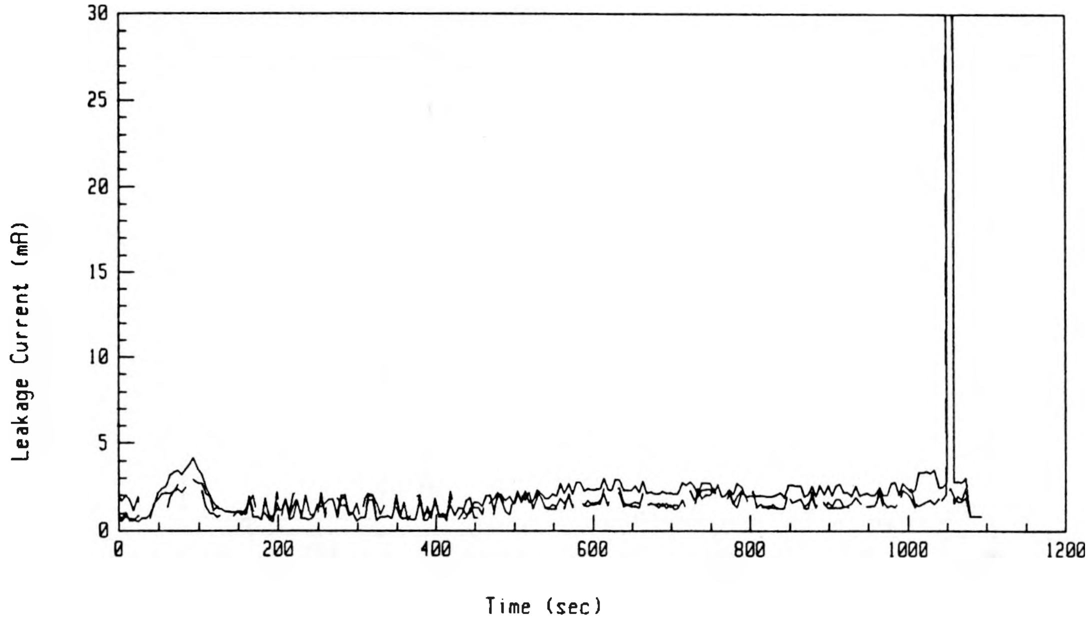


Test 28; Cable 1

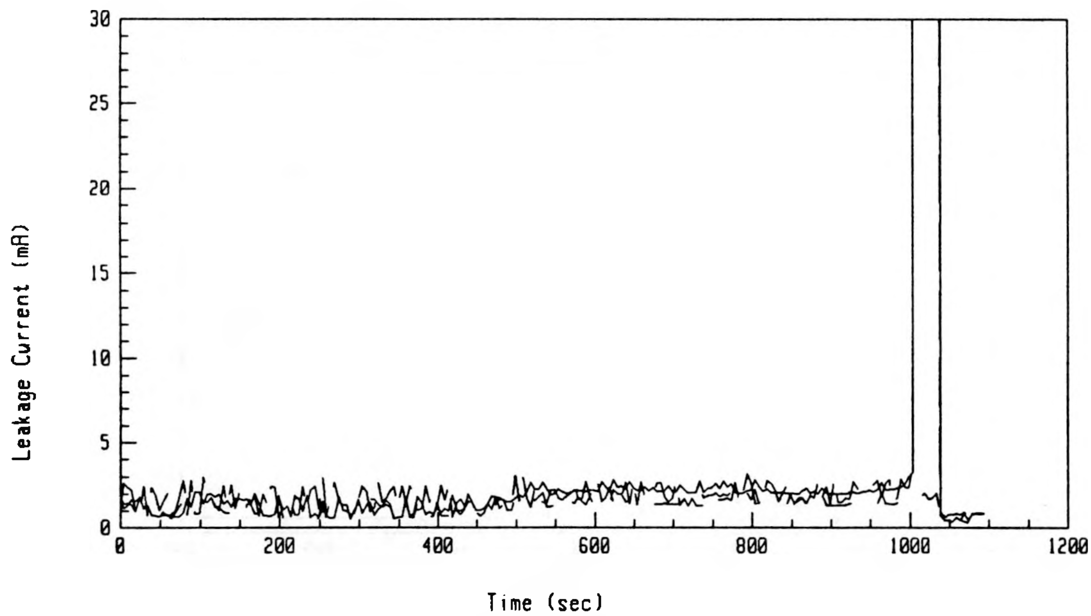


Test 28; Cable 2

Figure A-25: Leakage Current Data For Test 28 Involving an Unaged BIW Cable at an Exposure Temperature of 400°C.

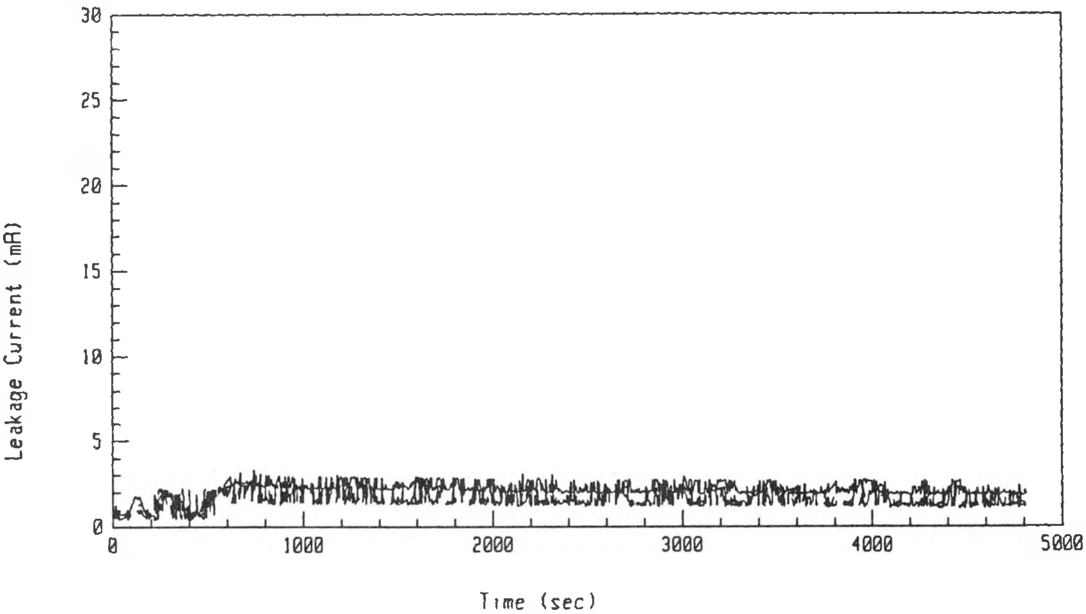


Test 29; Cable 1

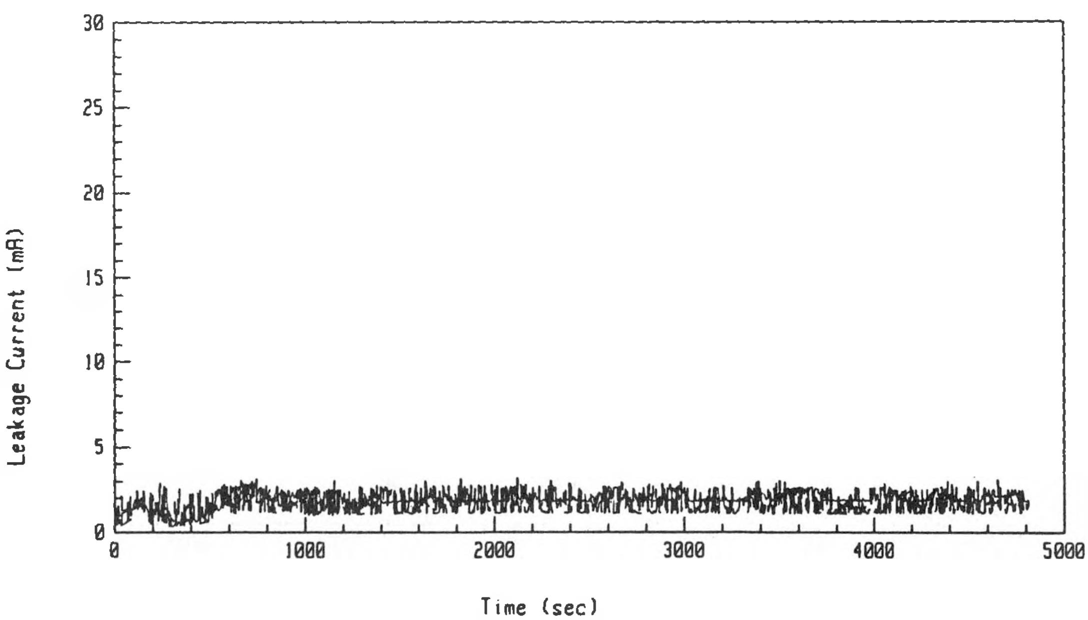


Test 29; Cable 2

Figure A-26: Leakage Current Data For Test 29 Involving an Unaged BIW Cable at an Exposure Temperature of 375°C.

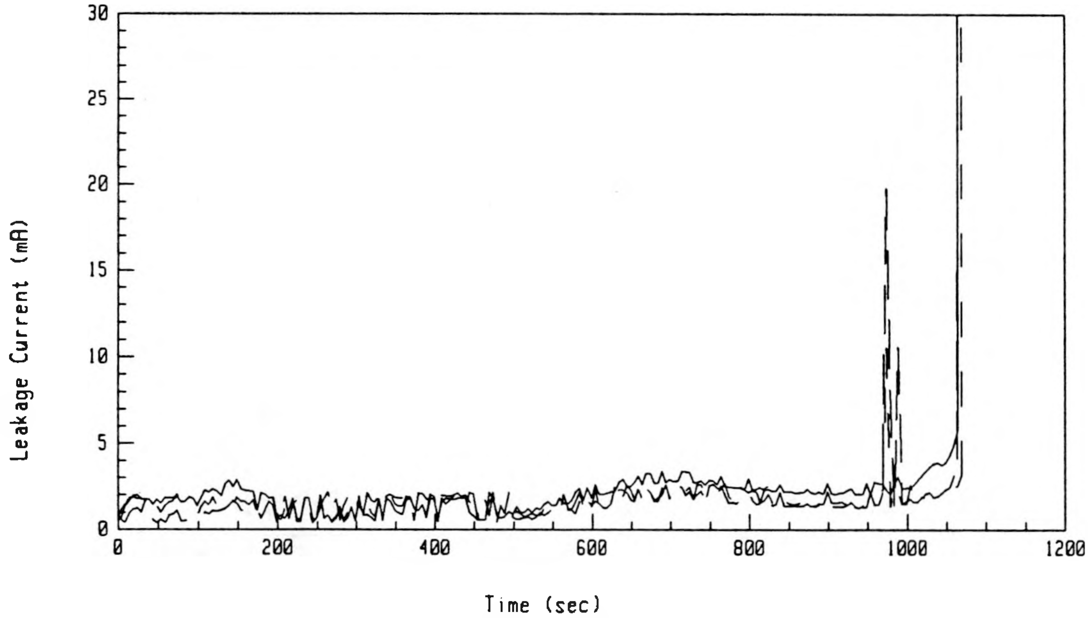


Test 30; Cable 1

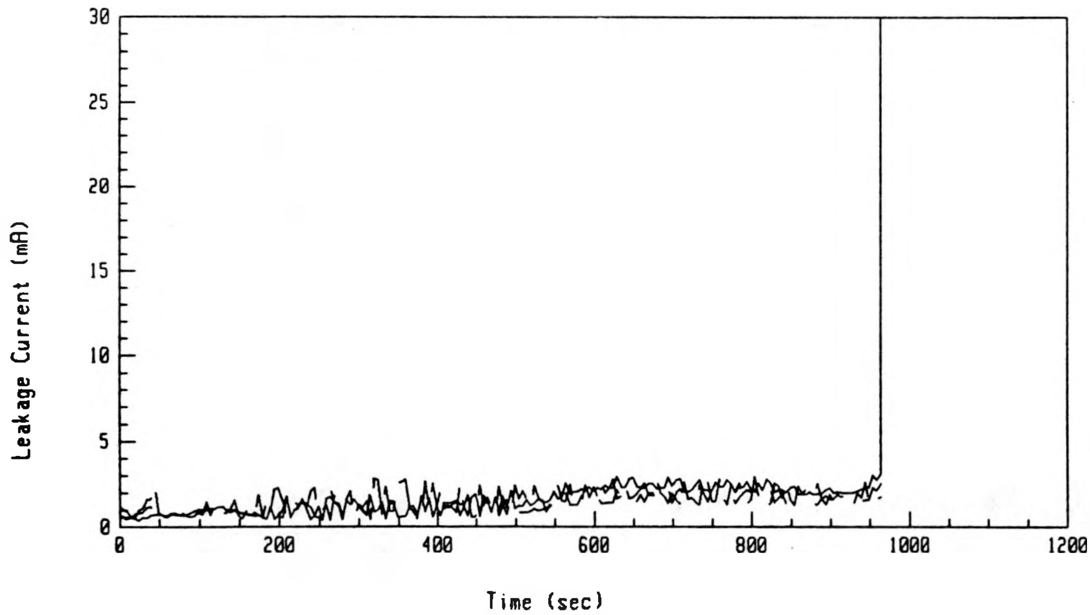


Test 30; Cable 2

Figure A-27: Leakage Current Data For Test 30 Involving an Unaged BIW Cable at an Exposure Temperature of 365°C.

