DEVELOPMENT OF 500 KV AC CABLE EMPLOYING LAMINAR INSULATION OF OTHER THAN CONVENTIONAL CELLULOSIC PAPER

EPRI Research Project 7810-1
ERDA Contract EX-76-C-01-1426

Final Report

August 1978

Prepared by

General Cable Corporation
800 Rahway Avenue
Union, New Jersey 07083

Principal Investigators:
George Bahder
George S. Eager, Jr.
James J. Walker
Attila F. Dima

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

and

Department of Energy
Office of Energy Technology
Division of Electric Energy Systems
Washington, D. C. 20545

LEGAL NOTICE

ABSTRACT

This final report presents the results of an investigation to develop a 500 kV ac laminar dielectric power cable and joint having insulation with lower losses than conventional cellulosic paper insulation. Background information is presented on proposed low-loss synthetic and composite synthetic/cellulosic paper insulations and experiments covering a period of 20 years. Two types of insulations were chosen from these studies: (1) fibrous polypropylene paper tape and (2) cellulosic paper-polypropylene film-cellulosic paper composite paper (PPP). Extensive testing of hand-wrapped cable models fabricated with each type of tape served to eliminate from further consideration the fibrous polypropylene paper tape. Cable model tests indicate that the PPP tape is satisfactory for insulation in 500 kV ac cable. The cable model tests further indicate that oil impregnants now used in conventional cellulosic paper insulated cables are unsuitable for both types of the above insulation, but that silicone oil with an additive is satisfactory for PPP tapes.

Laboratory data taken on three full-size factory-made prototype pipe-type cables and on a prototype joint indicate PPP insulation is suitable for 500 kV ac operation. Unlike cellulosic tapes, PPP tapes do not permit passage of oil during normal load cycling and the oil must travel through the butt spaces. Consequently, it is necessary to use a significantly lower viscosity impregnating oil which has a greater tendency to drain from pipe-type cables than conventional oil. This may require a moisture seal having higher impedance to the flow of oil than conventional moisture seals and/or a modification of installation techniques to provide assurance that any oil lost from the cable is replaced prior to application of service voltage. Four final pipe-type cables having conventional moisture seal were manufactured in the factory for possible future field testing. The dielectric loss of the final cables is one-fifth that of conventional cellulosic paper insulated cables. The estimated installed cost per MVA-mile of the PPP insulated cable, neglecting the cost of losses, is higher than cellulosic insulated cables impregnated with conventional mineral oil. However, the capacitance of the cable insulated with PPP tape is 25% lower than conventional cable, and therefore, the reactance necessary to compensate for the cable charging current is significantly reduced. The design of a pipe-type cable and joint developed in this project are satisfactory for self-cooled and forced-cooled service at 500 kV. The PPP insulation structure also is suitable for self-contained oil-filled cable systems rated 500 kV ac operating at reasonably high oil pressure.

CONTENTS

CONTENTS (continued)

FIGURES

FIGURES (cont'd)

TABLES

TABLES (continued)

TABLES (continued)

SUMMARY

The objective of this project was to develop a 500 kV ac laminar dielectric power cable and joint having lower losses than conventional cellulosic paper insulated systems of the same rated voltage and to manufacture sufficient lengths of pipe-type cable for field testing at the Waltz Mill Test Site. Initially, polypropylene paper made by the 3M Company was subjected to physical and electrical tests utilizing laboratory cell techniques. This material has satisfactory electrical properties for 500 kV ac cable based on results of the Research Project RP 78-4 initiated by the Electric Research Council. Compatibility tests with naphthenic base mineral oil, paraffinic base mineral oil and synthetic polybutene oils were conducted. All of these oils caused excessive swelling of the 3M paper. Silicone oil was added to the program and on the basis of single sheets, no swelling was observed. Hand-made cable models using factory-slit tapes and having an insulation wall thickness of one inch (25.4 mm) were subjected to special tests which simulate factory processing procedures. These models, 18 inches (45.7 cm) long, sealed at the ends to allow only radial drying and impregnation, were impregnated with each of the above impregnating oils. It was observed that deep longitudinal creases developed in the insulation wall during the impregnating processes. The deep creases are not acceptable and consequently the 3M material is not satisfactory as insulation in EHV cables. Trials were made to eliminate these creases by (1) selected processing changes in the 3M manufacturing process, (2) embossing the 3M paper, (3) placing cellulose tapes at locations such as lay reversals throughout the insulation wall of the cable models, and (4) reducing the drying and impregnating temperatures. None of these trials were successful in eliminating the creases in the insulation wall of the models. Other studies of the 3M paper also revealed that (1) it is difficult to splice the tapes, (2) the density of the material, air resistance, and dielectric strength are quite variable and (3) mandatory low taping tensions used to prevent wrinkling of the tapes causes an excessively soft insulation structure. Consequently, the 3M polypropylene paper was abandoned as a candidate insulation for 500 kV cable.

