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Energy Division

Report

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A LIFE ASSESSMENT OF RAYCHEM HEAT SHRINKABLE HIGH VOLTAGE TERMINATIONS	35
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Raychem Corporation
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Rev.	Page	Paragraph	Description	Date
1	16	Two	Correct typographical error "calssified" to classified	1/4/84
1	33	One	Change activation energy of HVTM from 30 kcal to 27.7 kcal	1/4/84
1	33	Two	Change activation energy of SCTM from 25 kcal to 31.5 kcal	1/4/84
1	29	No. 16	Deletion of Item 16 and renumbering of subsequent references	1/4/84

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2	2	Item 1.2.4	Correction of spelling of "requirements"	1/22/85
2	6	Item 2.6.2	(d) Capitalization of 'u' in Unusual	1/22/85
2	9	Figure	Insertion of figure "Aging Time to Reach 100% Elongation (Hours)"	1/22/85
2	9		All pages renumbered accordingly	1/22/85
2	10	Item 3.2.1	Correction of spelling for word "measurable" in sub 1 and 2.	1/22/85
2	13	Figure	Insertion of figure "Time (Hours) to Reach 20% Elongation"	1/22/85
2	15	Item 3.3.1	Deletion of 18 in parenthetical phrase (14, 15, 16, 17...)	1/22/85
2	16	First	Correction of spelling of Plane in Line 6, capitalization of l in "Liquid..." in Line 5.	1/22/85
2	18	Figure	Insertion of figures 3, 4, 5, 6	1/22/85
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2	21	Item 4.2.2.1 Paragraph under sub c	Change "(see section 3.2.1.5)" to "(see section 3.2.2.5)" Change "These impedances were 3 X 10^8, 7 X 10^8" to "...0.7, 3 and 7 X 10^8."	1/22/85 1/22/85

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2	25	Item 4.3	Correction of spelling of "Overvoltage" to "Overvoltage"	1/22/85
2	27	Item 4.4.2	Addition of the following: "Accelerated artificial pollution tests for use with cable accessories ..... is needed before a formal guide can be written."	1/22/85
2	29	Number 15	Substitution of reference "The Outdoor Performance of ...."; with "Some Parameters Affecting ...."	1/22/85
2	30	Number 25	Addition of reference "Report of Working Group 12-39...."	1/22/85
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4	35	Appendix B	Corrected "From reference 22" to "From reference 13"	2/27/87
4	-	-	Added revision records and indicated in text where revisions were made	2/27/87
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5	2	Item 1.2.2	Added paragraph "In 1996,.....the original 74^{o}C (see 3.2.3)	11/6/96
5	10	Item 3.2.2.1	Added paragraph "In the 1996 testing,....135 specimens." (see ref. 15206-14)	11/6/96
5	11	Item 3.2.2.2	Added paragraph "In 1996, ...temperatures of 135^{o}C and 120^{o}C."	11/6/96
5	11	Item 3.2.2.3	Added paragraph "In 1996,.....ultimate elongation at 2"/min."	11/6/96
5	11	Item 3.2.2.4	Added paragraph "In 1996,......elongation was determined."	11/6/96
5	12	Item 3.2.3	Added 1996 data to Table 3 and modified table titles	11/6/96
5	14	Figure	Added 1996 data to figure	11/6/96

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5	11/6/96	Kathy Maher	Kathy Maher	Bernard de Brunier	

CONTENTS

A LIFE ASSESSMENT OF RAYCHEM HEAT SHRINKABLE HIGH VOLTAGE TERMINATIONS

1. FOREWORD

1.1 Summary

There is no specification which can be used to predict the service life of a power cable termination. The design factors involved are complex including parameters such as environmental conditions, applied voltage, pollution level, operating and ambient temperature, and loading conditions. The synergistic effects of such parameters would defeat the best computer algorithm.

In determining our statement of life, this report presents results and discusses the significance of the following factors:

1.1.1 Thermal stability of the materials used in the terminations.

1.1.2 Weathering stability of the materials used in the terminations.

1.1.3 Load cycling tests on the terminations.

1.1.4 Overvoltage tests on the terminations.

1.1.5 Accelerated tests in various working environments.

Normal, abnormal and emergency operating conditions on the terminations have also been considered.

The conclusions stated below are based on our best engineering judgement using the data presented.

1.2 An Overview of the Presented Results

1.2.1 Thermal Endurance of Red Non-Tracking Material (HVTM)
The Arrhenius data shows that this material can be rated at 90°C for 40 years with a retention of 100 percent ultimate elongation (see 3.1.2.1). As discussed in the text this end point is extremely conservative.

1.2.2 Thermal Endurance of Stress Control Material (SCTM)
SCTM can have a lower rated temperature than that of HVTM or the cable insulation because the SCTM does not contact the conductor or lug. After analyzing the total data presented we have concluded that the thermal endurance of SCTM provides the overall design life limit of the indoor terminations. The data can be interpreted in several ways

depending on the customer operating conditions. The life predictions shown in statements 1.3.1 are based on this data. These predictions are based on Arrhenius plots using a retention of 20 percent ultimate elongation, a conservative limit considering typical high voltage cable applications (see 3.2.1).

In 1996, a limited thermal endurance test was performed on SCTM tubing which was manufactured from the same raw materials except for the sourcing of the raw materials. An endpoint of 25% ultimate elongation was chosen. The results of the limited thermal endurance indicate that the 40 year lifetime of the current SCTM tubing is 79°C rather than the original 74°C (see 3.2.3).

1.2.3 Weathering Data of HVTM

Analysis of the data presented shows that the material will retain more than 100 percent ultimate elongation after 30 years in sunlight equivalent to that of Phoenix, Arizona. The material will give better physical performance in more temperate zones. Indoor terminations will not be limited by these test results.

1.2.4 Load Cycling Tests on the Installed Terminations

The data presented shows corona (partial discharge) stability far in excess of any known specification requirements. Overvoltage life analysis of the load cycled samples shows that the termination performance is well above specification requirement after the equivalent of 16.2 years. The overvoltage tests outlined in 1.2.5 indicate life extrapolation to 40 years is not unreasonable.

1.2.5 Overvoltage Life Tests

The data presented shows a calculated minimum termination life of 5,000 years when subjected to overvoltage testing.

1.2.6 Accelerated Testing on Outdoor Test Sites

Raychem has used six monitored test sites to assess termination life. Results from these sites, whilst not completely comprehensive, show no evidence that the life outdoor terminations will be less than thirty years.

1.3 Conclusions

Based on the data presented, specifically the parameters discussed in Section 1.1, the following assessment is made.

This life assessment is made assuming that the reader requires the terminations to be compatible with the cable (XLPE is normally rated at 90°C maximum conductor normal operating temperature) and installed in equipment which may have a life expectancy of 40 years. Operating conditions such as load cycling and maximum ambient will affect the life statement; hence several assumptions have been made and the life predicted based on those assumptions. Clearly increasing the maximum operating temperature of the cable conductor will reduce the life, and reducing the maximum operating temperature would correspondingly increase the life.

1.3.1 <u>Indoor Terminations</u> (Type HVT-I-XXX and NHYT-I-XXX. Data presented does not include exposure to radiation environment.)

1.3.1.1 40 years at 90° maximum operating condition for the cable conductor.

Assumptions made:

The load will cycle in a manner no worse than that described in Appendix A. SCTM operates approximately 10°C cooler than cable conductor, as described in Appendix B.

1.3.1.2 40 years at 86.5°C maximum operating condition for the cable conductor.

Assumptions made:

The ambient does not exceed 40°C, load is continuous for 40 years.

1.3.1.3 40 years at 81°C maximum operating condition for the cable conductor.

Assumptions made:

The ambient does not exceed 55°C, load is continuous for 40 years.

1.3.1.4 40 years at 85°C maximum operating condition for the cable conductor.

Assumptions made:

The ambient does not exceed 51.8°C, load is continuous for 40 years.

1.3.1.5 40 years at 90°C maximum operating conditions for the cable conductor.

Assumptions made:

The ambient does not exceed 37.4°C, load is continuous for 40 years.

1.3.1.6 29.4 years at 90°C maximum operating condition for the cable conductor.