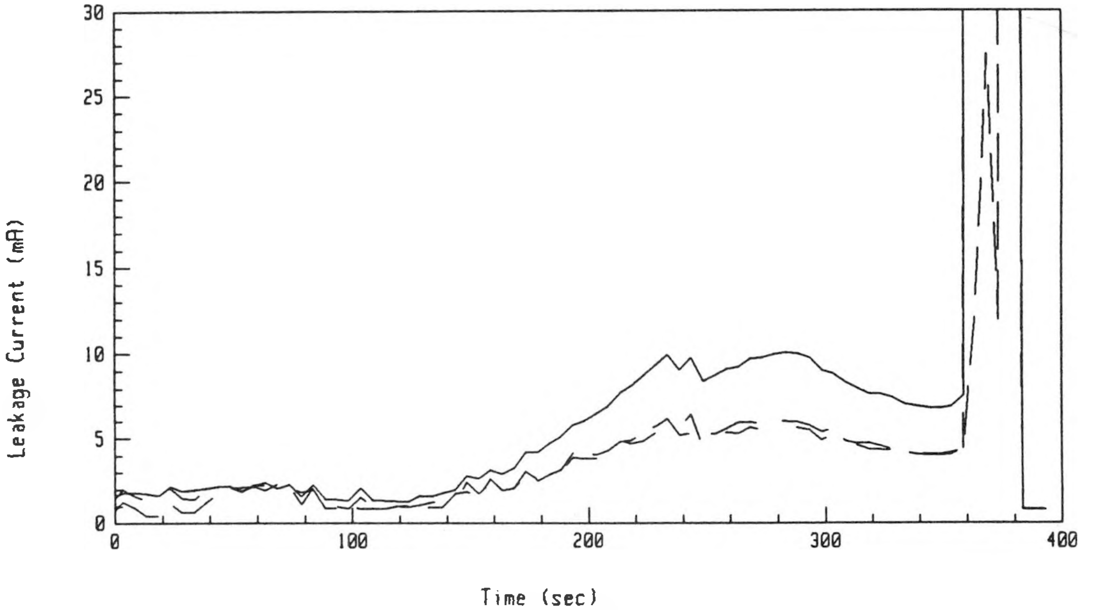


Test 31; Cable 1

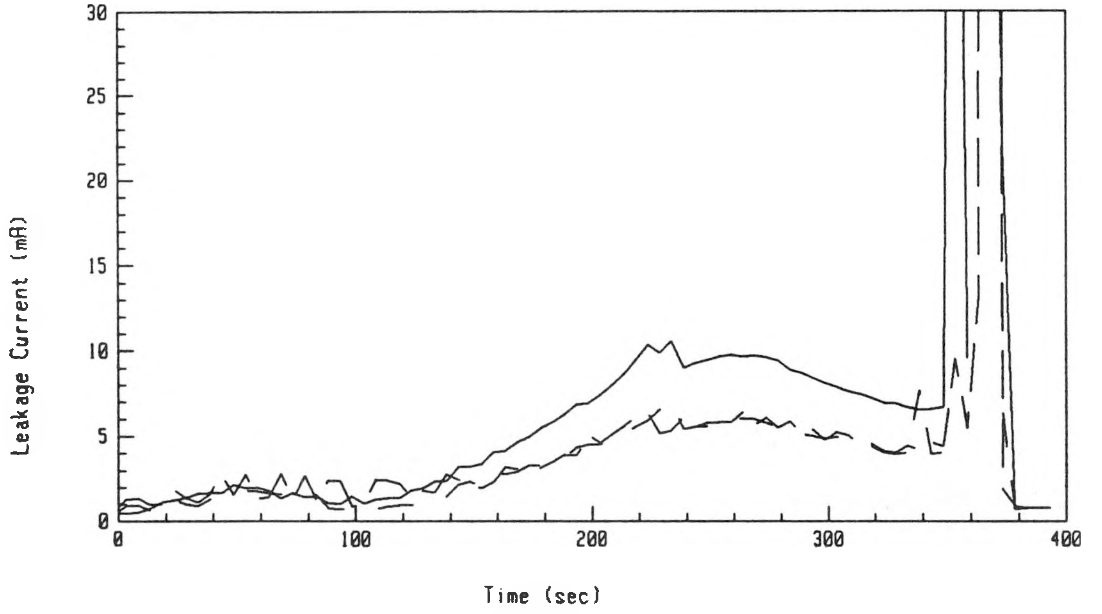


Test 31; Cable 2

Figure A-28: Leakage Current Data For Test 31 Involving an Unaged BIW Cable at an Exposure Temperature of 370°C.

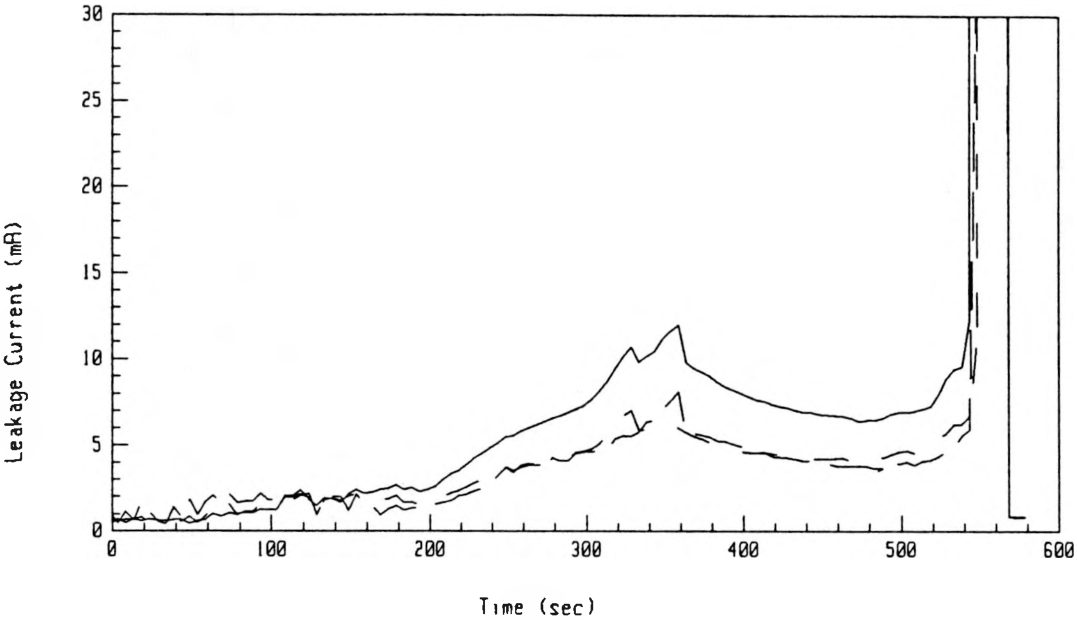


Test 32; Cable 1

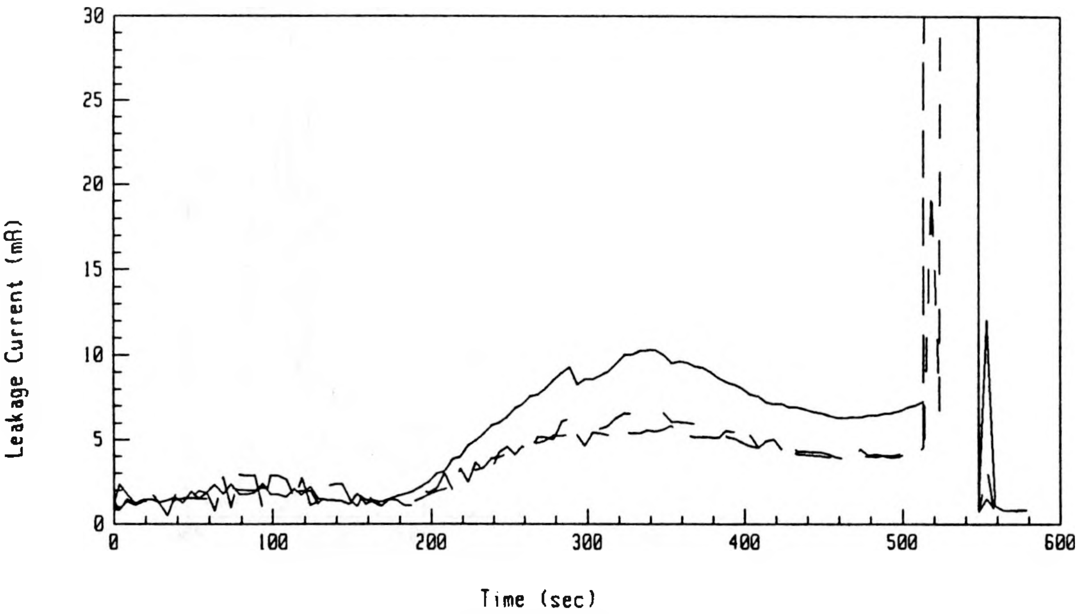


Test 32; Cable 2

Figure A-29: Leakage Current Data For Test 32 Involving an Aged BIW Cable at an Exposure Temperature of 425°C.

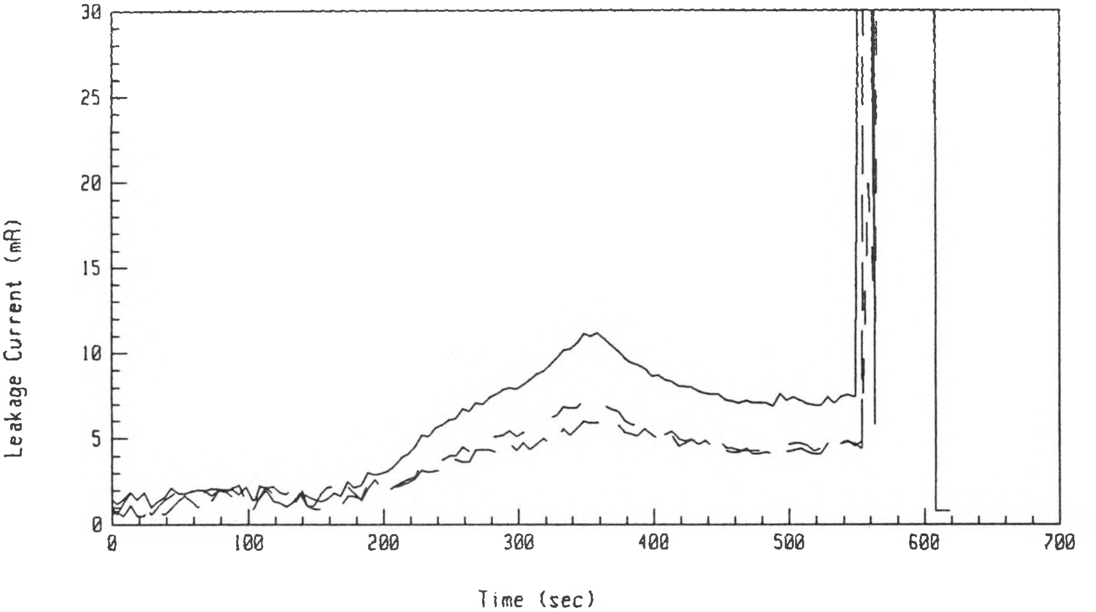


Test 33; Cable 1

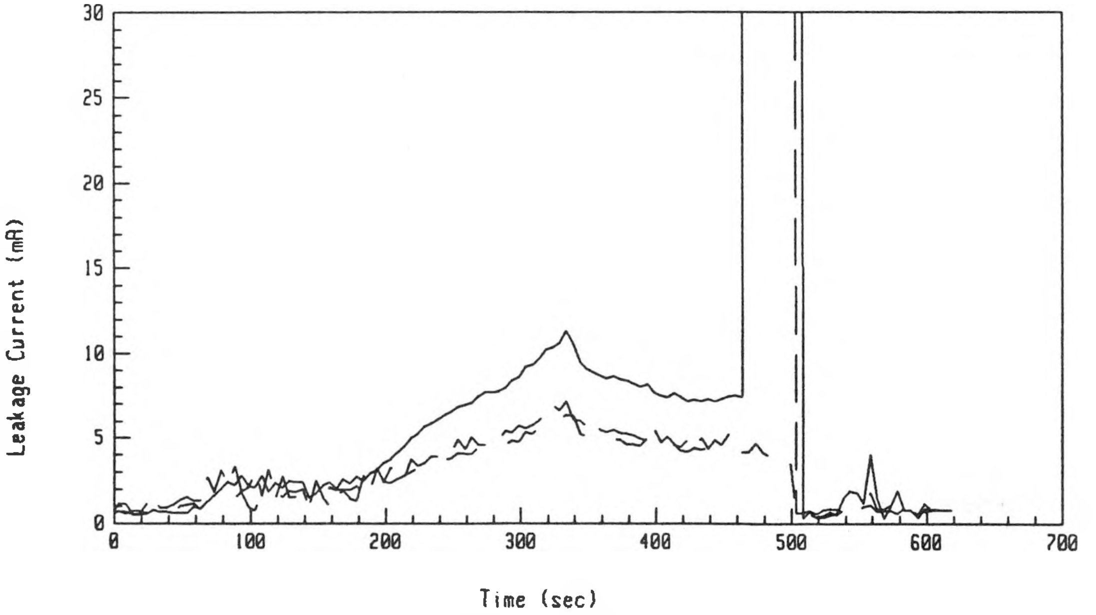


Test 33; Cable 2

Figure A-30: Leakage Current Data For Test 33 Involving an Aged BIW Cable at an Exposure Temperature of 400°C.