As the deficiencies of the 3M polypropylene paper became apparent, studies were conducted on cellulosic paper-polypropylene film-cellulosic paper composite

tape (PPP) made by Tudor Pulp & Paper Company. Tests were conducted on two types:(1) a plain PPP composite tape and (2) the same tape, but having an embossed pattern impressed by heat and pressure. Some control tests were made on an earlier GCC composite tape made with cellulosic paper-polyethylene-cellulosic paper. The polyethylene was crosslinked by irradiation to increase the thermal rating and then embossed.

Studies using laboratory cell tests, tests on cable models having an insulation thickness of one inch (25.4 mm), and voltage-soak tests on cable models having 0.030 inch (0.76 mm) insulation thickness indicated that both the plain and embossed PPP tapes are excellent candidates for EHV cables. Dimensional changes in the plain PPP tapes, when exposed to mineral and polybutene oils, were excessive and the use of the plain tape was restricted to silicone oil only. The embossing of the PPP tape permitted the insulation wall of the cable models to absorb the swelling due to the mineral oil and this version of the PPP tape appeared suitable for use with either polybutene oil or silicone oil.

Because of the acceptable properties of the PPP tapes, prototype pipe-type 500 kV cables with plain and embossed PPP tapes, having a tinned copper conductor, size 2000 kcmil (1011 mm^2), and insulation thickness of 1.025 inches (26 mm) were taped in the factory using commercial equipment and processes. The design of a suitable joint with PPP paper was also completed.

The first prototype cable evaluated was made with plain PPP tape and impregnated with silicone oil DC200-200. This oil has a viscosity at 25^{o}C close to that of the mineral oil currently used for pipe filling in commercial pipe-type cables. Prototype Cable No. 1 was subjected to cyclic aging, impulse, dielectric loss, special thermal-decay and high-voltage-time tests. All properties of this cable were satisfactory except for ionization due to oil-starvation found in the thermal-decay test. In this test, the dissipation factor (tan δ) was continuously monitored at the test voltage while the cable cooled from maximum down to the ambient temperature. During thermal decay tests on Prototype Cable No. 1, ionization was often observed which was attributed to oil-starvation. Because of this characteristic, the prototype was removed from test. Due to the presence of ionization, silicone oil gassing tendencies under voltage stress were studied and found to be excessive compared to conventional mineral and polybutene oils.

Prototype Cable No. 2 was manufactured, insulated with embossed PPP tapes and impregnated with a less viscous silicone oil DC200-50 with 5% dodecylbenzene added. This additive gives to silicone oil the property of absorbing small amounts of gasses which may be evolved during short periods of ionization. The use of embossed PPP tapes and lower viscosity oil each provided easier flow of oil through the insulation structure during thermal-decay, and thereby reduced the likelihood of oil-starvation.

Prototype Cable No. 2 was subjected to cyclic aging, thermal-decay, high-voltage-time and impulse tests. No evidence of oil- starvation was found and all electrical properties were satisfactory for 500 kV cable. The use of embossed tapes and low viscosity silicone oil appear to have solved the problem of oil-starvation. However, the embossed tapes are significantly more expensive than plain tapes. It was observed that during impregnation much of the embossing was lost and the cable became too soft for commercial use. Studies on individual emobssed tapes also revealed an undesirable reduction of dielectric strength because of fracture of cellulose fibers in the cellulosic layers.

Prototype No. 3 was manufactured, insulated with plain PPP tapes and the same low viscosity silicone oil as used in Prototype Cable No. 2 except that dodecylbenzene was not added. Thermal-decay tests on this prototype indicated no oil-starvation. The use of the low viscosity oil in combination with plain PPP tapes appears to provide a cable not prone to oil-starvation and not having excessive soft spots. Dielectric loss studies of Prototype Cable No. 3 indicate values within expectations for 500 kV cable. The cable was load-cycled at 1.5 x rated voltage stress at a pressure of 100 psi (7.04 kg/cm^2) and conductor temperature of 100°C. The cable failed 4 hours after the start of the thermal-decay on the 26th daily load cycle.

Examination of the insulation structure indicated radial faults in butt spaces near the conductor. Additional tests of the silicone oil impregnant revealed the dielectric strength of silicone oil could be improved by the use of a special filtered oil, designated DC200-50 EG. These tests also revealed that the DC200-50 EG grade oil has approximately the same voltage breakdown strength as polybutene oil now used on commercial pipe-type cable and is 15% higher than the commercial grade of silicone oil used in Prototypes Nos. 2 and 3.