Assumptions made:

Ambient does not exceed 40°C, load is continuous for 29.4 years (AIEE #1).

1.3.1.7 27.2 years at 85°C maximum operating condition for the cable conductor.

Assumptions made:

The ambient does not exceed 55°C, load conditions continuous for 27.2 years (AIEE #1).

1.3.1.8 40 years at 74°C continuous operating SCTM temperature.

1.3.1.9 5.7 years at 90°C continuous operating SCTM temperature.

1.3.2 Outdoor Terminations

A life of at least 30 years can be expected based on weathering data of HVTM. The life must be derated if the operating conditions limit the performance requirements to the assumptions made in statements 1.3.1.6, 7 or 9 above.

2. CONSIDERATION5 IN DEFINING PROSPECTIVE LIFE

2.1 General

The manufacturer generally uses a testing technique during development which is best understood by analogy to a ladder. Once a material is tentatively selected, it must be subjected to a series of tests to determine its suitability for its intended service. This series of tests is the first rung on the ladder. One of these tests is thermal aging. Another is an examination of the effects of various environmental factors expected in service on the mechanical and electrical properties of the material.

Once the results of this series of tests indicates the material to be a good candidate, the stage is set for the second step which is the testing of the combination of materials in an insulation system (the product). Product tests are functional tests and realistic criteria must be used to define failure. Stability of the corona extinction voltage (CEV) is a primary requirement. Standardized design tests are used for product testing wherever possible. Special tests are devised whenever no standardized test covers adequately a service requirement.

The testing ladder is an idealized concept. In real time the completion of thermal aging tests on the materials may take several years, especially if demonstration of compliance to a 40-year life requirement is involved.

The selected end points must be realistic. For instance, since Raychem's red high voltage non-tracking material (HVTM) is in contact with the lug, the life of this material must be adequate at the temperature of the lug, which is close to but below the rated conductor temperature. The stress control material, however, is not in contact with the lug or conductor and it is important to select a realistic temperature for examining the prospective thermal life of this material. This temperature will obviously be somewhat less than rated conductor temperature.

2.2 Thermal Rating

The thermal rating of an electrical apparatus is that temperature which corresponds to the sum of the highest expected service ambient temperature and the temperature rise expected under full load operation (2). In order to qualify for a thermal rating, data are required to demonstrate that the life is equal or better than that of equipment which has operated successfully for many years. Oven aging tests at various temperatures are performed and data on times to a preselected "failure" point are collected and analyzed statistically. An Arrhenius plot is made, and the plot is extrapolated to the desired rated temperature. IEEE #1 and #98 (3,4) are guides which define how accelerated oven aging tests should be made and how the results should be treated mathematically to produce an Arrhenius plot. The statistical aspects of such testing are defined in reference 5.

2.3 Emergency Rating

According to reference one, "Operation at the emergency overload temperature of 130°C (as is required of XLPE and EPR cables with a 90°C rating) shall not exceed 100 hours in any twelve consecutive months nor more than 500 hours during the life of the cable." It is important to determine the stability of the insulation system when subjected to overload conditions.

2.4 Short Circuit Rating

The short circuit rating of a crosslinked polyethylene cable is that current which, when applied for specified time (6, 7), produces a conductor temperature of 250°C and intense short circuit forces. Since the operation of breakers isolates the faulted circuit from the source in a time which is normally less than 2 seconds, the thermal mass of the cable limits the average temperature rise to a relatively small value. The effect of this temperature rise on termination life is considered small and negligible and therefore no consideration of this is included in this report.

2.5 Electrical Factors

2.5.1 Design tests (8) are consensus judgements on tests required to demonstrate qualification for operation under system conditions. The details of how Raychem terminations relate to these requirements are published elsewhere (9). All the tests (ac withstand, lightning and switching impulse, wet withstand, dc withstand and CEV) relate to system requirements which are essential to insulation coordination as well as providing assurance of adequate safety factor against failure under a number of possible system conditions.

2.6 Normal and Abnormal Service Conditions

2.6.1 Normal Service Conditions

Aside from the electrical factors above, reference 8 specifies ambient temperature and altitude levels. When the installation is in an enclosure, the maximum ambient is 55°C (and the conductor 85°C). Otherwise, the ambient is 40°C (and the conductor may be at the 90°C rated temperature). The minimum ambient is -30°C. The Maximum Altitude is 1000 meters (3300 ft.). Equipment rarely operates at rated temperature for its design life. This is discussed in Appendix A.

2.6.2 Non-Standard Conditions

Any condition outside the above range is considered nonstandard. Examples are: (8)

(a) Ambient temperatures less than -30°C and more than +40°C.

(b) Altitude exceeding 1000 meters (3300 ft.) where atmospheric air is part of the thermal and/or dielectric system.

(c) Damaging fumes or vapors, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture or dripping water, etc.

(d) Unusual mechanical conditions such as: vibration, shock, cantilever loading, wind loading, icing, etc.

3. Materials Tests

3.1 Thermal Endurance of Red Non-Tracking Material (HVTM)

Thermal endurance tests were made on two batches labeled A and B.

3.1.1 Test Details

3.1.1.1. Specimens

Dumbbell tensile specimens were cut from injection molded slabs to be not closer than 25mm to the edge of the slab. The specimens were then randomized before heat treatment.

3.1.1.2 Heat Treatment

The specimens were mounted in aging ovens to be clear of any oven wall by at least 3 inches and heat aged at the following temperatures: 250°C, 230°C, 210°C, 190°C, 170°C, 150°C, and 135°C.

3.1.1.3. Sampling

Five specimens were removed from the oven at selected times of aging.

3.1.1.4 Measurements

Decay curves of average ultimate elongation against time of exposure were drawn and the time required for the elongation to fall to 100 percent was determined. The standard deviation of the elongation data was calculated. This was converted into a standard deviation on time by multiplying by the negative inverse of the slope of the decay curve.

3.1.2 Test Results

3.1.2.1. Ultimate elongation was chosen partly because it is a functional property and partly because its value decreases monotonically with aging time. A level of l00 percent elongation was chosen partly to limit the required aging time, and partly because at l00 percent elongation a very large safety factor with respect to the elongation produced by any conceivable flexure of the termination in usage exists. Actually from the flexure standpoint, even l0 percent would be adequate. However, in consideration of the requirement that the material be resistant to localized surface discharges in moist conditions, a safety factor was considered advisable even though no data exists which indicates that the resistance to surface tracking decreases with age. To the contrary, available data show that at least down to l00 percent elongation, no loss in resistance to surface tracking exists.

3.1.2.2. The mean values of the aging times to reach 100 percent ultimate elongation at the various temperatures are shown in Table 1 and on Figure 1. 95 percent confidence limits on the means were calculated. These values are also plotted on Figure 1 as bars above and below the points. Due to lack of specimens, no elongations less than

100 percent could be obtained at 135°C. The point in the table and plot was obtained by extrapolation from higher elongations to 100 percent, and confidence limit estimates were omitted.

TABLE 1
Hours to 100% Elongation

Temperature	A	B
250	2.8	3.6
230	6.9	8.1
210	35	34
190	120	120
170	640	620
150	1920	2250
135	6700	7000

3.1.3 Analysis of Data

According to specifications (3, 10, 11) the exposure temperatures shall be selected so that the highest temperature gives a life of at least 100 hours and the lowest temperature gives a life of at least 5000 hours. This eliminates temperatures above 190°C from consideration. The lives at the four remaining temperatures were subjected to at least squares regression analysis to derive the intercept and slope values. The lines on Figure 1 are drawn to fit these values.

The predicted hours are at 90°C.
Group A 412,762 hours = 47 years
Group B 506,407 hours = 58 years

3.1.4 Conclusions

Since the product in service will never experience elongations exceeding a few percent, the prognosis that the product made from this material will live more than 40 years at a rated temperature of 90°C is considered extremely conservative.