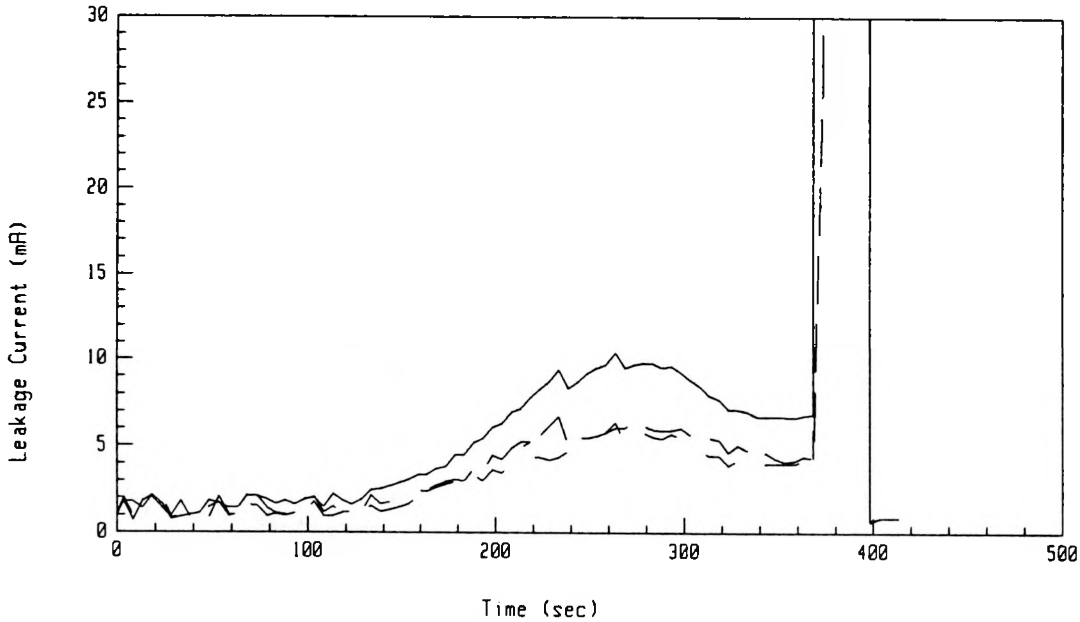


Test 34; Cable 1

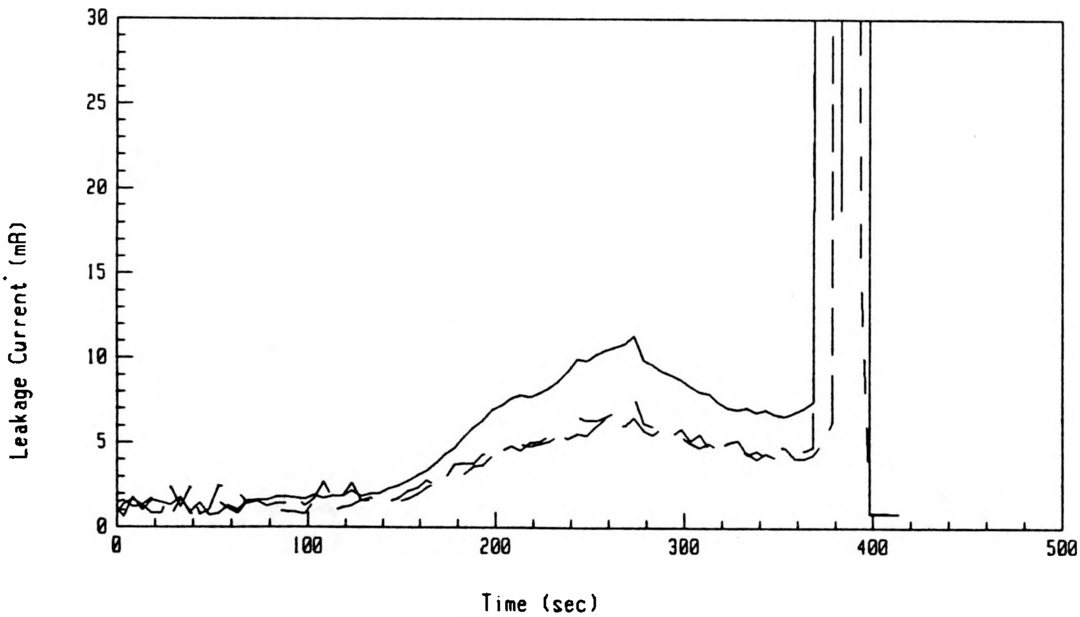


Test 34; Cable 2

Figure A-31: Leakage Current Data For Test 34 Involving an Aged BIW Cable at an Exposure Temperature of 400°C.

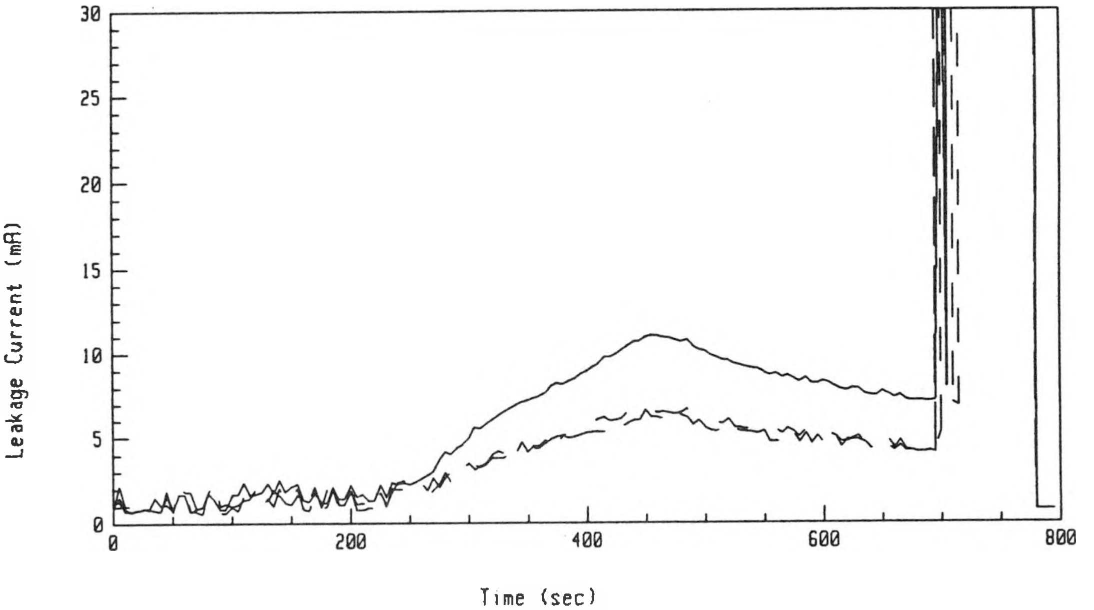


Test 35; Cable 1

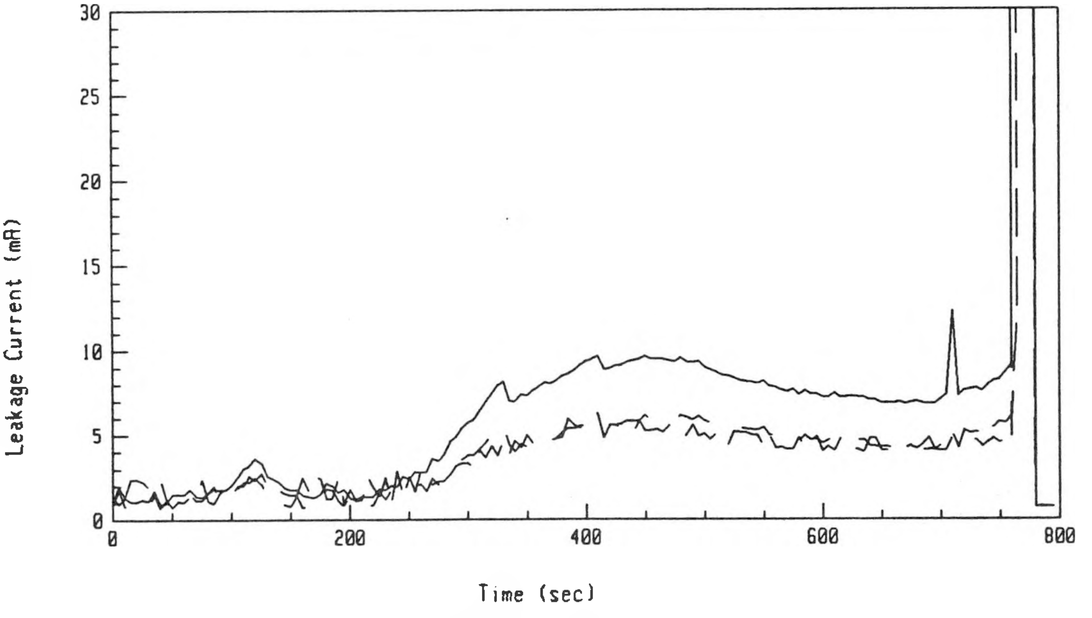


Test 35; Cable 2

Figure A-32: Leakage Current Data For Test 35 Involving an Aged BIW Cable at an Exposure Temperature of 425°C.

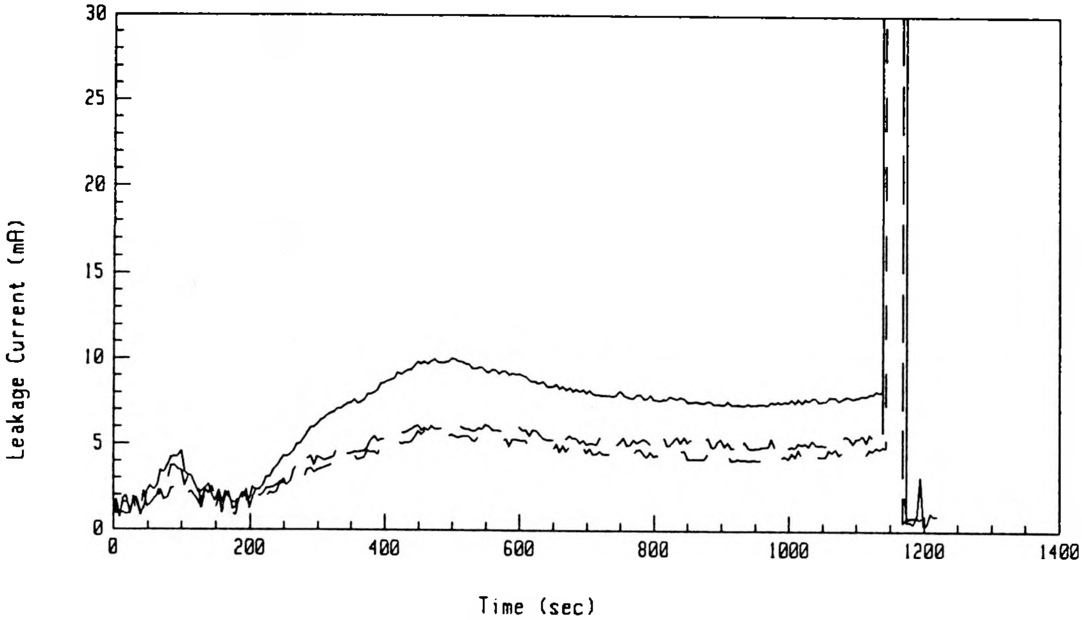


Test 36; Cable 1

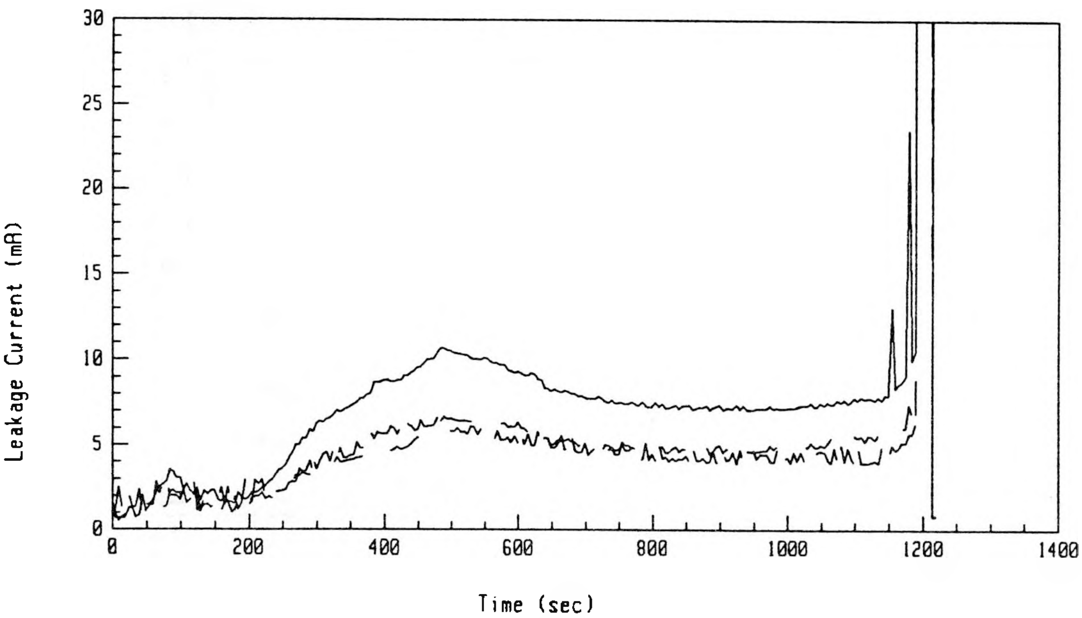


Test 36; Cable 2

Figure A-33: Leakage Current Data For Test 36 Involving an Aged BIW Cable at an Exposure Temperature of 375°C.