The final design of the cable was based on data obtained from the three prototype cables and their insulation structure components. To assure an adequate margin of safety the conductor size was increased to 2500 kcmil (1263 mm^2) in place of 2000 kcmil (1011 mm^2), the insulation thickness was increased to 1.20 inches (30.5 mm) in place of 1.025 inches (26 mm) and the thickness of the PPP tapes next to the conductor was decreased to 3 mils (0.075 mm) from 5 mils (0.127 mm). The first two changes decrease the voltage stress in the butt spaces and the third change increases the voltage breakdown stress in the butt spaces near the conductor. Plain PPP tapes were used throughout the insulation structure, but narrower tapes, i.e. 1/2 inch (1.27 cm), 3/4 inch (1.91 cm) and 1 inch (2.54 cm) rather than only 1 inch (2.54 cm), were used throughout the insulation wall to reduce the impedance tothe flow of oil during thermal-decay and to provide a higher margin of safety against oil-starvation. The improved grade of low viscosity silicone oil with 5% dodecylbenzene was used as the impregant and the pipe-filling oil.

Four 400 foot (122 meter) lengths of the final 500 kV pipe-type cable were manufactured in the factory. All normal AEIC specification production tests were conducted except high-voltage full-reel tests. In the full-reel high-voltage test, ionization was observed at approximately 50 kV on the first reel and therefore this test was not conducted on the remaining three lengths. The ionization was due to the drainage of the low viscosity oil following normal factory procedures. This drained oil would normally be replaced by the pipe-filling oil. Further studies would be required, including changes in factory handling, to reduce oil drainage. For current commercial production of pipe-type cable, some customers recognize this drainage characteristic and do not permit full-reel high voltage testing at the factory. The final cables at present are stored under a nitrogen blanket and are available for further field tests.

A length of final cable was removed from the first production length and subjected to special tests in the General Cable EHV Laboratory. A joint made with the PPP tapes was placed in the cable and tested to simulate a commercial joint. The cable and joint were subjected to thermal-decay testing at 1.5 x rated voltage from 80°C and neither the joint nor the cable showed any signs of oil-starvation as judged by monitoring tanδ. The dielectric loss was 20% of conventional 500 kV cable made with cellulosic paper insulation. The cable and joint withstood a high-voltage-time test of 430 V/mil (16.9 kV/mm) average voltage stress for 6 hours. The cable and joint were then subjected to cyclic aging which was aborted during the 11th daily load cycle due to an inadvertant pressure loss which precipitated a failure.

A second replacement length of the final cable was evaluated in the outdoor General Cable EHV Laboratory. Initial measurements of tanδ were taken at ambient temperature of 4°C and indicated a rise in tanδ beginning at 160 kV which indicated ionization in the cable. This rise in tanδ disappeared after several heat cycles to 80°C. Thermal-decay tests were then conducted and no evidence was found of oil-starvation. Thermal-decay tests were conducted at 300 kV using a bridge-type partial discharge detector and no evidence of partial discharge was detected in the cable. One of the terminals used on the test set-up had about 1000 picocoulombs discharge at 300 kV. The sample was subjected to further load cycling up to a conductor temperature of 90°C and voltages as high as 1.25 times rated voltage. There was no apparent deterioration of the cable during this cyclic loading. It is believed that the final cables are satisfactory for further field testing. This testing should include a full investigation of ionization which may be present in the cable if it is energized initially at low temperature. During this project there was not time to investigate this phenomena which became evident at the end of the project. If the initial ionization is significant, it may affect subsequent operation of the cable.

Section 1

INTRODUCTION

1.1 BASIC REQUIREMENTS OF SYNTHETIC TAPES FOR 500 KV CABLES

For over 20 years,various laboratories have studied polymeric insulation materials with low dissipation factor (tan δ) to determine their suitability for use in laminar dielectric power cables rated 500 kV and higher. The studies have been conducted because self-cooled power cables having cellulose paper insulation have excessive dielectric loss and excessive charging currents for long self-cooled circuits rated 500/550 kV and for most self-cooled circuits rated 765 kV and higher. The potential maximum MVA rating for self-cooled HPOF pipe-type cable insulated with conventional cellulose paper peaks at a voltage slightly higher than 550 kV. Further increase in voltage under the self-cooled mode does not yield any increase in MVA capability.[1]

The dissipation factor (100 tan δ) of high quality cellulose paper is approximately 0.18 and the dielectric constant approximately 3.5. The judgment of most investigators is that 100 tan δ should not exceed 0.10 in order to justify the use of insulation tapes made of polymeric materials and that a value not exceeding 0.06 at operating temperature is desired. Most polymeric materials under consideration for insulation tapes have dielectric constants in the range 2.2 to 2.5. The judgment of most investigators is that the dielectric constant should not exceed 2.5. Thus, if a synthetic material having a 100 tan δ of 0.06 and a dielectric constant of 2.5 is employed on 500 kV cable in place of the high quality conventional cellulose material, the dielectric loss will be reduced by a factor of approximately 4, and the cable charging current reduced by approximately 30%.