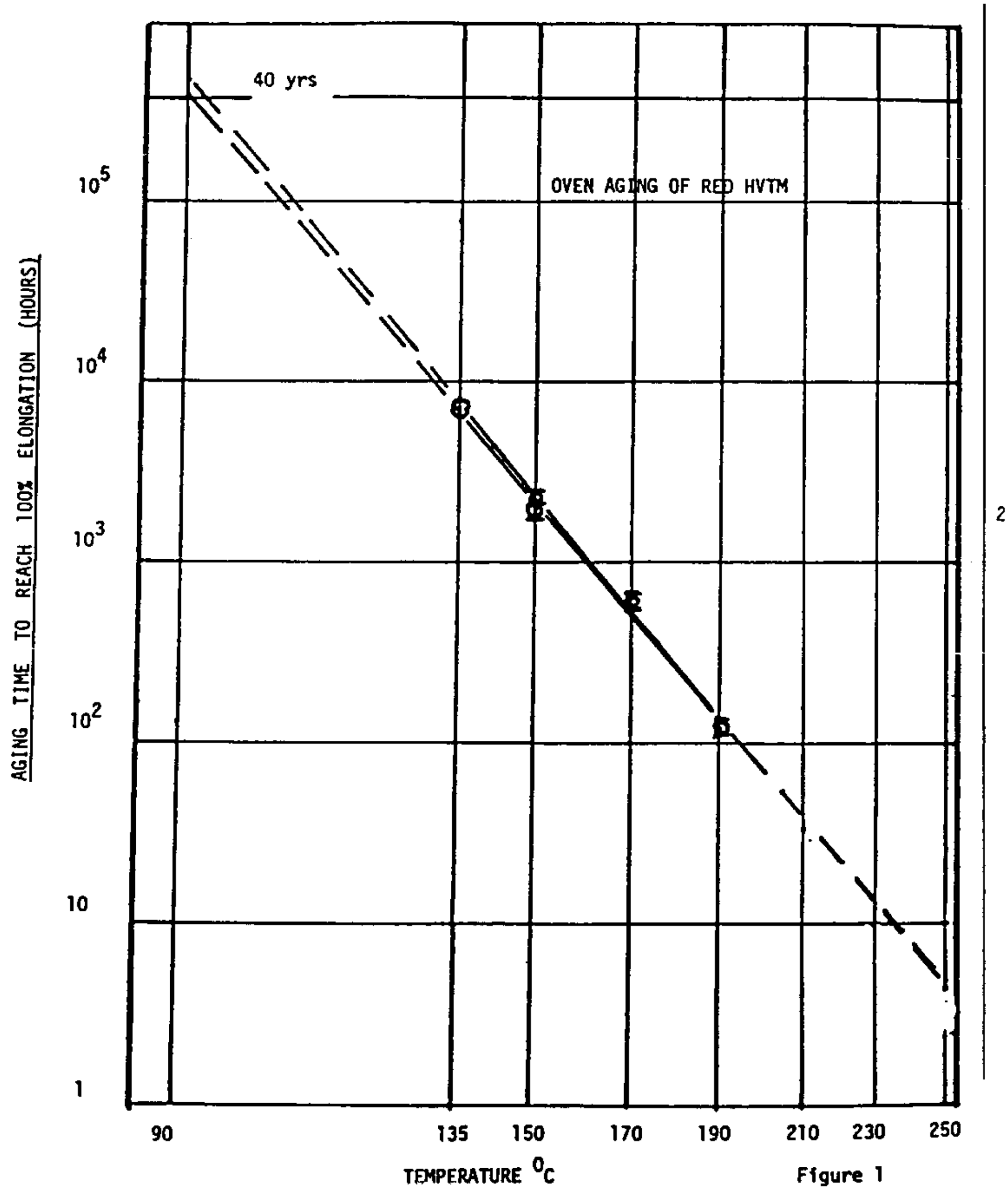

40 yrs
OVEN AGING OF RED HVTM
AGING TIME TO REACH 100% ELONGATION (HOURS)
10^5
10^4
10^3
10^2
10
1
90
135
150
170
190
210
230
250
TEMPERATURE ^{0}C
2

Figure 1

3.2 Thermal Endurance of Stress Control Material

3.2.1 The results of an oven aging test program will be given here in order to indicate the effect of thermally induced degradation on projected life. It is important to note that stability to electrical and thermal stress are also important. Test programs have been run to determine these factors and the results are in the open literature (12). In essence these tests show:

1. Effect of stress at room temperature on electrical properties. Result: No measurable effect at stresses as high as 20kV/cm for times up to 20,000 hours.

2. Effect of temperature of SCTM on electrical properties. Result: Effect is barely measurable from room temperature to 125°C.

3. Effect of time at 50°C and 100°C on electrical properties. Result: A slight, insignificant drop in impedance for times to 20,000 hours. More drop occurred at 100°C than at 50°C.

4. Effect of load cycling [150 load cycles to 95°C conductor temperature (5 hours on/3 hours off)] on electrical properties of SCTM. Result: Capacitance of SCTM increases slightly (1.4 to 2.0 pf/cm) while dissipation factor of SCTM drops from 0.284 to 0.235 and then is restored to 0.284.

These tests show that the electrical properties of SCTM are stable under conditions similar to those met in the field. In the following test program, the 20 percent elongation point has been chosen as describing an "end of life" characteristic. 100 percent elongation was chosen for HVTM. If mechanical requirements alone were considered, 20 percent would have been chosen for both, for in the application, the amount of flexure of cable terminations is very small, corresponding to a maximum of 10 percent. However, the SCTM is protected while the HVTM is not. Moreover, the surface of the HVTM is subjected to leakage currents and it is important to require that the material retain a larger percent elongation at least until data are available to show that it is not required.

3.2.2 Test Details

3.2.2.1. Test Specimens for Mechanical Testing

SCTM tubing (41/21 size) was fully recovered by placing in a 150°C oven for 10 minutes. 200 dumbbell tensile specimens were cut from this tubing, and randomized by tumbling.

In the 1996 testing, SCTM tubing (42/19 size, EW42821) was tested using the same sample preparation and cutting only 135 specimens (see ref. 15206-14)

3.2.2.2. Aging

The 200 specimens were hung in four circulating air ovens at temperatures of 135°, 120°, 105° and 100°C.

In 1996, the specimens were hung in two air circulating ovens at temperatures of 135°C and 120°C,

3.2.2.3. Sampling

For mechanical testing, at predetermined aging times, five samples were removed from an oven and tested for ultimate elongation at 100mm/min.

In 1996, the five samples were removed from the oven and tested for ultimate elongation at 2”/min.

3.2.2.4. Calculations

Arithmetic means and 95 percent confidence limits on ultimate elongation are calculated.

Plots on elongation versus aging time were examined and found to contain an initial rapid drop followed by a slowly dropping linear portion. A regression analysis of mean elongation versus aging time on the linear section was performed for each aging temperature. From this regression, the time required to reach 20 percent elongation was determined.

In 1996, the time required to reach 25 percent elongation was determined.

3.2.2.5. Electrical Testing

A parallel test program was run in which mandrel specimens of the SCTM were checked periodically for electrical properties. These specimens were aged thermally in a similar manner to the dumbbell specimens. Three specimens were aged at each temperature.

The specific impedance* which is the electrical property related to stress control was measured. The design range for SCTM is 10^7 ohm-cm to 9×10^8 ohm-cm (the function and reason for this design range is given in reference 12). Any drift of the impedance was noted.

*Specific impedance is a term coined by Raychem. It is measured by applying a power frequency voltage V to a specimen and measuring the current I. If A is the specimen area and L is its length, the specific impedance is given by:

$$Z_{sp} = \frac{V}{I} \frac{A}{L}$$

3.2.3 Aging Data for SCTM

3.2.3.1. Uniformity of the Data

For the forty samplings, the 95 percent confidence limits were as follows:

TABLE 2
95% Confidence Limits on Elongation

Maximum	30%
Minimum	5%
Average	14.6%

The original data (internal Raychem report) indicated no correlation between 95 percent confidence limits and the absolute value of ultimate elongation.