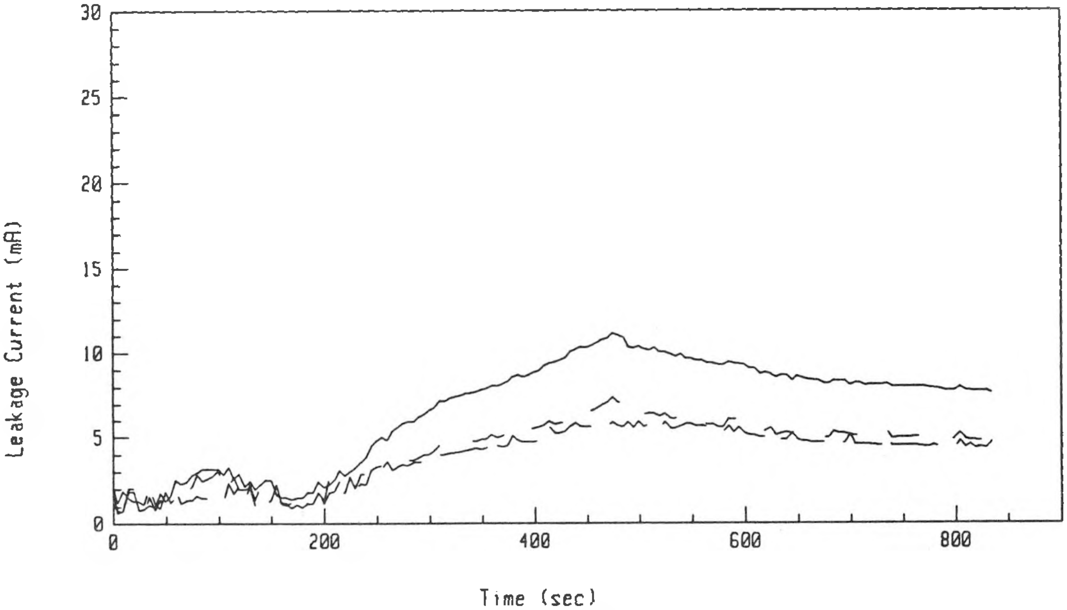


Test 37; Cable 1

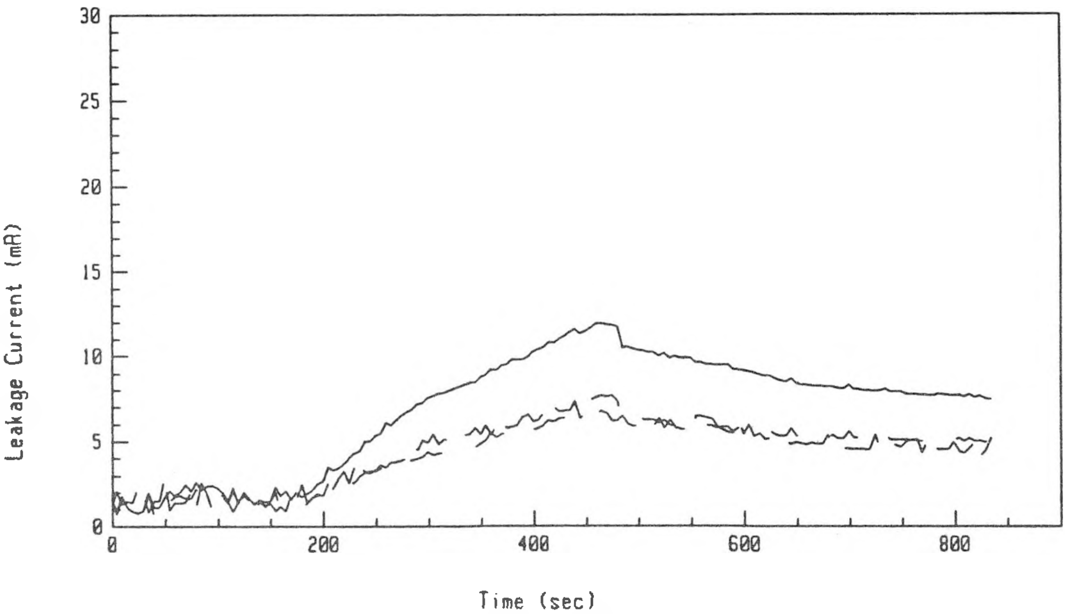


Test 37; Cable 2

Figure A-34: Leakage Current Data For Test 37 Involving an Aged BIW Cable at an Exposure Temperature of 365°C.

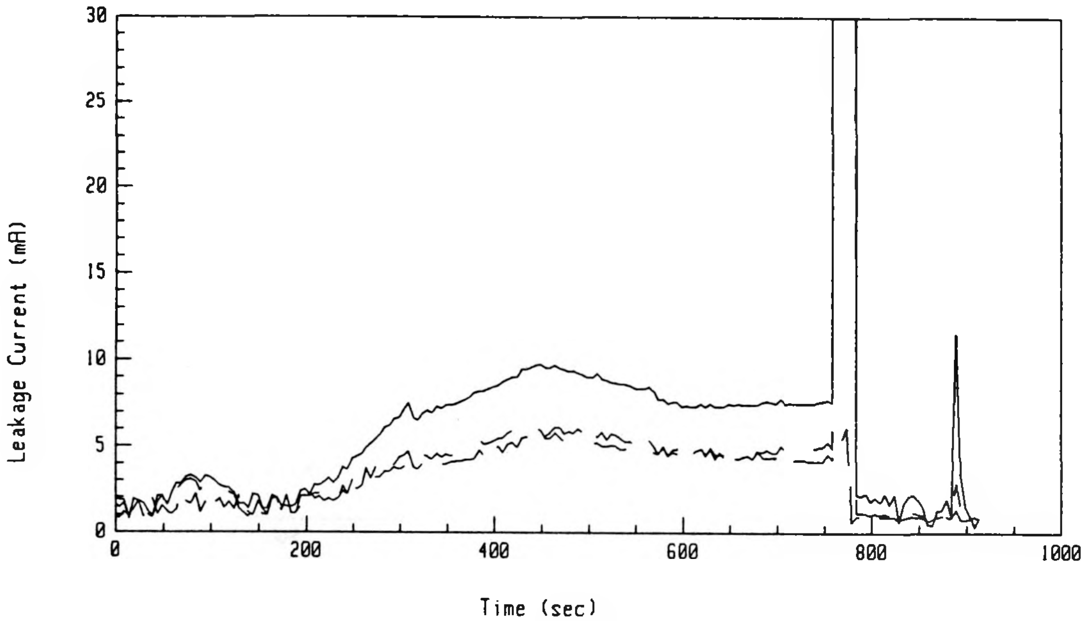


Test 38; Cable 1

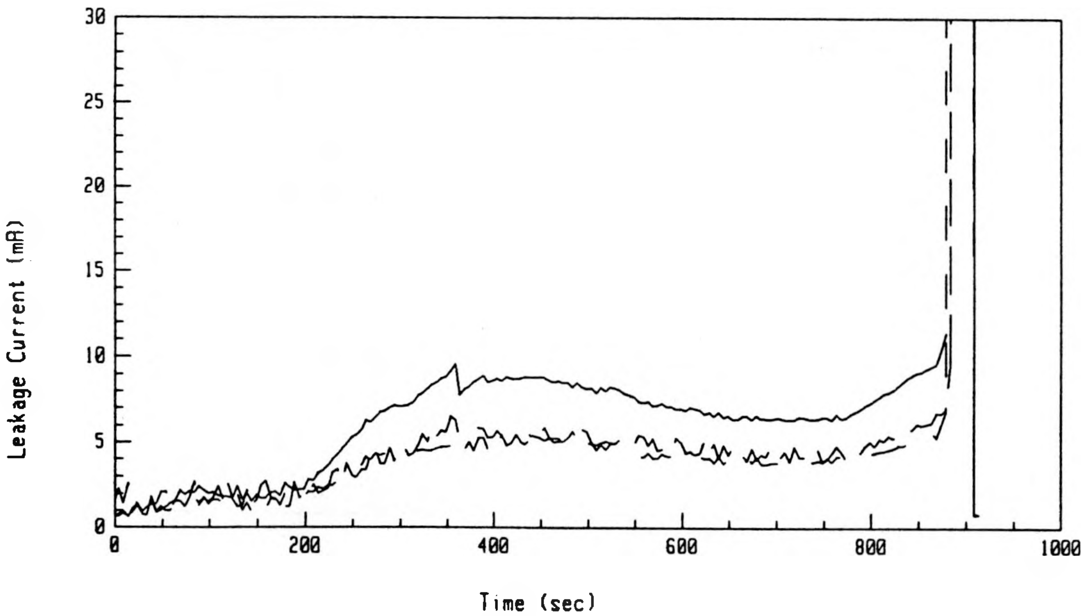


Test 38; Cable 2

Figure A-35: Leakage Current Data For Test 38 Involving an Aged BIW Cable at an Exposure Temperature of 365°C. Note that a failure in the data logging system occurred prior to the observed cable failures.

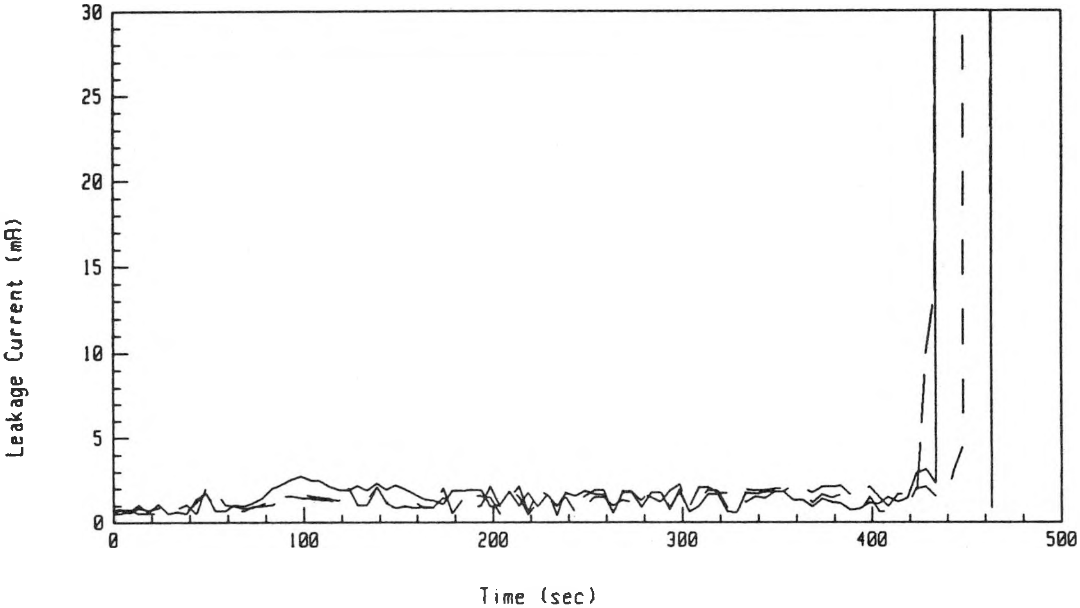


Test 39; Cable 1

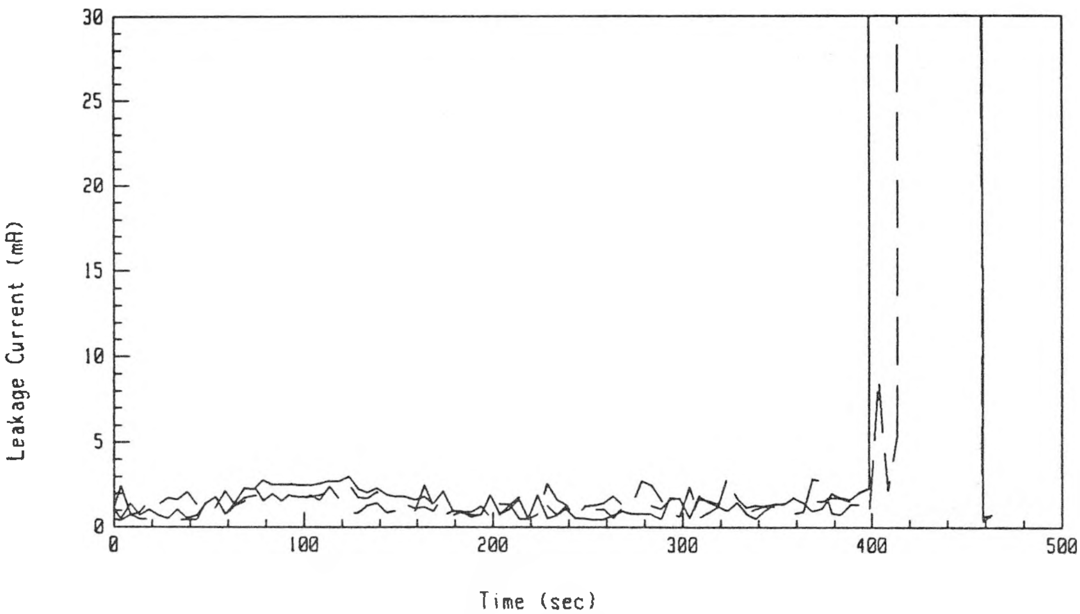


Test 39; Cable 2

Figure A-36: Leakage Current Data For Test 39 Involving an Aged BIW Cable at an Exposure Temperature of 375°C.