---

(1) G. Bahder, et al, "550 kV and 765 kV High Pressure Oil-Filled Pipe Cable System", IEEE Trans., Vol. PAS-95, No. 2, pp 478-488, March/April 1976

Aside from the above electrical requirements of polymeric materials, the voltage breakdown strength is important and it is desirable that this property exceed cellulose paper so that the insulation thickness of the cable can be maintained equal or less than cable with cellulose paper insulation.

Mechanical properties of the synthetic material are extremely important. The synthetic tape must have sufficiently high modulus of elasticity in tension so as to maintain its dimensions and not elongate during the taping operation in the factory. The tape must have sufficient stiffness so as to not wrinkle when the cable is bent during installation or handled in the factory particularly prior to impregnation, and for the same reasons the synthetic tape, when sliding on itself, must have a reasonably low coefficient of friction. The tensile strength must be sufficiently high so that the tape does not break during taping on high-speed commercial taping heads and the tearing strength must be reasonably high so tearing does not occur at tape edges during taping and during bending of the cable if the butt spaces become excessively small. In addition to these mechanical properties it is desirable to have a material which is permeable to air and oil so that the cable can easily be vacuum dried and impregnated and oil can flow readily during cooling periods when the cable is in service.

1.2 BASIC REQUIREMENTS OF IMPREGNATING AND PIPE-FILLING OILS

The impregnating and pipe-filling oils currently used in pipe-type cable systems where the insulant is cellulosic paper are the result of many investigations, fairly well documented in the literature. The electrical properties of these oils are most important. The important electrical properties are (1) voltage breakdown strength, (2) dissipation factor, (3) dielectric constant, and (4) stability of electrical properties under high voltage stress and operating temperature conditions. The physical properties are also important in pipe-type cables. The important physical properties are (1) viscosity, (2) gassing tendencies, (3) thermal transfer characteristics, (4) freezing characteristics, (5) coefficient of expansion, and (6) stability of these properties under high voltage stress and operating temperature conditions.

If cellulosic paper insulation is replaced with synthetic insulation in a pipe-type cable, the above electrical and physical properties remain important, but in addition, compatibility of the oils with the synthetic insulation becomes an important property. This is because the suitable synthetic insulations for high voltage cables are of the polymeric type and have a tendency to swell and to dissolve in oils forming a wax-like substance in the butt spaces of the tapes. This compatibility problem turned out to be one of the major areas of the present investigation as none of the oils currently used in cellulosic paper insulated cables was found to be compatible with the polymers chosen.

In a cable insulated with polymeric tapes the voltage breakdown of the oils is more critical than in a cable insulated with cellulosic tapes. The weak spots in the insulation structure are the butt spaces which contain oil only. Polymeric materials have higher voltage breakdown than cellulosic paper and have a lower dielectric constant. To compensate for the higher voltage stress in the butt space because of the lower dielectric constant of the insulation tapes, the voltage strength of the oil should be higher when used with polymeric tapes. To take advantage of the higher voltage breakdown strength of the polymeric tape, the voltage strength of the oil should be higher in the synthetic insulated cable.

A requirement of insulation tapes for polymeric cables is low dissipation factor. Therefore, the oils used in synthetic cables must have lower dissipation factor at all operating temperatures so as not to raise the dielectric loss of the insulation structure.

The viscosity of the impregnating oil must be sufficiently low to flow between and through the insulation tapes during periods of cable cooling, otherwise, a deficiency of oil will develop in localized areas of the insulation structure thus creating voids where localized ionization may occur at operating voltage stress. On the other hand, it is desirable that the impregnant have sufficient viscosity so as not to drain from the cable while in storage or enroute from the factory to installation in the pipe. Drainage could be reduced if the impregnant has a low coefficient of expansion; however, this physical property does not vary significantly between available oils.

The viscosity of the pipe-filling oil must be low so that it can readily flow in and out of the insulation structure during daily load cycles. Impregnating oil flows from the insulation structure during each cycle as the conductor becomes heated and when the conductor cools the pipe-filling oil must readily move into the insulation structure to prevent local ionization. If the pipe-filling oil is force cooled, the viscosity of the oil must be low to permit pumping at reasonable cost.

If local ionization occurs in the insulation structure, the gassing properties of the oil become important. Ionization causes decomposition in the oil and one of the products of decomposition is hydrogen, usually in small quantities. If the oil rejects the hydrogen, the gaseous regions become larger and ionization increases finally causing voltage breakdown of the structure. On the other hand, if the oil can absorb small quantities of gas, the insulation structure will maintain its integrity. Consequently, it is desirable to use oils which are gas absorbers.

The thermal conductivity of oil should be as high as possible to facilitate the conductivity of heat from the conductor and thereby increase the MVA capacity of a given configuration or system.