3.2.3 Time to 20 or 25 Percent Ultimate Elongation

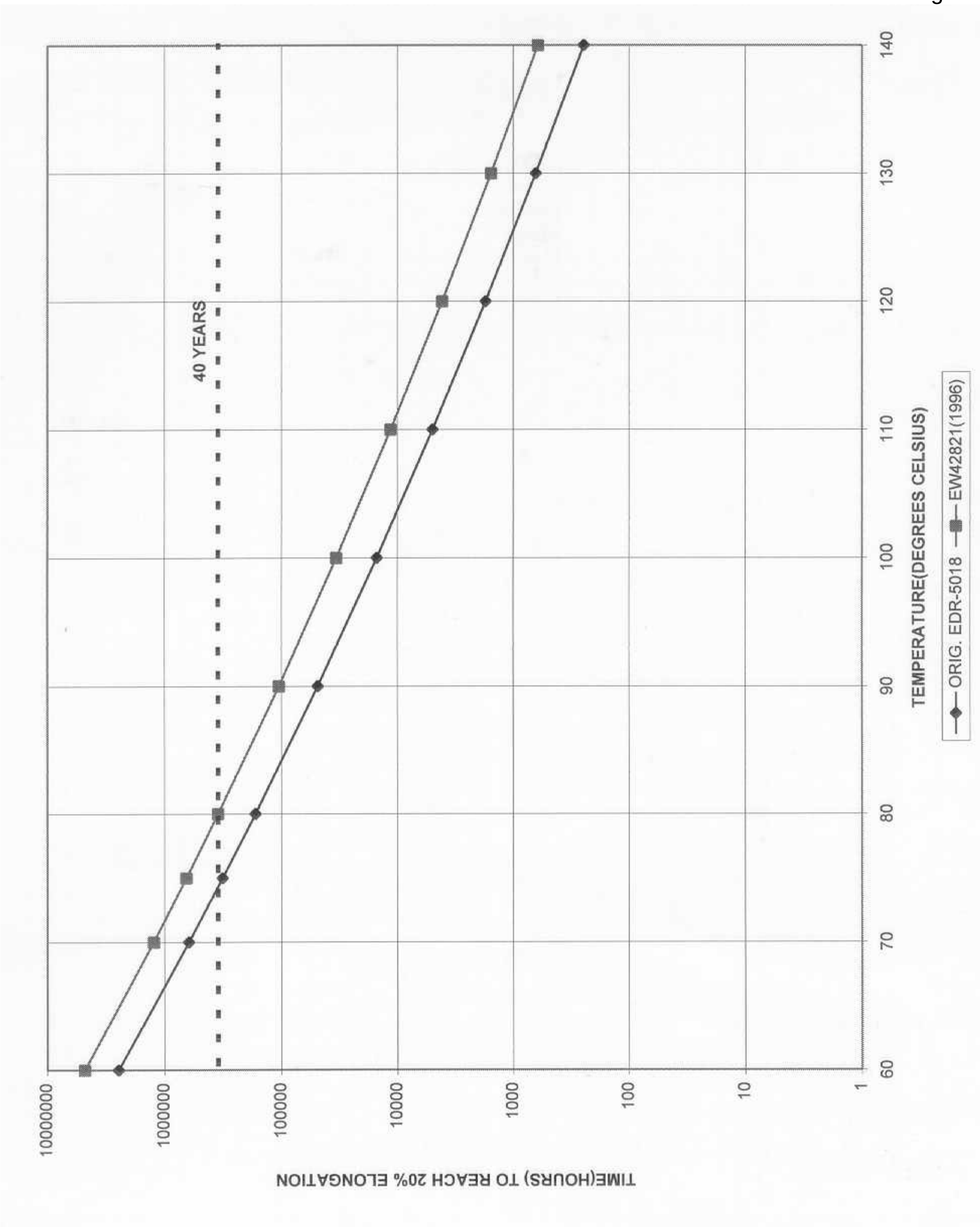
The times are given in Table 3 as determined by the procedure of 3.2.2.4.

TABLE 3
Time (Hours) to Reach 20% or 25% Elongation at Various Temperatures

Temperature °C	Original EDR-5018 Hours to 20% E	1996 Hours to 25% E
135	403	970
120	1686	4100
105	8310	Not tested
100	15686	Not tested

3.2.3.3. Aging of Electrical Properties

The initial values and values of specific impedance at the 20 percent elongation time were identical in all cases, ranging from 3 to 5 x 10^8 ohm-cm. At about twice the 20 percent elongation time, the impedance dropped sharply. Since 20 percent elongation is taken as the end of life. and the impedance was in the required range at the 20 percent elongation time, this data is not included here.


40 YEARS
TIME(HOURS) TO REACH 20% ELONGATION
10000000
1000000
100000
10000
1000
100
10
1
60
70
80
90
100
110
120
130
140
TEMPERATURE(DEGREES CELSIUS)
ORIG. EDR-5018
EW42821(1996)

3.2.4 Analysis of the Data

3.2.4.1. Worst Case Situations

Section 2.6.1 stated that the worst case situation for a cable termination with respect to temperature is a conductor temperature of 85°C in a 55°C ambient in an enclosure or a conductor temperature of 90°C in a 40°C ambient outside of an enclosure. Cable temperature ratings are assigned on the 90°C/40°C basis. The basic reason for this change to 85°C/55°C is that the aging of a cable is generally considered to be related to the average temperature of the dielectric. The 85°C value is the considered judgement of cable engineers on the reduction in conductor temperature required to achieve the same average dielectric temperature in a 55°C ambient as would occur when operating at a conductor temperature of 90°C in a 40°C ambient. Therefore, both these conditions should be considered in the analysis.

3.2.4.2. The temperature requirement for SCTM is less then the HVTM because it does not contact the conductor or lug (See Section 2). A realistic temperature requirement may be obtained through thermal analysis. Such an analysis is included in Appendix B. In it, the temperature which the SCTM will assume in a cable termination installed on a 250kCM, 15kV cable with XLPE insulation (175 mils) is determined. With the conductor at 90°C and operating in a 40°C ambient, the temperature is 76.6°C. The projected estimate of the life at this temperature is given in Table 4. With the conductor at 85°C in a 55°C ambient, the SCTM temperature is 77.2°C. The projected life at this temperature is also given. These life estimates can be made to exceed 40 years either by assuring that the ambients are maximum ambients which never exceed 40°C or 55°C, or by allowing the ambient to be continuous and setting it at a new level. According to AIEE #1, the first is the preferred engineering approach. Indeed, the 40°C and 55°C values are defined therein to be maximum ambients ever observed. Noting that the differences between the 40 year life temperature of SCTM (74°C) and the SCTM temperatures calculated for continuous 40°C and 55°C ambients (76.6°C and 77.2°C) are small, hypothetical continuous ambient temperatures slightly less than 40°C and 55°C may be estimated at which 40 year life would be assured at continuous full load operation. These temperatures are given in Table 5.

TABLE 4

Projected Life of SCTM in Worst Case Situations

Situation	Projected Life
1. 90°C conductor temperatures in 40°C ambient (SCTM at 76.6°C)	29.4 years
2. 85°C conductor temperature in 55°C ambient (SCTM at 77.2°C)	27.2 years
3. 86.5°C conductor temperature in 40°C ambient (SCTM at 74°C)	40 years
4. 81°C conductor temperature in 55°C ambient (SCTM at 74°C)	40 years

TABLE 5

Maximum Ambient Temperatures for Full Load Rating
(as defined in AIEE #1) for 40 Year Life (SCTM at 74°C)

Condition	Max. Continuous Ambient Temperature
In enclosure (normally 55°C ambient)	51.8°C
Outside enclosure (normally 40°C ambient)	37.4°C

3.2.4.2. All of these test data are conservative since the tests are made with the material fully exposed. In the application, the SCTM tubing is covered and protected by an over-layer of HVTM which will undoubtedly prolong the life.