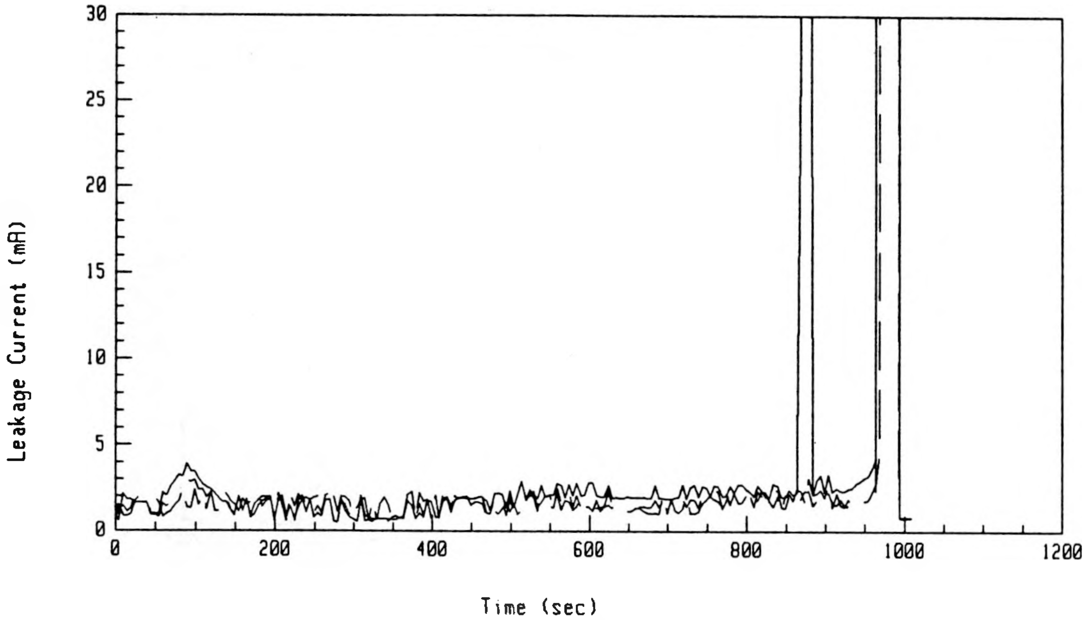


Test 40; Cable 1

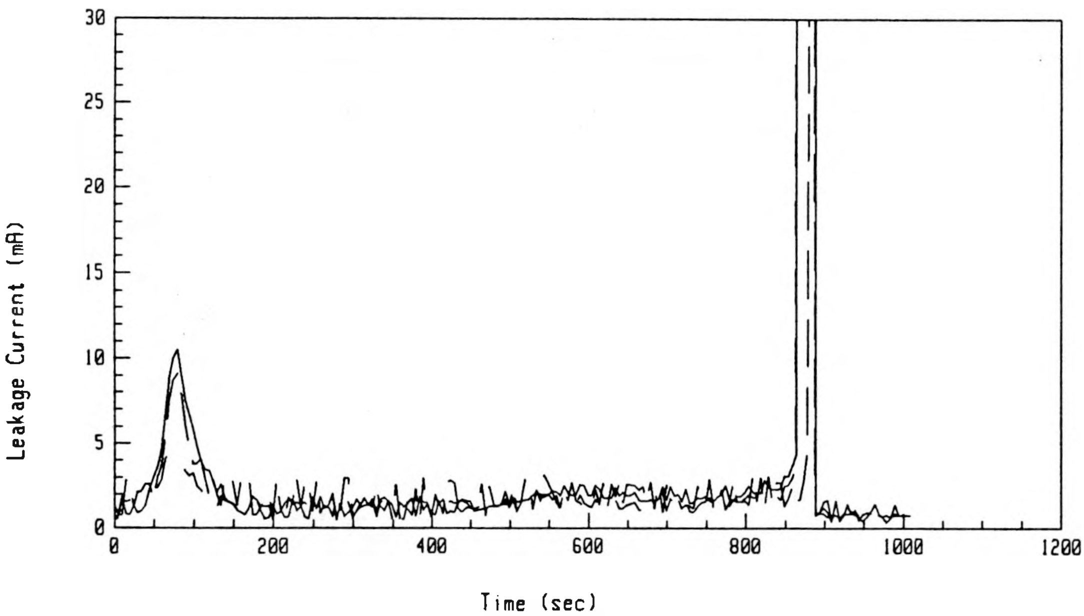


Test 40; Cable 2

Figure A-37: Leakage Current Data For Test 40 Involving an Unaged BIW Cable at an Exposure Temperature of 400°C.

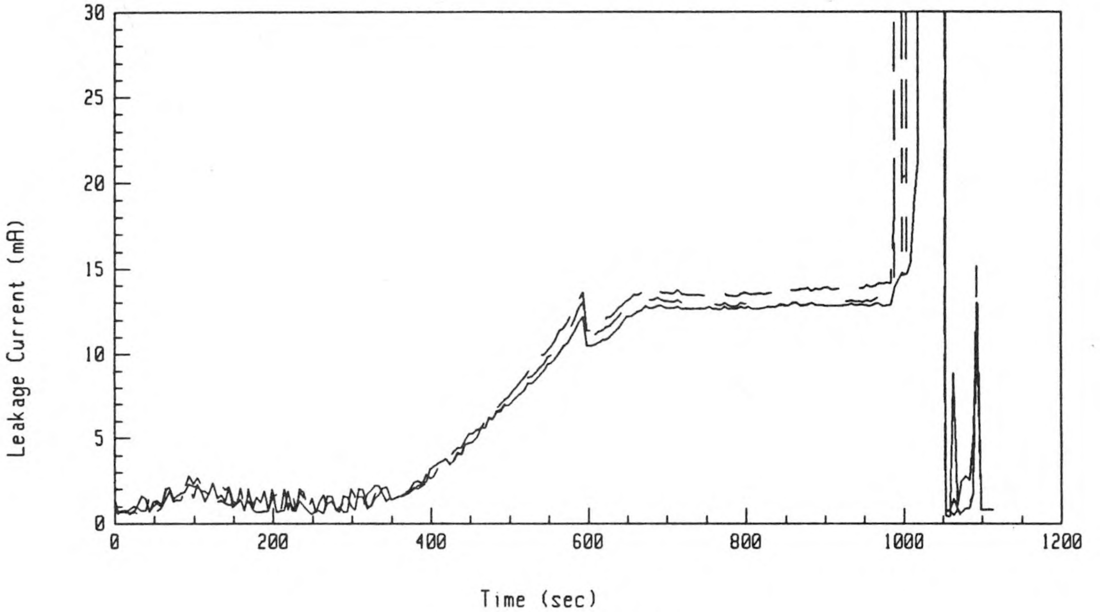


Test 41; Cable 1

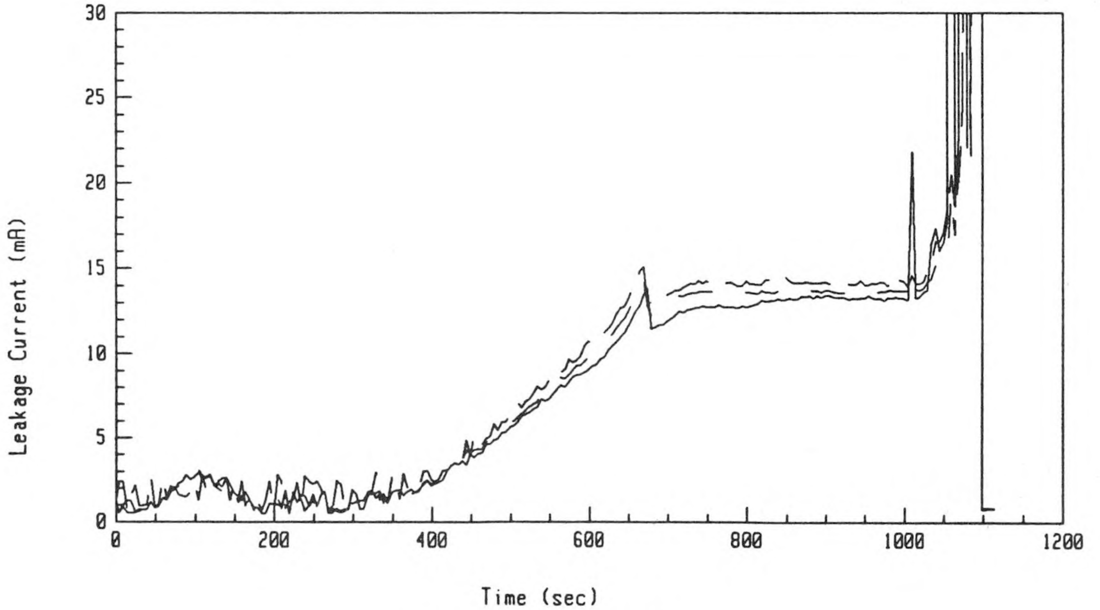


Test 41; Cable 2

Figure A-38: Leakage Current Data For Test 41 Involving an Unaged BIW Cable at an Exposure Temperature of 375°C.

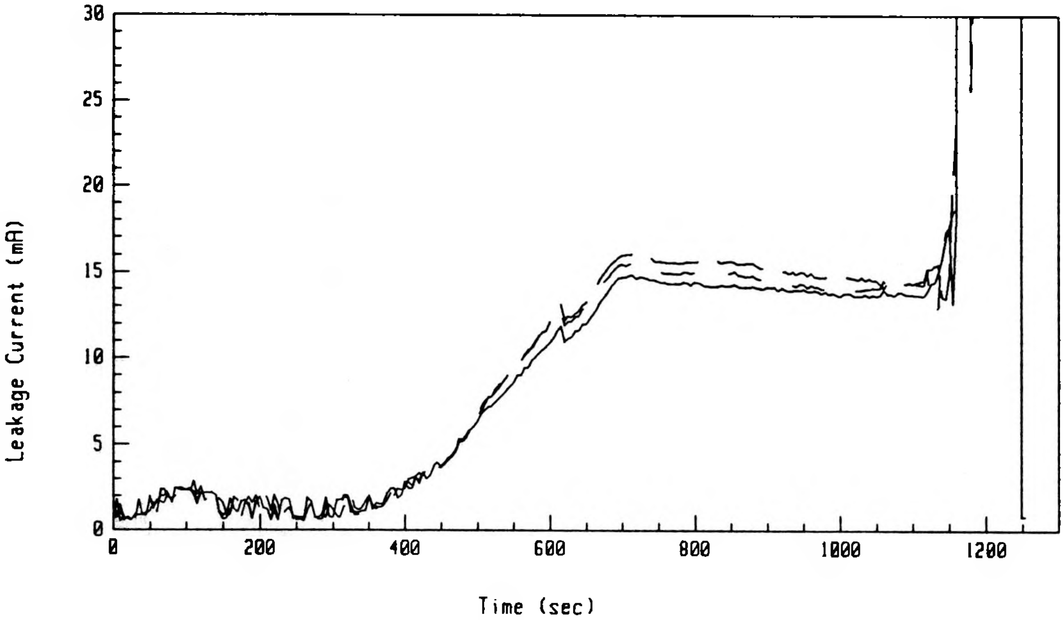


Test 42; Cable 1

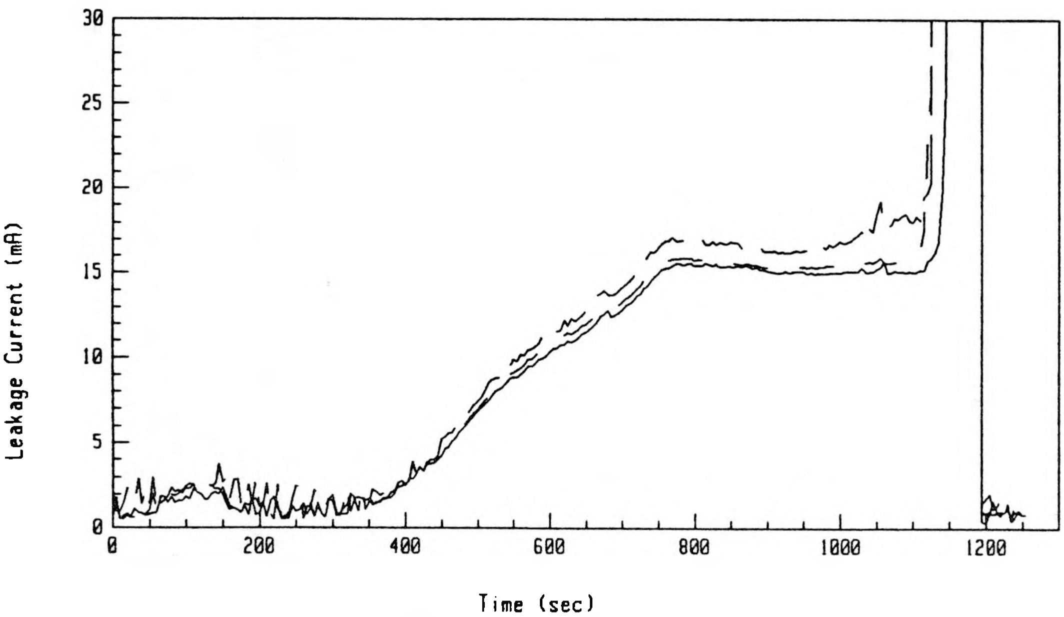


Test 42; Cable 2

Figure A-39: Leakage Current Data For Test 42 Involving an Aged Rockbestos Cable at an Exposure Temperature of 370°C.