1.3 PAST STUDIES OF SYNTHETIC INSULATING TAPES

The IIT Research Institute conducted a 5 year study[(2)] to determine polymers suitable for extra-high-voltage cables for the Edison Electric Institute.

This study was concluded in 1967. Cable models were used to establish the suitability of selected polymeric insulations and oils. The cable model tests were performed on seven polymers: PPO, FEP, TFE, Polycarbonate, Polysulfone, Poly-4-Methylpentene and Polysiloxene Terpolymer in conjunction with four dielectric oils: Polybutene 15-H, Sun XX, Paraffinic Mineral Oil and Silicone Oil. The study showed that TFE, PPO, Polysulfone, Polycarbonate, and Poly-4-Methylpentene can be used in extra-high-voltage insulation and can be expected to exhibit low and stable dissipation factor values. No full-size cables were made during this study.

The AKZO Laboratories, Arnheim, Holland investigated polymeric materials for extra-high-voltage insulation. This investigation established that Poly-2, 6-Diphenyl-Para-Phenylene Oxide is a suitable material. This material was abandoned before full evaluation for use on high voltage cables could be completed because it was too expensive.

Other laboratories have conducted investigations to develop a polymeric insulation for high voltage cables. The 3M Company studied the applicability of their proprietary polypropylene paper under the Electric Research Council Research Project RP 78-4 and established that their paper had sufficient promise for high

(2) IIT Research Institute Report No. IITRI-U-8001-57 dated Dec. 31, 1967

voltage cable to warrant further study by a cable company. The present project was devised to initially study the 3M material.

General Cable Corporation Research Center has investigated many new materials and improved cellulosic papers which may be suitable for high voltage cables since about 1950. A tabulation of the important materials studied is given in Table 1-1. This table presents selected key electrical and physical properties only, chosen as the most pertinent concerning cables. In most cases extensive testing including cable models; and in some cases full-size high voltage cables were fully evaluated. A typical cellulose paper is included in the tabulation in order to permit a comparison to the other candidate materials. In all cases, the data presented were taken in the General Cable Research Center using test techniques as used to establish properties for cellulosic paper materials and similar techniques were used on all materials to permit a direct comparison. The Gurley stiffness and the air resistance were corrected to 5 mils (0.127 mm) tape thickness to permit a direct comparison as a 5 mil (0.127 mm) thick tape material was not always available. The dielectric constant and dissipation factor were measured at 100°C as this is the proposed maximum operating temperature of a synthetic insulated cable. The maximum processing temperature is presented in Table 1-1 because this is an important property pertaining to factory drying and impregnation procedures. The most promising high voltage insulation material from the General Cable investigations is PPP - a cellulose paper - polymeric film-cellulosic paper composite tape.[3] This composite tape in one form is made commercially by Tudor Pulp and Paper Company. The PPP tape, consists of two layers of cellulose paper having low dissipation factor with extruded polypropylene film between them. The three components are calendered together immediately after the polypropylene film is extruded so as to form a high bond between the three components without the use of adhesives. This form of PPP tape, which appeared to be the most promising for high voltage cables, was proposed for complete evaluation in full-size cables in the event the 3M polypropylene tape was found unsuitable.