3.3 Stability to Weather Conditions

3.3.1 General

This subject is covered in publications (14, 15, 16, 17). Raychem has done considerable work to provide an HVTM material with outstanding resistance to U.V. exposure and adverse weathering. This property is conventionally measured by exposure in a weatherometer. The rate of degradation is affected by the spectrum of the lamp used and also by the presence of gaseous pollutants such as ozone and sulfur dioxide. In the weatherometer Raychem uses the Zenon arc to provide a spectrum as close to that of natural sunlight as possible. Also, in recognition of the importance of this property, we have employed alternative accelerated aging tests to the weatherometer. The criteria used to defined stability in these tests are all the usual ones (surface checking and crazing, hardness, ultimate elongation, etc.) with one more. It is most important that the resistance to surface tracking and erosion under a test such as ASTM-D-2303, "Liquid-Contaminant, Inclined Plane Tracking and Erosion of Insulating Materials" shall remain stable. A variety of materials have been shown to degrade during outdoor aging to surface tracking as measured by this test. The reasons are not completely understood, but a few tentative concepts seem to recur. One is that aging tends to increase the carbonaceous char content of a polymer, tipping the balance of the chemical reaction which is responsible for resistance to tracking. Another is that pollution which itself is easily carbonized may lead to tracking by transferal to the non-tracking material. A third is that the aging alters the material and makes it susceptible to tracking. The only way to insure that this will not happen is to measure the effect of outdoor aging on the resistance to tracking.

Raychem's material is classified as "non-tracking" because it will not exhibit tracking on the most severe tests used by industry to measure this property. ASTM-D-2302 is one of these methods. The references show that HVTM remains non-tracking after up to 14,000 hours in the weatherometer. This, as will be indicated below, is equivalent to over 30 years outdoor exposure.

3.3.2 Test Methods

3.3.2.1. Weatherometer

Atlas Electric Devices Company equates 300 hours exposure to approximately one year in Chicago, Illinois. Our own data (14) indicate that for HVTM, the figure should be between 400 and 500 hours.

3.3.2.2. Emmaqua Technique

Reflected natural light is used. Mirrors increase the solar radiation rate by a factor of 7 to 8 in the Desert Sunshine Exposure Test, Inc., facility in Phoenix, Arizona. Blowers keep the surface temperature the same as though the specimens were mounted on conventional racks at 45° facing south. The specimens are sprayed for 8 minutes per sun hour with distilled water. An Emmaqua device is shown on Figure 3. The data can be converted to expected lifetimes at 45° facing south in Phoenix.

3.3.3 Test Data

3.3.3.1. Weatherometer

The effects of exposure time on tensile strength, elongation and electric strength are shown on Figures 4 and 5.

3.3.3.2. Emmaqua

The effects of exposure time on physical properties is shown on Figure 6.

3.3.4 Discussion of Data

Using our conversion factor of 450 hours per year for weatherometer data, HVTM has more than 100 percent elongation after 33 years in regions similar to Chicago. This elongation is several times that required for a functional termination.

The trends of Emmaqua data place 15 years at 45° south in Phoenix as equivalent to about 800 hours in the Weatherometer (16 to 20 years in Chicago). Thus, extrapolation of the Emmaqua data using the trend line of the Weatherometer data indicates that it will take about 30 years in Phoenix to reach the 100 percent elongation level.

3.3.5 Conclusion

As has been mentioned above, an ultimate elongation of 100 percent is far in excess of the minimum allowable ultimate elongation for a functioning product.

HVTM remains non-tracking during accelerated outdoor exposure tests to the equivalent at least 30 years outdoor exposure in a temperate climate.

Allowing for the difficulty in interpreting the results in accelerated tests in terms of projected service life in a world of widely varying climatic conditions it is safe to say that Raychem's HVTM material can be expected to perform well in severe outdoor locations for at least 30 years.

4. PRODUCT TESTS

4.1 Overview

There is no simple way to prove that a cable termination will last 40 years. Yet there are well accepted principles which the designer can use which produce a high degree of confidence. These principles are:

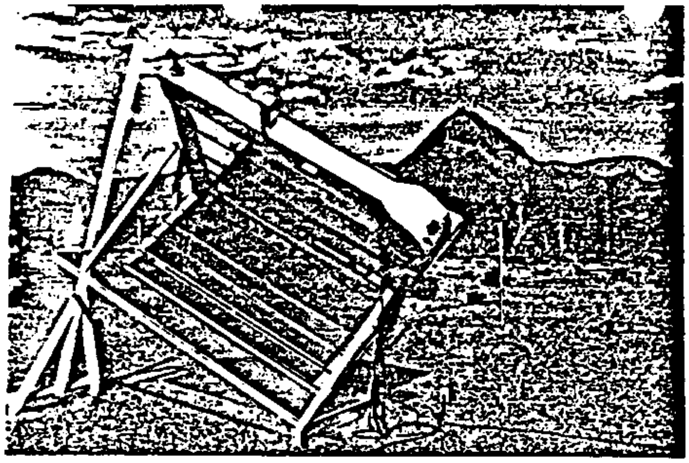


Figure 3. EMMAQUA Device.

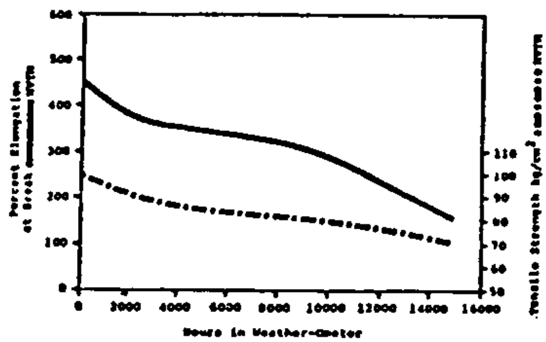


Figure 4 Weather-Ometer Data for Red HVTM

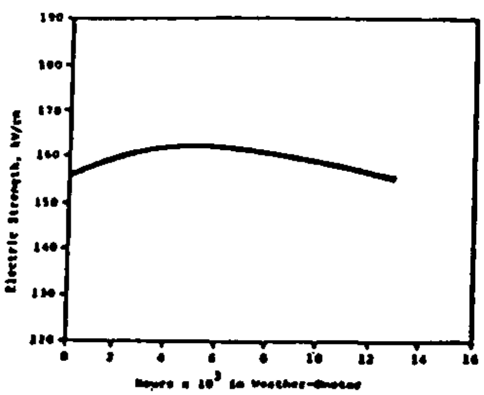


Figure 5 Electric Strength after Weather-Ometer Exposure for Red HVTM

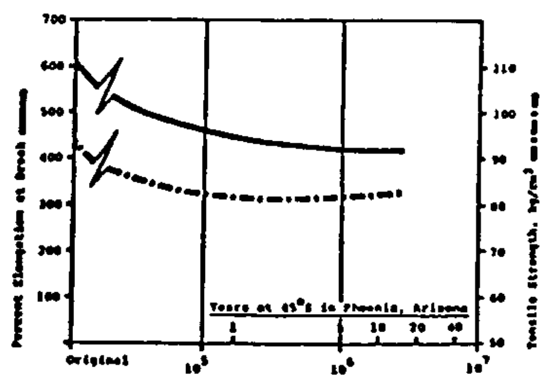


Figure 6 EMMAQUA Aging of Red HVTM

4.1.1

The corona extinction voltage must be far above normal line to ground voltage. Standards (1, 6, 8) call for a multiple of 1.5. A generalization can be stated. For any kind of cable termination (tape, push-on, etc.) the corona extinction voltage is related to the carefulness of the workman in preparing the cable for termination. The most critical part of the preparation is that of removing the insulation shield.

4.1.2

The allowable discharge magnitude versus voltage curve shall be in accordance with the requirements of reference 1. That is, at voltages corresponding to the multiples of normal line to ground voltage of 1.5, 2.0, 2.5, and 3.0 the maximum allowable discharge magnitudes are 5, 20, 35 and 50 picocoulombs respectively. Basically, this provides assurance that discharges much more intense than 50 pC do not exist in the range of voltages which may be experienced during switching surges. If such intense discharges did occur, they could result in damage which would lead to continuous discharging at normal use voltage.

4.1.3

The corona extinction voltage must be reasonably stable and remain above 1.5 normal line to ground voltage (1.5Vg) during a load cycle test similar to that called for in section B-3 of reference 1. While this calls for the application of twice normal line to ground voltage, (2 Vg) during the 90°C portion of the load cycle, and 3 Vg during the 130° portion, Raychem uses 2.6 Vg throughout. While (1) calls for 21 daily load cycles at each temperature, Raychem uses three 5 hours on/3 hours off load cycles per day. This is considerably more severe. The durations of the Raychem and the load cycles of (1) are identical, 21 days at each temperature, though Raychem often extends its tests beyond this time. This is one of the most searching tests Raychem uses. It is part of the qualification sequence of all new designs.