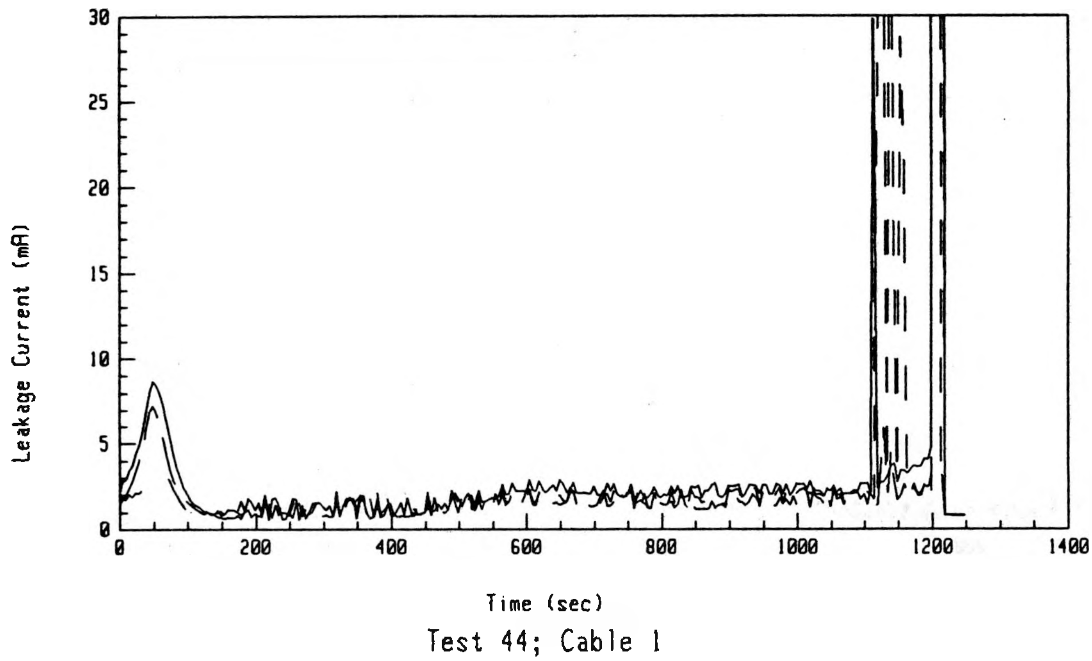


Test 43; Cable 1



Test 43; Cable 2

Figure A-40: Leakage Current Data For Test 43 Involving an Aged Rockbestos Cable at an Exposure Temperature of 365°C.



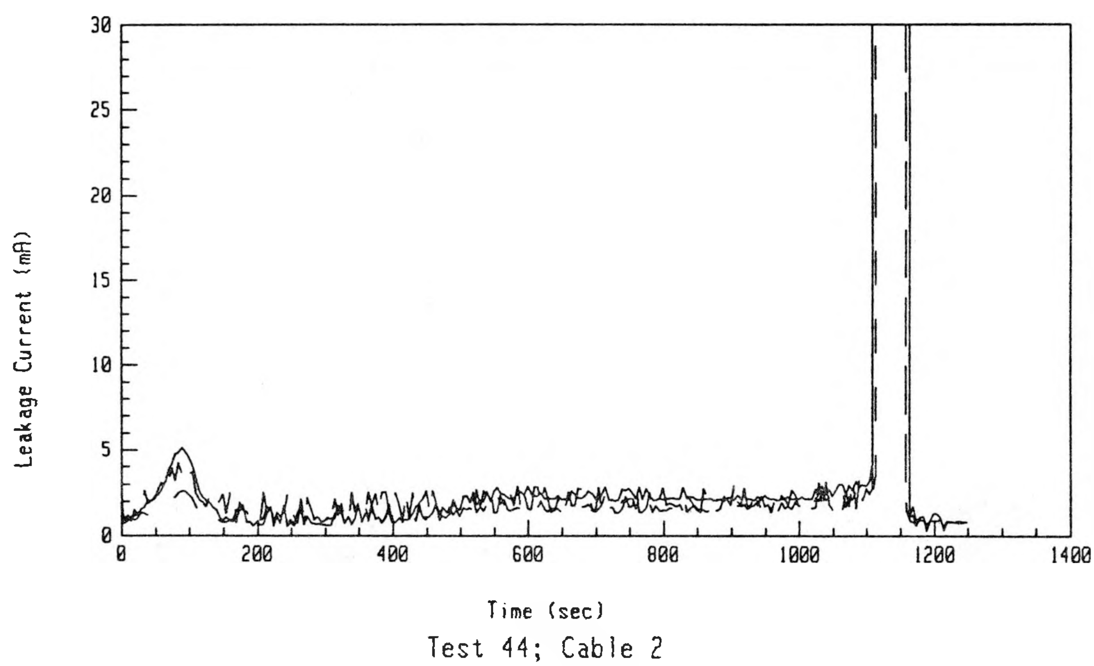
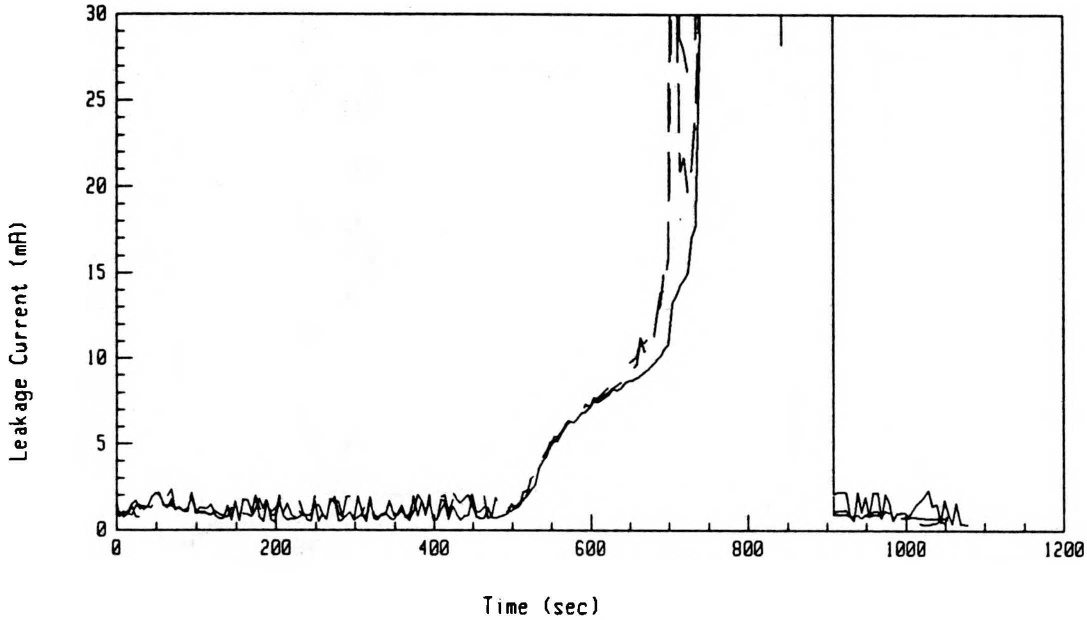
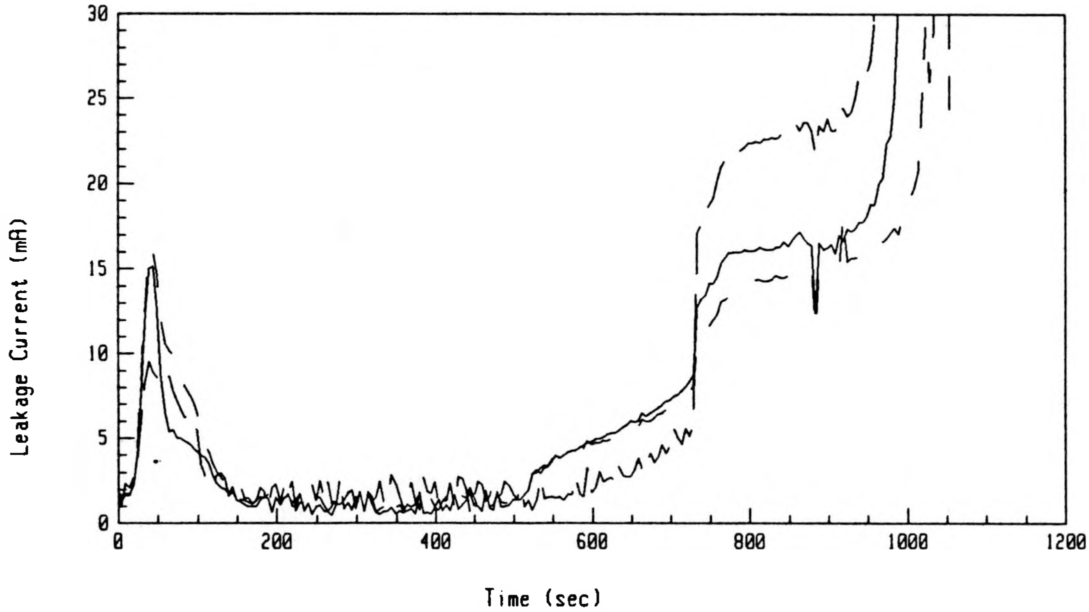


Figure A-41: Leakage Current Data For Test 44 Involving an Unaged BIW Cable at an Exposure Temperature of 370°C.