(3) U. S. Patent 3194872 July 13, 1965 - Garner

Table 1-1

IMPORTANT POLYMERIC INSULATIONS FOR HIGH VOLTAGE POWER CABLES
INVESTIGATED BY GENERAL CABLE RESEARCH CENTER

:YPE OF MATERIAL	MANUFACTURER	DIELECTRIC CONSTANT, (1) AT 100°C	DISSIPATION FACTOR, (1) 100 TAN δ, AT 100°C	AIR RESISTANCE, GURLEY SECONDS	MODULUS OF ELASTICITY IN TENSION, psi X10^{-5}	M.D. GURLEY STIFFNESS, (2) at 25°C	MAXIMUM PROCESSING TEMP., °C
ulose Paper	Tudor Pulp & Paper	3.50	0.18	650	6.50	375	130
styrene Film	Dow Chemical	2.50	0.03	∞	2.40	-	75
ethylene Film	DuPont	2.25	0.02	∞	1.00	60	90
Film	DuPont	2.10	0.03	∞	0.50	70	250
Film	DuPont	2.10	0.03	∞	0.58	70	200
ethylene- phtalate Film	DuPont	3.25	1.30	∞	5.50	375	150
propylene Film	DuPont	2.10	0.06	∞	1.25	36	150
carbonate Film	General Electric	3.20	0.04	∞	3.00	200	150
imide Film	DuPont	2.28	0.20	∞	4.00	112	500
imide Paper	DuPont	3.31	0.50	∞	-	210	500
ethylene Tere- late Paper	DuPont	2.30	0.26	0	-	37	150
acrylonitride Paper	American Cyanimid	3.45	5.60	11.5	-	108	200
Density ethylene Paper	DuPont	1.45	0.03	145	0.55	44.8	115
Density ethylene Film	Phillips Petroleum	2.17	0.06	∞	0.67	126	115
ethylene Encapsulated ulose Fiber Paper	National Lead	2.53	7.97	∞	-	453	90
ulose Paper-Polypropylene -Cellulose Paper Composite	Tudor Pulp & Paper	2.38	0.07	∞	10.0	290	120
-Siloxsone Film	Delaware Res. & Dev.	2.12	0.05	∞	0.60	18	150
phenylene Oxide Film	General Electric	2.50	0.07	∞	3.60	114	140
ulose Paper-Polyethylene -Cellulose Paper Composite	GCC Experimental	2.30	0.05	∞	8	500	90
ulose Paper-Polyethylene -Cellulose Paper Composite- diated	GCC Experimental	2.40	0.06	∞	9	500	130
-4-Methylpentene Film	Imperial Chemical Industries	2.20	0.10	∞	1.6	-	200
fied Polyphenylene Oxide	General Electric	2.70	0.08	∞	3.5	-	150
tetrafluoroethylene Paper	3M	2.30	0.14	12	-	8	260
amide Paper	3M	2.30	0.17	160	-	-	200
propylene Paper	3M	2.20	0.04	9700	-	110	130
ous Porous TFE	Chemplast	2.30	0.14	12	-	7.0	250
ester Fiber Paper	3M	2.90	1.30	11.5	-	80	150
sulfone Film	Union Carbide	2.90	0.14	∞	-	100	-
ulose Paper- propylene Composite	Union Mills	2.65	0.18	∞	-	835	150

:s: (1) Measured at 60 Hz, 50 V/mil
(2) Corrected to 5 mil (0.127 mm) thickness
(3) All paper and composite materials, electrical properties measured after impregnation with polybutene oil

1.4 SCOPE OF PROJECT

The scope of this project was (1) to investigate polypropylene paper tape as manufactured by the 3M Company and PPP tape as manufactured by Tudor Pulp & Paper Company and to establish the design criteria and manufacturing conditions for a 500 kV ac cable and normal joint, (2) to manufacture sufficient quantity of completed 500 kV ac pipe-type cable and normal joints for evaluation at Waltz Mill, and (3) to subject the cable for Waltz Mill to qualification testing prior to furnishing such cable and joint materials for evaluation at Waltz Mill.

1.5 METHODS OF EVALUATION

1.5.1 Preliminary Tests

Limited laboratory tests were conducted to establish final specifications of the insulation tapes to be used in the project.

1.5.2 Model Cable Tests

Model cables made in the laboratory by hand served to establish the final composition of the 3M and the PPP tapes. Tests for compatibility with suitable oils and other cable components such as metals, etc. were conducted. Dimensional and electrical stability was established by aging tests and voltage soak tests on models. All pertinent electrical and mechanical properties of the tapes were established on the actual tapes employed in cable models. Preliminary studies were made to obtain some information on the complete impregnation cycle.

1.5.3 Prototype Cable Evaluation

Full-size 500 kV ac cables having plain and embossed PPP tapes as insulation were designed and manufactured on regular factory taping equipment. These prototype cables were vacuum dried and impregnated in a special 70 foot pipe made for the purpose. The complete impregnation cycle was established.

Selected mechanical tests, including physical properties of the insulation tapes, cold bend, and installation-handling were performed on the prototype cables.

Selected electrical testing including dielectric loss tests, radial power factor tests, impulse tests, high-voltage-time tests and load cycle tests up to a conductor temperature of 100°C and voltage up to 1.5 times operating were conducted on the prototype cables. Thermal-decay tests were conducted to establish if there was evidence of oil-starvation within the insulation structure. These tests were conducted by continuously monitoring the dissipation factor during cooling periods up to 5 hours.

A normal joint was designed and subjected to the above electrical testing.

1.5.4 Final Cable Evaluation

Four lengths of 500 kV pipe-type cables having tinned copper segmental conductor size 2500 kcmil (1266 mm^2), insulation thickness of 1.20 inches (30.5 mm) using plain PPP tapes and impregnated with silicone oil were manufactured. Selected mechanical tests, including cold bend tests, were conducted on samples. Full-reel dissipation factor tests were performed.

Selected electrical tests including dielectric loss, radial power factor and load cycle tests were conducted. Thermal-decay tests were conducted to establish if there was evidence of oil-starvation within the insulation structure. These decay tests were conducted by continuously monitoring the dissipation factor and partial discharge during cooling periods up to 5 hours.

Section 2

INVESTIGATION OF INSULATING TAPES AND IMPREGNANTS

2.1 DESCRIPTION OF INSULATING TAPES

Two principal materials were investigated for use as insulating tapes. One was a paper-like material made of polypropylene fibers by the 3M Company. This material had been developed during Research Project RP 78-4 sponsored by the Electric Research Council. The other material was a laminate, or sandwich, consisting of a layer of extruded polypropylene film between two sheets of cellulosic paper. This material, designated "PPP", was provided by the Tudor Pulp & Paper Company. This material has been used commercially in capacitors and designated Type 45810 Polycoat.