4.1.4

The life at voltages far above normal line to ground must be adequate. Not only must the life be adequate to assure no failures on the one minute and six hour tests of reference (8), it must be adequate to assure that no failures will occur in 40 years of normal voltage application.

Actually, items 1, 2, and 3 of this section already provide a good part of this assurance. They assure that during normal operation, no discharges will occur. Without discharges the life should be infinite. An overvoltage life test is primarily a test for searching for any possible weaknesses which may not have appeared in tests of items 1, 2, and 3.

The literature is full of overvoltage life test data, and of volt-time curves based on this data and attempts by researchers to assign some basic significance to them. Some examples are given (18 through 23). If the voltage endurance is to be determined, a volt-time curve is needed. | 2

Using the information in the references, it is possible to assign some significance to a single overvoltage test.

Several of the references note that volt-time curves in general follow a trend expressed by an empirical equation:

$$\text{Life} = \frac{K}{V^n}$$

Where K and n are constants and V is the applied voltage.

The lowest value of n which we have been able to find in the literature is 5 (22).

Comparing life, L_{ov}, at an overvoltage, Vov, to life Lg at normal line to ground voltage in service, Vg, we have:

$$\frac{Lg}{L_{ov}} = \left(\frac{Vov}{Vg}\right)^n$$

As an example, if Vov/Vg = 4.5 and n = 5 the ratio Lg/Lov = 1845 and from this we may deduce that 285 hours at 4.5 x Vg is equivalent to 60 years (at least) at Vg. This is not a rationale for concluding such a test at 285 hours. The tests are run to thousands of hours in order to collect information on strengths and weaknesses of the insulation system.

4.1.5 The four tests above are good for indicating the stability of the internal construction. On the other hand, there are features of external surface stability under ambient conditions which must be checked. The following test program has been followed:

1. Select test sites which are recognized as extremely severe by respected testing organizations. Install terminations and monitor.

2. Install terminations in a company-owned test site.

These tests are made with power frequency voltage applied, sometimes overvoltage, sometimes not.

There are two basic reasons for doing so much testing. First is the variability of climatic conditions in the field. No one test can possibly cover them all. The second reason is simply the recognition of the importance of stability of the outer surface relative to life.

In wet and polluted environments, leakage currents across the outer surface become sufficient to cause localized drying which leads to dry banding. Localized arcing across these bands will cause erosion and may result in surface tracking or localized degradation. Material tests of every batch of non-tracking material are made to assure that the material properties are meeting company specifications. In addition, the design of the insulator, the shape of the sheds, the interface between the sheds and the tube of nontracking material, the length of the termination, the number of sheds, all have effects on the response to the leakage currents.

4.2 Test Data Relative to Corona and Load Cycling of Terminations

4.2.1 General/Corona Extinction Voltage (CEV)

Two termination designs are used to eliminate the triangular void at the end of the cable insulation shield. One uses a grease type void filler with extruded semicon cable shields, and the other uses conductive paint. Data will be presented with respect to both designs.

4.2.2 Load Cycle Tests

4.2.2.1. Test Details

Three cable types were used:

a. 185mm^2 (365kCM) 30KV, XLPE, graphite dispersion layer, conductive shielding tape, copper tape, jacket.

b. 350kCM (177mm^2) 15KV, XLPE (4.4mm) extruded insulation shield, copper tape, jacket.

c. 150mm^2 (296kCM) 20KV, XLPE, graphite dispersion layer, conductive shielding tape, copper tape, jacket.

For both a and b, three batches of SCTM representing the minimum, median and maximum levels of specific impedance (see section 3.2.2.5) were tested. These impedances were 0.7, 3, and 7 x 10^8 ohm-cm. Using cable (a) two cable loops (four terminations) for each impedance level were placed on load cycle at 95°C conductor temperature 5 hours on/3 hours off for 150 cycles at 2.6 Vg. Similarly on a separate test at 130°C, six cables were placed on test at 2.6 Vg for 150 cycles.

Using cable (b) two loops for each impedance level were placed on load cycle at 95°C for 150 cycles, again at 2.6 Vg.

For cable (c) one SCTM representing the median level of impedance was tested. Three cable loops (6 terminations) were placed on load cycle at 95°C conductor temperature, 5 hours on/3 hours off for a total of 200 load cycles at 2.6 Vg.

Corona extinction voltage was measured initially and at the end of the test. This was defined at the 3 picocoulomb level.

Discharge magnitude was measured at 2.9 Vg. After the load cycle a visual examination was made to determine:

(a) Position and degree of discharge--if any.
(b) Tightness of stress control and red nontracking tubings.

4.2.2.2. Test Results

The data for cable types a and b are shown in Table 6. The data for cable type c is in Table 7. The visual examination revealed no evidence of any instability.

4.2.4 Discussion

4.2.4.1. 150 load cycles at 130°C with 5 hours on/3 hours off is 1.5 times a full check of the 500 hour emergency warranty of the cable.

4.2.4.2 The load cycle test is a type of overvoltage life test and as such has some relationship to projected life in service. If the voltage exponent is 5, the life indicated by 150 load cycles is 16.2 years. This is greater than AEIC #5 requirements. Using the same exponent, the AEIC #5 test is equivalent to 15.8 years with 14 of these years at emergency conditions. That is, 21 days at 2 Vg is equivalent to $\frac{21}{365} \times 2^5$ or 1.84 years, and 21 days at 3 Vg is $\frac{21}{365} \times 3^5$ or 15.8 years. Our test is not sequential.

We test to the equivalent of 16.2 years at 95°C and 130°C. The load cycle test is an extremely severe test and the implication of passing such a test is considered to be significant with respect to a much longer life than 16 years. Using the same examination technique, the 200 load cycle test of cable c at 2.5 Vg is equivalent to 18 years at Vg.

The usual criterion for passing a load cycle test is simply continued operation at the end of the test. However, Raychem would prefer to have a termination which meets initial corona specifications at the end of this test. Many competitive termination products do not meet this criterion. As the following will show, we have met this goal.

Both initially and after 150 load cycles all 18 of cable types a and b terminations meet requirements of references 1 and 8 with respect to CEV and discharge magnitude versus voltage.

Table 6

Discharge Magnitude at 2.9 Vg and 1.5 Vg

for Load Cycled Specimens

Cable Rating/ Conductor Temperature		30kV/130°C		30kV/95°C		15kV/95°C		
		Cable a		Cable a		Cable b		2
		1	2	1	2	1	2	
Initial Picocoulombs at 2.9 Vg	Low	0	0	0	0	0	0	
	Med	0	0	0	0	0	0	
	High	0	0	0.7	0	0	0	
150 Load Cycles Picocoulombs at 1.5 Vg	Low	0	0	0	0	0	0	
	Med	0	1.2	0	1	0	0	
	High	0	0	0	0	0	0	
150 Load Cycles Picocoulombs at 2.9 Vg								2
	Low	0	11	0	0	0	0	
	Med	0	22	2	5	0.8	0	
	High	0	0	0	0	0	0	

Table 7

Corona Data for Load Cycled | 2

Specimens of Type c (20kV rating)

Specimen	1	2	3
Initial CEV at 5 pC	40kV	40kV	34kV
CEV After 200 Cycles at 5 pC	24kV	35kV	35kV

For cable type c, CEV's were measured at 5 picocoulombs. The data show that after 200 load cycles the CEV's met specifications with a comfortable margin.

These data confirm the data with types a and b. It is not certain that the discharges in those specimens which exhibited discharges were in the terminations. They may have been in the cable. The cables tested, however, were chosen for excellent stability during load cycling.

4.3 Test Data Relative to Overvoltage Life

4.3.1 General

The following test program includes cables with extruded insulation shield and with the graphite dispersion layer. The program will ultimately include 4 voltage levels for each cable. To conserve testing equipment the test was started at the highest voltage.