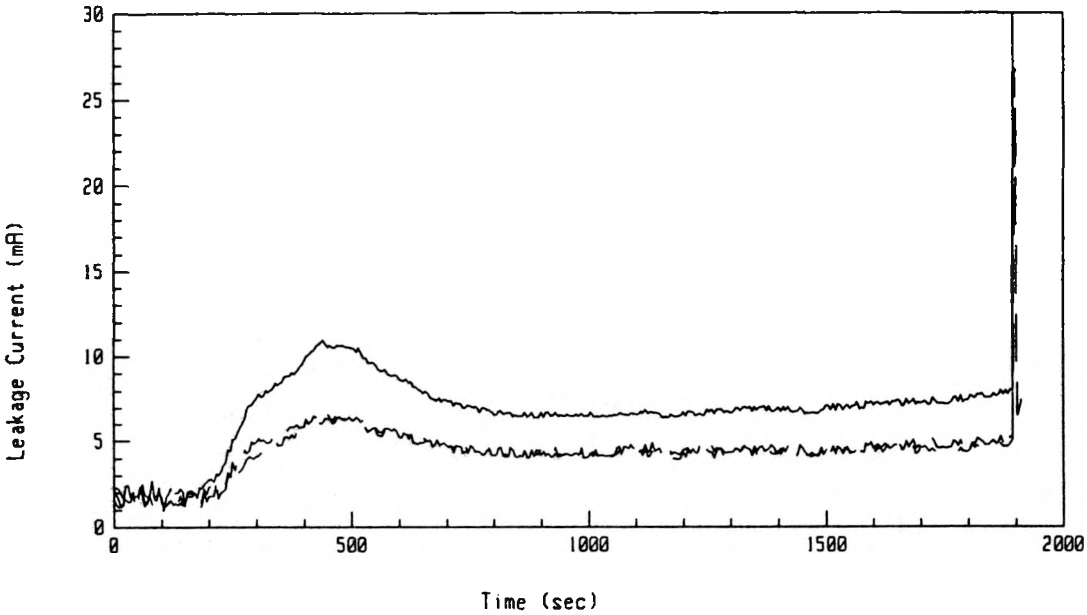


Test 45; Cable 1

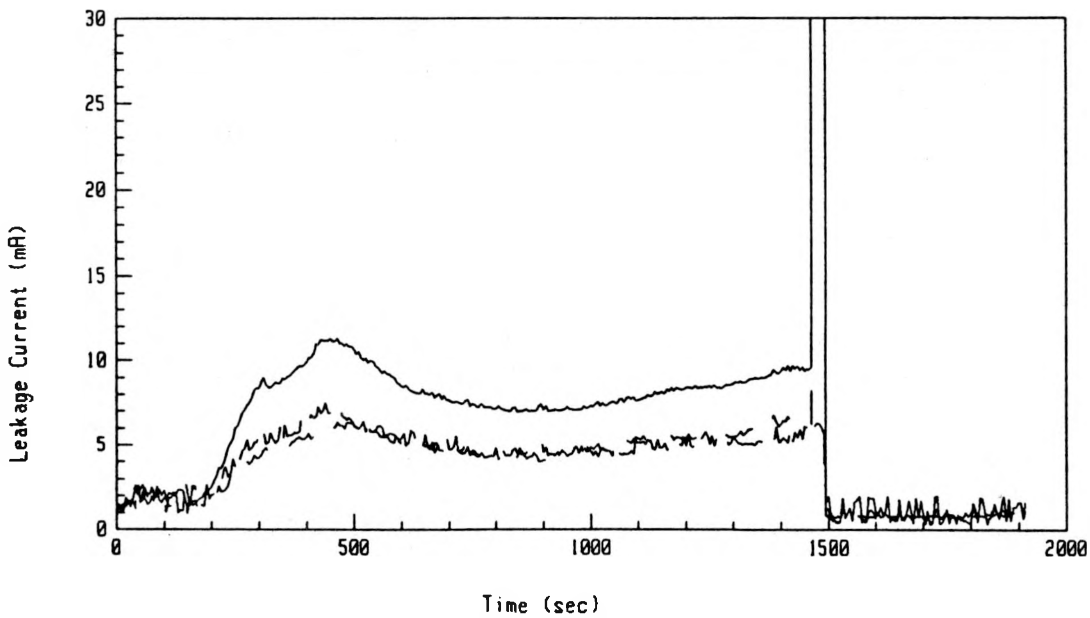


Test 45; Cable 2

Figure A-42: Leakage Current Data For Test 45 Involving an Unaged Rockbestos Cable at an Exposure Temperature of 330°C.

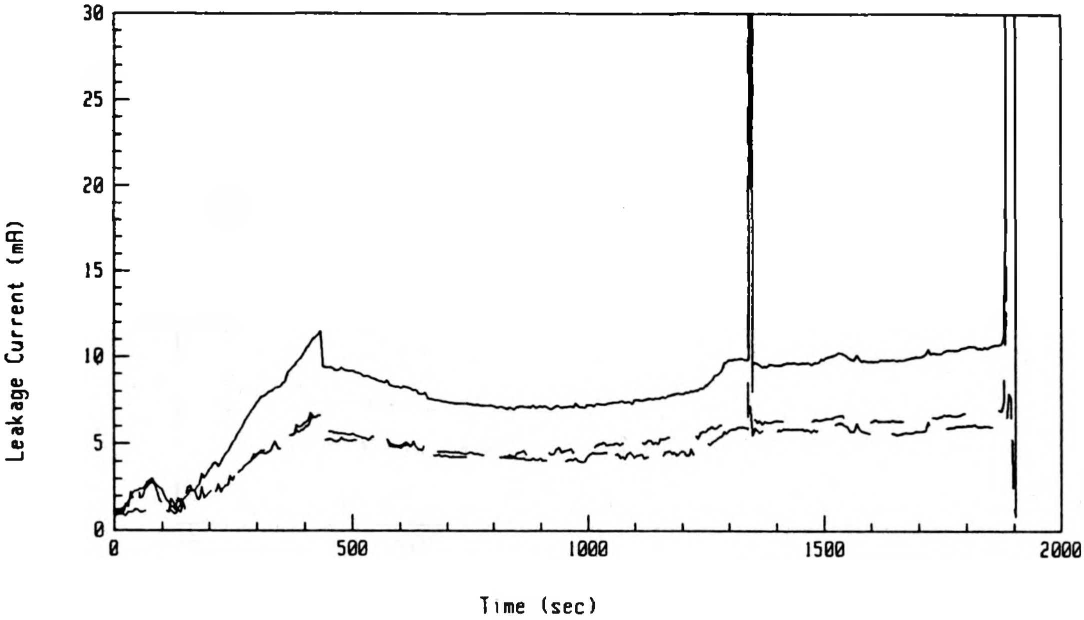


Test 46; Cable 1

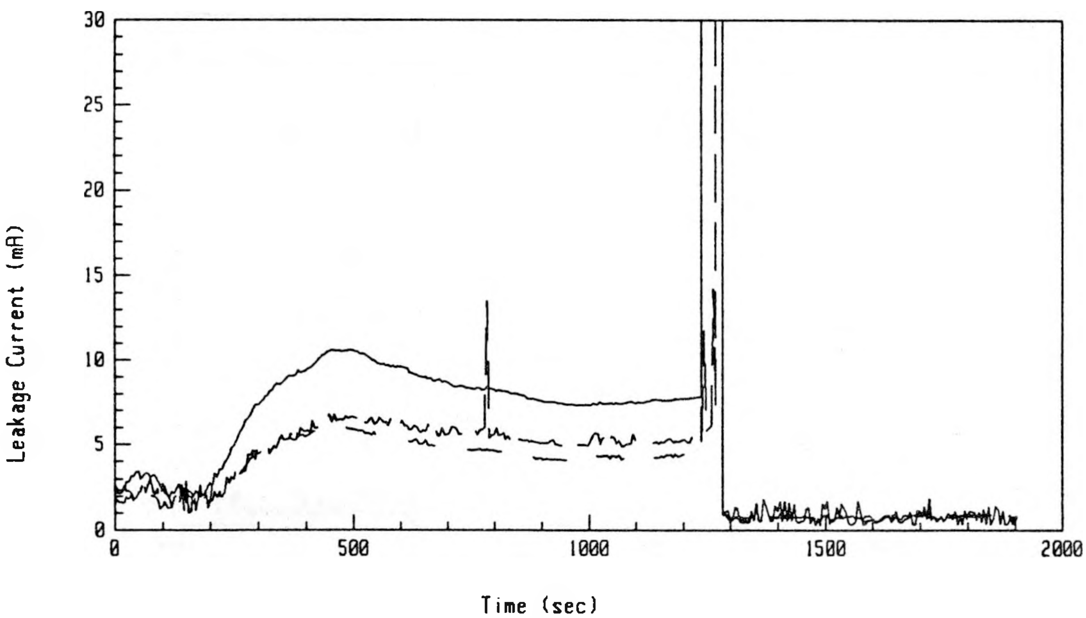


Test 46; Cable 2

Figure A-43: Leakage Current Data For Test 46 Involving an Aged BIW Cable at an Exposure Temperature of 360°C.

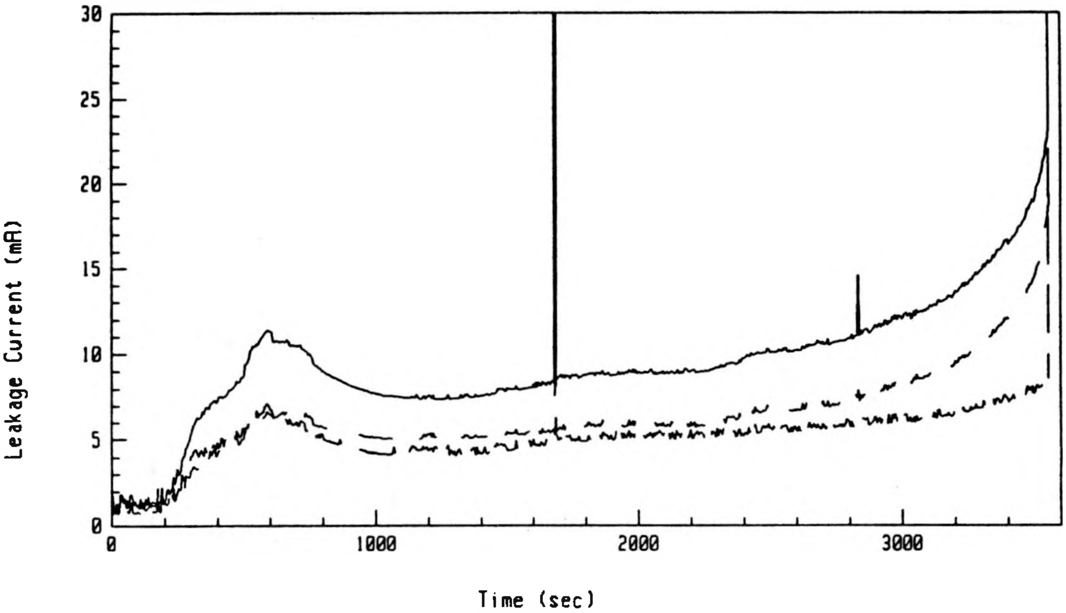


Test 47; Cable 1

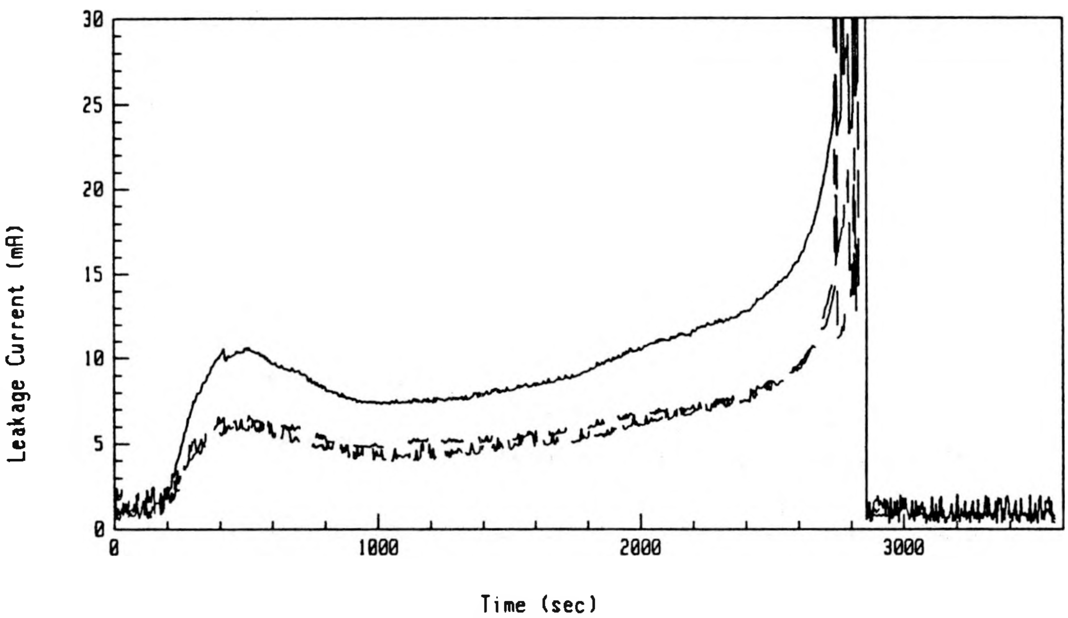


Test 47; Cable 2

Figure A-44: Leakage Current Data For Test 47 Involving an Aged BIW Cable at an Exposure Temperature of 355°C.