An alternate tape composed of fibrous polypropylene made by Riegel Paper Company under license from Exxon Corporation and a tape made of poly-2, 6-dephenyl-para-phenylene oxide (Tenax) developed by AKZO Laboratories, Arnheim, Holland were evaluated. However, as explained in Appendix 1, these materials were abandoned after preliminary testing.

2.1.1 Polypropylene Paper Tape

Table 2-1 contains the description of 3M polypropylene paper provided for each lot received during the project. The thickness was nominally 5 mils (0.127 mm) or 8 mils (0.203 mm) and the surface either plain or embossed. Each roll was 15 inches (38.1 cm) wide.

Rolls from each lot of material were slit into tapes 1 inch (2.54 cm) and 3/4 inch (1.91 cm) wide on a commercial slitting machine normally used with cellulose paper. The slitting was accomplished with difficulty because the rolls contained numerous splices that were weak, and in many cases incomplete across the full width of the roll.

Table 2-1

LIST OF INSULATING TAPES STUDIED

3M Polypropylene Paper Tape		
FOR PRELIMINARY EVALUATION	SURFACE	NOMINAL THICKNESS, MILS (mm)
XO-5713, Lot 22-44	Plain	5 (0.127)
XO-5713, Lot 22-510	Plain	5 (0.127)
SL-34248, Lot 113	Embossed (Burlap Pattern)	7 (0.178)
SL-34248, Lot 118	Plain	8 (0.203)
SL-34248, Lot 119	Embossed (Burlap Pattern)	10 (0.254)
Tudor PPP Laminate Tape		
FOR PRELIMINARY EVALUATION		
Lot A102A	Plain	5 (0.127)
623P	Plain	5 (0.127)
623E	Embossed (Leather Grain Pattern)	6 (0.152)
1110P	Plain	8 (0.203)
1110E	Embossed (Leather Grain Pattern)	8 (0.203)
FOR PROTOTYPE CABLES		
Lot 117	Plain	5 (0.127)
Lot 118	Plain	8 (0.203)
Lot 117	Embossed (Leather Grain Pattern)	6 (0.152)
Lot 118	Embossed (Leather Grain Pattern)	9 (0.229)
FOR FINAL CABLES		
Lot 172	Plain	3 (0.076)
Lot 117	Plain	5 (0.127)
Lot 173	Plain	8 (0.203)

Note: 1) The cellulosic layers of the 3 mil (0.076 mm) and a portion of the 8 mil (0.203 mm) PPP laminates for the final cables were made of low alpha pulp.

2) See Appendix 1 for information or polypropylene paper made by Riegel and Tenax made by Akzo.

During slitting, occasional minor imperfections such as holes, dirt spots, translucent slashes of melted paper, and creases that went diagonally across the width of a roll were observed in the paper. The 3M Company personnel felt that these imperfections could be eliminated during larger production runs.

2.1.2 PPP Laminate Tape

Included in Table 2-1 are descriptions of the lots of PPP that were received during the project. The thickness was either 5 mils (0.127 mm) or 8 mils(0.203 mm) and the surface either plain or embossed. Later in the project, PPP material having a thickness of 3 mils (0.076 mm) was evaluated. The thickness of each of the two cellulose paper components in PPP tape is approximately 1 mil (0.025 mm) and the thickness of the extruded polypropylene film is adjusted to achieve the desired total thickness. In all cases the cellulose paper for the PPP tapes is deionized water washed. The embossing was performed by Stauffer Chemical Company. The lots of PPP were slit without any difficulty on the same machine as used for the 3M polypropylene paper. PPP is a likely candidate as the cable insulating material because it has the basic attributes of low dielectric loss and high dielectric strength afforded by the synthetic component while possessing physical properties, such as stiffness and surface friction, about the same as conventional all-cellulosic paper.

The extruded polypropylene layer of the PPP laminate in all cases was Tenite 409 supplied by Eastman Chemical Products.

A potential deficiency in PPP tape is occasional micro-voids in the extruded polypropylene film. However, an examination of the cross-section of many specimens did not reveal any voids included in the film. PPP tape is impervious preventing radial flow of the impregnant which may result in the formation of isolated gaseous pockets within the insulation structure at operating voltage when the cable cools.

2.2 DESCRIPTION OF IMPREGNANTS AND PIPE-FILLING OILS

During the early investigative stage of the project, several different types of oils were evaluated as possible impregnants and pipe-filling oils. These included naphthenic and paraffinic mineral oils, polybutene and silicone oils. Table 2-2 is a list of the oils investigated.