4.3.2 Details of the Test

Power frequency - 50Hz

Cable types (termination type)

15kV, 350kCM, XLPE (175 mils)

(extruded insulation shield)

20kV, 185mm^2, XLPE

(graphite dispersion layer insulation shield)

Termination - standard indoor

No. of samples - 3 at each test voltage

4.3.3 Test Results

4.3.3.1. The test data are shown in Table 8.

Table 8

Overvoltage Life

Cable	Voltage	Time	Failures
20kV	69kV	6,000 hours	3 at 2800, 5800, and 6000 hours.
	62kV	11,000 hours	1 at 11,000 hours, 2 have not yet failed.
15kV	52kV	11,000 hours	1 at 9500 hours. 2 have not failed.
	45kV	11,000 hours	None.

4.3.3.2. Visual Examination and Comments

Tree-shaped areas of degraded SCTM were observed both at the cable dielectric and red non-tracking tubing interfaces. This is the expected mode of failure due to the extremely high voltage.

4.3.4 Discussion of Results

4.3.4.1. A preliminary estimate of the voltage exponent n may be determined as follows:

$$\frac{11,000}{2,800} = \left(\frac{69}{62}\right)^n \qquad n=12$$

4.3.4.2 Using a conservative value of 5 for n, the 11,000 hour life at 62kV is equivalent to over 5000 years at Vg. This simply is one indication of adequate voltage life at Vg.

4.3.4.3 The data thus far obtained on the 15kV cable is equivalent to over 9000 years at voltage exponent n value of 5. This prediction simply indicates that the mode of failure will not be by internal discharges. Long before the 9000-year point is reached it is certain that some other mode of degradation such as thermal degradation will have led to need for replacement not only of the terminations, but the complete distribution system.

4.3.4.4. The most significant fact that this test reveals is that the 0.5 picocoulomb discharges measured at about 2.4 Vg on these terminations are not having a significant effect on useful life. That is, they may be determining the life but their effect is so small that even at 62kV (5.3 Vg) the life is greater than 11,000 hours. This correlates with the fact that discharge magnitude increases very slowly with voltage.

4.4 Data Regarding Life in Polluted Test Sites/Surface Stability

Several test sites have been chosen to assess the performance of Raychem terminations. Table 9 gives the relevant data. The predicted service life has been derived from the classical life equation using a voltage exponent n of 5. It may be added that all 17 terminations at the Raychem test site shown in Table 9 were recently removed for testing. All CEV's were over 22kV.

4.4.2 The data in Table 9 must be supplemented with field data on tens of thousands of terminations installed outdoors in all parts of the world for an estimated average installed life of 5 years. (Maximum installed life in use conditions 10 years.)

Accelerated artificial pollution tests for use with cable accessories have been proposed in a recent publication (25) which is a step toward a guide and possibly a standard. World wide progress is reviewed and a status report is included. It is concluded that interlaboratory work involving the tests themselves and comparisons with outdoor service is needed before a formal guide can be written.

TABLE 9

LIFE TESTING RAYCHEM H.V. TERMINATIONS ON OUTDOOR TEST SITES

Test Site and Testing Authority	Type of Pollution	Termination Voltage Class ph/ph	Cable Type	Test Voltage ph/Ground	Number of Samples	Date Energized	Date Removed	Predicted Service Life at Working Voltage ph/Ground	Comments
Menlo Park Calif. USA Raychem	High ultra violet radiation and salt fog.	15kV	Single conductor XLPE various constructions	17kV or 2 Vg	17	April 1975	----	128+ yrs	No signs of deterioration. No failures
Mannheim Test Site W. Germany F. G. H.	Heavy industrial pollution	20kV	Single conductor XLPE, tape & dispersion layer	11.54kV or 1 Vg	2	February 1972	----	7+ yrs*	No failures Leakage currents lower than porcelain
Muir Beach Calif. USA PG&E	High ultra violet radiation and salt fog	15kV	Single conductor XLPE concentric neutral	12kV or 1.38 Vg	1	July 1971	June 1978	35.8 yrs	Burn marks apparent on top skirt which caused small split (0.04 in.) in skirt
Jackson Michigan USA Consumers Power Co.	Industrial pollution	15kV	Single conductor XLPE concentric neutral	15kV or 1.73 Vg	1	July 1972	December 1978	88.9 yrs	Dulling in color. No failure
Brighton England CERL	Heavy industrial and marine pollution	11kV	Three conductor belted paper lead	6.3 kV or 1 Vg	3	July 1969	September 1975	6+ yrs*	No failure

+ Where no damage has been observed a (+) has been added to show that the samples will last longer.

* As these tests were made at working voltage, no acceleration factor is applied.

REFERENCES

(1) AEIC #5, "Specifications for Polyethylene and Crosslinked Polyethylene Insulated Shielded Power Cables Rate 5 Through 69kV"

(2) IEEE #1, "General Principles Upon Which Temperature Limits are Based in the Rating of Electric Equipment"

(3) IEEE #98, "Guide for Procedures for Thermal Indexes of Solid Electrical Insulating Materials"

(4) IEEE #99, "Guide for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment"

(5) IEEE #101, "Guide for the Statistical Analysis of Thermal Life Test Data"

(6) IPCEA Pub. No. 5-66-524, "Cross-linked-thermosetting Polyethylene -insulated Wire and Cable for the Transmission and Distribution of Electrical Energy"

(7) IPCEA, P-32-382, "Short Circuit Characteristics of Insulated Cable"

(8) IEEE #48, "Standard for High Voltage Alternating Current Cable Terminations"

(9) Raychem Report #110

(10) IEC Publication #505, "Guide for the Evaluation and Identification of Insulation Systems of Electrical Equipment"

(11) ISO 2578

(12) Blake, A. E., Clarke, G. J., and Starr, W. T., "Improvements in Stress Control Materials," Proc. 1979 Transmission and Distribution Conference, 79 CH 1399-5-PWR, pgs. 264-270

(13) Marks Standard Mechanical Engineering Handbooks, pgs. 4-70, Table 11

(14) Raychem Report #79, Penneck, R. J., February 18, 1977

(15) Clabburn, R. J. T., Penneck, R. J., and Swinmurn, C. J., "Some Parameters Affecting the Outdoor Performance of Plastic Materials Used in Cable Accessories," Trans. IEEE, PAS 92 1833-42 (1973).

(16) Nyberg, D. D. and Penneck, R. J., "Improvements in Non-Tracking Materials," 1979 IEEE Underground Transmission and Distribution Conference, CH 1139-5-79-0000-341, pgs. 341-346

(17) Penneck, R. J., Clabburn, R. J. T., and Swinmurn, C. J., "Laboratory Methods Useful in Predicting Outdoor Service Life of High Voltage Insulation Materials"

(18) Occhini, E., "A Statistical Approach to the Discussion of Dielectric Strength in Electric Cables" IEEE paper 72 TP 157 PWR

(19) Metra, P., Occhini, E., and Portinari, G., "High Voltage Cables With Extruded Insulation - Statistical Controls and Reliability Evaluation," Trans. IEEE, PAS 94 (3) pp. 967-75 May-June 1975

(20) Kreuger, F. H., and Bentvelsen, P.A.C., "Breakdown Phenomena in P.E. Insulated Cable," CIGRE Paper 21-05 1972

(21) Simoni, L., and Pattini, G., "A New Research into the Voltage Endurance of Solid Dielectrics," Trans. IEEE, EI, 10 pp. 17-27 March 1975

(22) Lawson, J. H., and Vahlstrom, W., Jr., "Investigation of Insulation Deterioration in 15kV and 22kV Polyethylene Cables Removed from Service Part II," Trans. IEEE, PAS 92 824-35 (See Discussion by G. H. Hunt)

(23) Starr, W. T., and Endicott, H. S., "Progressive Stress-A New Accelerated Approach to Voltage Endurance," Trans. IEEE-PAS 80 Aug. 1961, pp. 515-22

(24) IEEE #4 Standard Techniques for High Voltage Testing. This describes short time artificial pollution tests. Extended time tests are run under similar ambients.