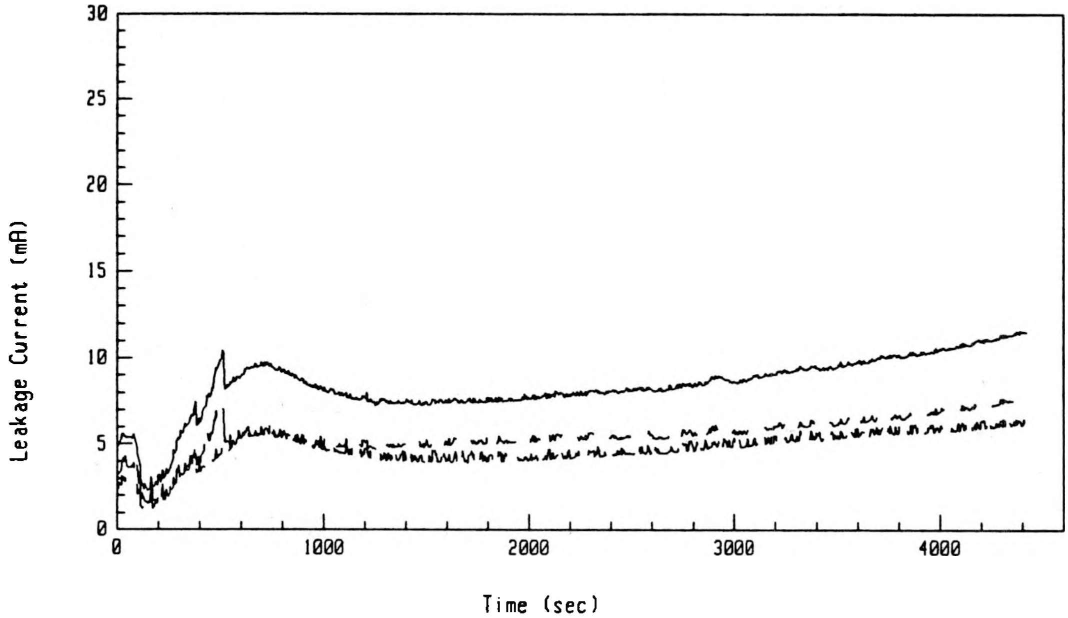


Test 48; Cable 1

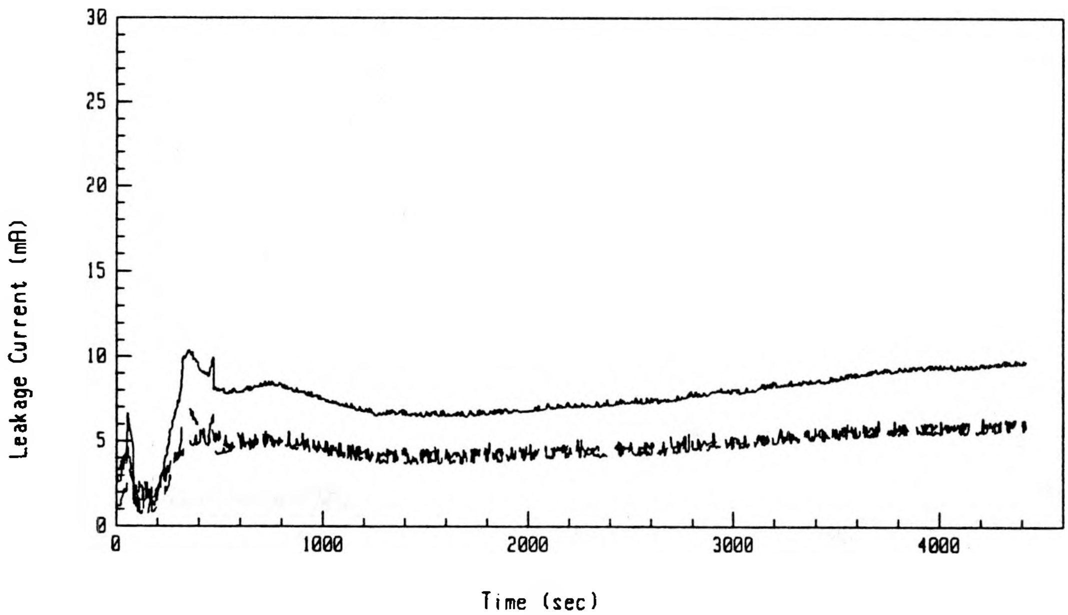


Test 48; Cable 2

Figure A-45: Leakage Current Data For Test 48 Involving an Aged BIW Cable at an Exposure Temperature of 350°C.

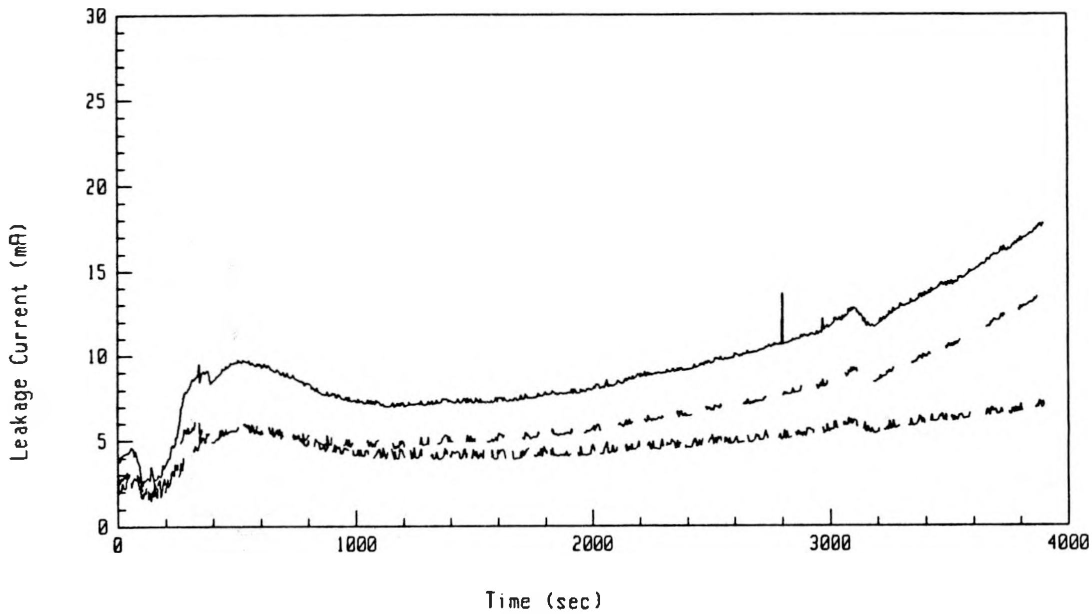


Test 49; Cable 1

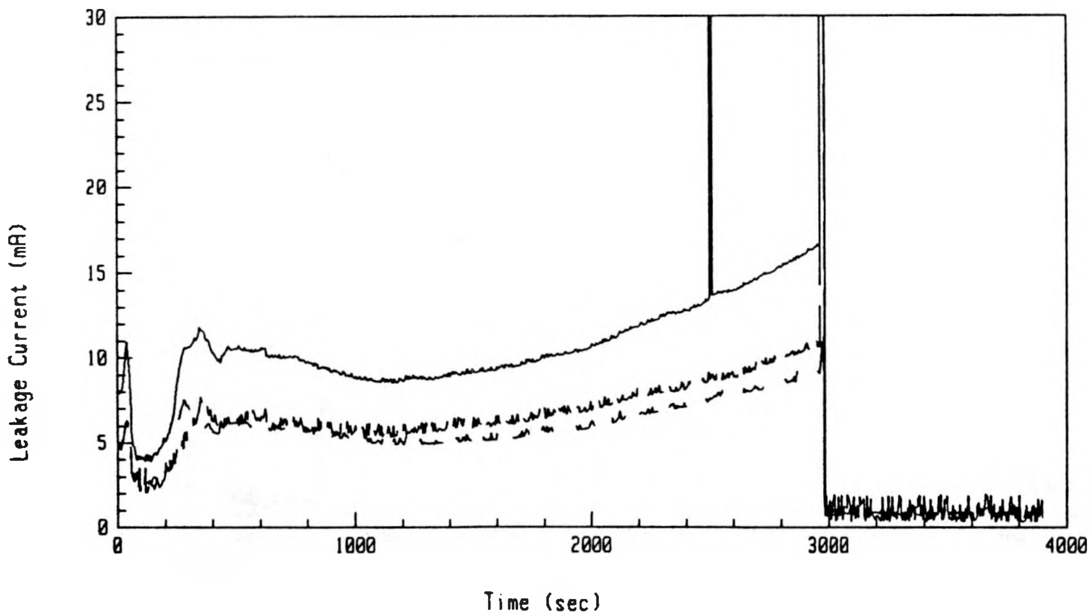


Test 49; Cable 2

Figure A-46: Leakage Current Data For Test 49 Involving an Aged BIW Cable at an Exposure Temperature of 345°C.

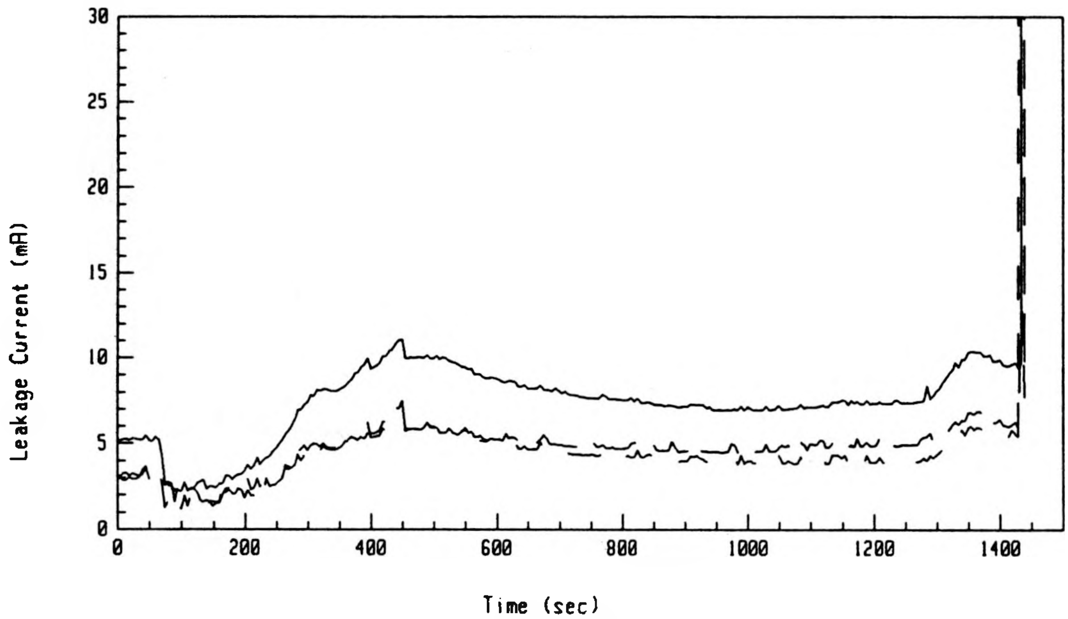


Test 50; Cable 1

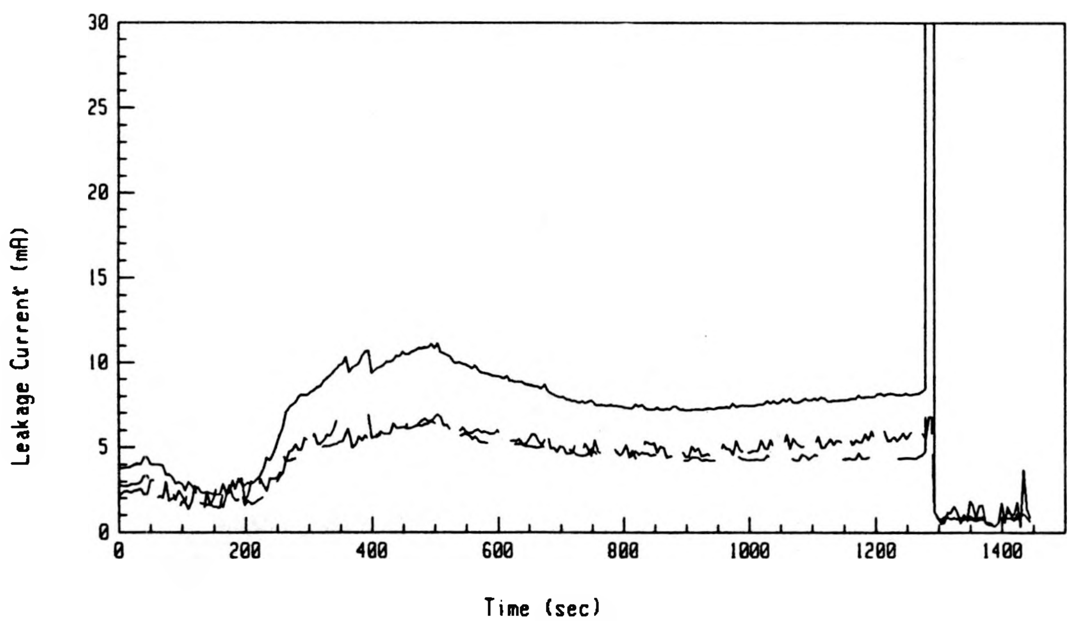


Test 50; Cable 2

Figure A-47: Leakage Current Data For Test 50 Involving an Aged BIW Cable at an Exposure Temperature of 350°C. Note that a failure in the data logging system occurred prior to the failure of Cable 1.



Test 51; Cable 1



Test 51; Cable 2

Figure A-48: Leakage Current Data For Test 51 Involving an Aged BIW Cable at an Exposure Temperature of 360°C.

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11. ABSTRACT *(200 words or less)*

This report documents the findings of an experimental investigation of the effects of thermal aging on the fire damageability of electric cables. Two popular types of nuclear qualified cables were evaluated. For each cable type, both unaged (i.e., new off the reel) and thermally aged samples were exposed to steady-state elevated temperature environments until conductor-to-conductor electrical shorting was observed. Plots of the time to electrical failure versus the exposure temperature were developed and thermal damage thresholds were determined. For one cable type, the thermally aged cables were less vulnerable to thermal damage than were the unaged samples as demonstrated by an increase in the thermal damage threshold for the aged samples, and an extended survival time at exposure temperatures above the damage threshold for aged samples compared to unaged samples. For the second cable, the threshold of thermal damage was lowered somewhat by the aging process, an indication of an increased vulnerability to thermal damage due to aging. However, for the higher temperature exposures, no statistical difference between the damage times for aged and unaged cable samples was noted. For both cable types, the changes in the thermal damage threshold observed were not considered significant in terms of fire risk.

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