(25) Report of Working Group 12-39 on Weathering of the Insulated Conductor Committee of the IEEE (Principal Author - W. T. Starr) "Proposed Extended Time Artificial Pollution Tests for Polymeric Cable Accessories." Paper No. 845M 503-9 Presented at Summer Power Meeting 1984. (To appear in PAS after 1/85).

APPENDIX A

I. DISCUSSION OF NORMAL OPERATING CONDITIONS

When a temperature rating is assigned to a cable it is assumed that the cable is to be operated at full load for its entire life. Since this is seldom if ever met in practice, this results in a safety factor. It would be useful to examine a hypothetical worst case situation to determine the lowest value which this safety factor might assume.

In order to estimate the safety factor, we must have information on both the worst case temperatures met in service and their frequency of occurrence. We must also know something about the effect of these temperatures on the rate of aging.

In many applications, it is conventional for a newly installed system to be lightly loaded and a full load operation to be achieved only after about 10 years of operation. The load life curve might look like Figure 1A:

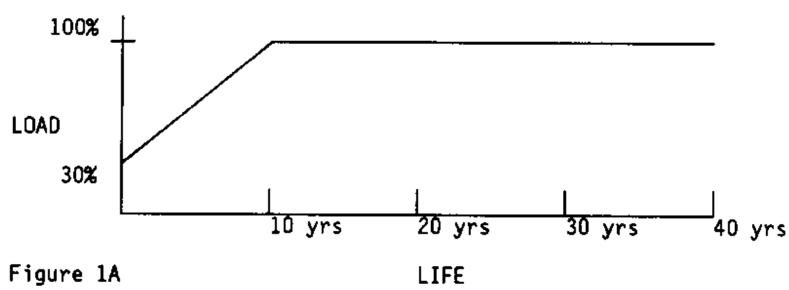


Figure 1A

In addition, during normal operation the load is cyclic, achieving full load levels only a few times during a year, and varying daily between a value of about 30 percent to 70 percent full load. (This is a recognized oversimplification). At 70 percent load, the temperature rise over ambient (ΔT) will be about 50 percent of full load tem- | 2
perature rise, and at 30 percent load ΔT will be about 10 percent. Thus, normally the temperature for a 90°C rated system in a 40°C ambient would vary between 45°C and 65°C. Since the 40°C ambient is defined in AIEE #1 as the extreme ambient for the United States, this condition might be considered as a worst case situation. But let us go farther.

Let us define a worst case situation as one in which the temperature varies in a sinusoidal manner between 50°C and 90°C for the entire lifetime of the cable. This defines the service temperatures and their frequency of occurrence.

Some information on the effect of temperature on the rate of aging is included in this report. The slope of the aging curves defines the apparent activation energy, E. The effect of E on aging rate, R, can be expressed as follows:

$$R = Ae^{-\frac{E}{kT}}$$ 2

where k is the constant 1.97

T is temperature in degrees Kelvin

and A is a constant

but T varies with time, x.

$$T = \bar{T} + \frac{(90 - 50) \sin x}{2} = \bar{T} + 20 \sin x$$ 2

where $\bar{T}$ is the average temperature (273 + 70 = 343 in this case)

So that:

$$R = Ae^{-\frac{E}{1.97\ (343 + 20 \sin x)}}$$ 2

A computer can be used to evaluate the exponential term with an assigned value of E and for incremental values of x. Taking increments of 10° (angle) for x and adding the 36 values obtained in a complete temperature cycle, we obtain a sum. By dividing this sum by 36, we obtain the average aging rate as expressed by the exponential term. Finally, we can determine that temperature which produces this aging rate.

The safety factor is the ratio of the exponential term with 90°C and with the above determined temperature. The following table lists for various values of apparent activation energy the equivalent steady temperature as well as the safety factors:

Apparent Activation Energy (k Cal)	**Equivalent Steady Temperature**	**Safety Factor**
15	74.7°C	2.52
20	76.9°C	2.86
25	78.1°C	3.26
30	79.2°C	3.62

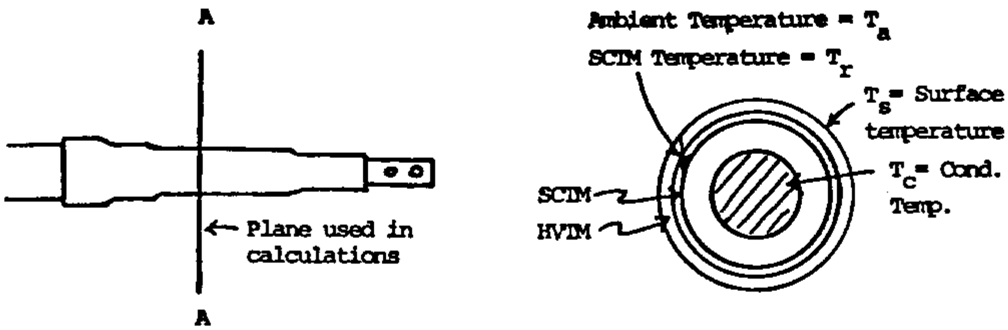
Since the apparent activation energy of the HVTM is about 27.7 k Cal, the rated life temperature corresponding to 90°C rated temperature is about 80°C.

This statement cannot be made about the SCTM. It is not in contact with the conductor and is approximately 10°C cooler than the conductor with a temperature excursion of about 35°C. Its apparent activation energy is 31.5 k Cal. Combining these assumptions in the same type of analysis yields a rated life temperature of 69°C.

These values of Rated Life Temperature are not used in this report. They help to provide perspective with respect to life data. Remember, these values represent an estimate of a worst case situation.

APPENDIX B

II. THERMAL ANALYSIS OF A CABLE TERMINATION



Free Convective Cooling of a Raychem Termination

Use (1) 250 kCM, 15kV, XLPE-175 mils wall thickness
(2) SCTM thickness - 0.08 in.
(3) HVTM thickness - 0.08 in.
(4) Thermal conductivity of all cable materials

$$K = 0.18\ \text{BTU/(hr.)}\ (\text{ft.})^2\ (°\text{F/ft.})^*$$

(5) Combined convective and radiative heat dissipation coefficients $(h_c + h_r)$ for tube with emissivity 0.9 from (13).

Assume

(1) Surface temperature T_s, is uniform around cable.

Technique

The value of $(h_c + h_r)$ varies with temperature difference from cable surface to ambient. Perform first iteration using approximation $(h_c + h_r) = 2.0$. Then select precise value from reference 13. | 4

Step 1 - Heat Balance Equation

$$\frac{2\ KL\ (T_c - T_s)}{\ln D_o/D_i} = (h_c + h_r)\quad D_o\ L(T_s - T_a) \qquad (1a)$$

in consistent units

*Modern Plastics Encyclopedia

L = length (ft.)

D_o = outer diameter (ft.) = 0.1083

D_i = inner diameter (ft.) = 0.0479

substitute in 1a

$0.4413\ (T_c - T_s) = 0.2166\ (T_s - T_a)$

$0.4413\ (194 - T_s) = 0.2166\ (T_s - 104)$

$0.6579\ T_s = 108.14$

so that

$T_s = 164.37°F = 73.5°C$ (First estimate)

and

$T_s - T_a = 60.4°F$

From reference 13 | 4

$(h_c + h_r)$ for $60.4°F = 2.25$

$0.4413\ (194 - T_s) = 0.2437\ (T_s - 104)$

$0.6850\ T_s = 110.96$

and the surface temperature is:

$T_s = 161.98°F = 72.21°C$

<u>Step 2</u> - Temperature T_r at Mean Diameter (D_{sc}) of Stress Control Material

$$T_r = T_c - \frac{\left(T_c - T_s\right) \ \ln \frac{Dsc}{Di}}{\ln \frac{Do}{Di}} \qquad (2a)$$ | 2

$$T_r = 194 - \frac{194 - 161.98}{\ln \frac{0.1083}{0.0479}} \ \ln \frac{0.0886}{0.0479}$$

$T_r = 169.9°F = 76.6°C$ (for $T_c = 90°C$ and $T_a = 40°C$)

In a like manner,

$T_r = 171°F = 77.2°C$ (for $T_c = 85°C$ and $T_a = 55°C$)