Table 2-2

IMPREGNANTS AND PIPE-FILLING OILS INVESTIGATED
TYPES AND VISCOSITY

TYPE	COMMERCIAL DESIGNATION	MANUFACTURER	VISCOSITY, SUS at 37.8°C	at 98.9°C(i)
Naphthenic Mineral Oil	Sun XX(a)	Sun Oil Co.	3750	110
	Sun 6(b)	Sun Oil Co.	775	60
	Mobilect A(c)	Mobil Oil Co. (no longer made)	100	40
Paraffinic Mineral Oil				
	Mohawk 3.5(d)	Mohawk Indus. Inc.	1750	110
	Imprego 130-P(e)	Mohawk Indus. Inc.	1840	125
	2280(f)	Sun Oil Co.	2640	155
Polybutene Oil				
	15H(a)	Amer. Oil Co.	3600	165
	50(b)	Amer. Oil Co.	550	60
	015SH(a)	Cosden Oil Co.	3600	165
	06SH(b)	Cosden Oil Co.	575	60
	OSH	Cosden Oil Co.	150	40
	Blend C	Oronite Chem. Co.	3300	160
	50% 15H-50% 50	Amer. Oil Co.	1740	95
Silicone Oil				
	SF96-1000(g)	Gen. Elect. Co.	3700	1500
	SF97-100(h)	Gen. Elect. Co.	370	140
	200-50(g)	Dow Corning Co.	190	75
	200-200(g)	Dow Corning Co.	730	290
	200-350(g)	Dow Corning Co.	1300	540
	200-50 EG(h)	Dow Corning Co.	190	75

Notes:

(a) Commonly used as an impregnant for pipe-type cable
(b) Commonly used as a pipe-filling oil for pipe-type cable
(c) Commonly used as an impregnant for self-contained cable
(d) Approx. composition: 11% aromatic, 18% naphthenic, 71% paraffinic
(e) Approx. composition: 0% aromatic, 33% naphthenic, 67% paraffinic
(f) Approx. composition: 4% aromatic, 25% naphthenic, 71% paraffinic
(g) Commercial grade
(h) Electrical grade
(i) ASTM D88
(j) A small amount of dodecylbenzene was added to the silicone oil used in one prototype and the final cable.

2.3 EVALUATION OF INSULATING TAPES AND IMPREGNANTS

2.3.1 Physical and Electrical Tests on Sheets of Insulating Tapes

3M Polypropylene. A general investigation of the physical and electrical properties was made on single sheet specimens. Typical data are given in Table 2-3. The most significant observation is the wide variation in air resistance. This non-uniformity is excessive for EHV cable. This accounts for the large variation in dielectric strength. For example, typical variation in cellulose paper having the same thickness would be 400-800 Gurley seconds, i.e., a 2 to 1 variation.

The stiffness of the 3M polypropylene paper is low compared to cellulose paper. For example, a typical value for cellulose paper of the same thickness as the 3M paper data presented in Table 2-3 is 1500 mg Gurley instead of 172 maximum. This physical property is important because in the final cable construction each tape bridges the butt space of a radially adjacent tape, and a stiffer tape can resist collapsing into the butt space as a result of pressure developed during bending. Stiffness is also important because, for a given coefficient of friction, stiffer tapes have less tendency to buckle during bending of the cable. Embossing the plain material did not improve the friction angle or the stiffness. The elongation of both the plain and embossed tapes is satisfactory, and not significantly different than cellulose paper tapes. Aside from the extreme and unsatisfactory variation in voltage breakdown the electrical properties are satisfactory for cables rated 550 kV.

PPP Laminate. The results of physical and electrical tests performed on single sheet specimens of plain and embossed 5 mil (0.127 mm) PPP are given in Table 2-5. The friction angle and the stiffness in the machine direction are comparable to values for cellulose paper and these parameters are not changed significantly by embossing. The 100 tanδ of the plain and embossed PPP laminate is approximately 0.07 which is equivalent to 3M polypropylene paper. Embossing significantly lowered the dielectric strength of the PPP tape. The minimum value was reduced from 2270 V/mil (89.4 kV/mm) for the plain material to 1580 V/mil (62.2 kV/mm) for the embossed, but this latter level is above the average for 3M polypropylene paper and comparable to cellulose paper.

Table 2-3

TYPICAL PHYSICAL AND ELECTRICAL PROPERTIES OF 3M POLYPROPYLENE PAPER

PAPER-THICKNESS 8 MILS (0.203 mm)

AS RECEIVED (DRY)	PLAIN	EMBOSSED (a)
Thickness, mils, (mm)	7.8(0.20)-8.9(0.23)	9.40(0.24)-10.6(0.27)
Air Resistance, Gurley Sec., range	89-2565	100-740
Apparent Density, gm/cm^3, range	0.59-0.64	0.51-0.57
Stiffness, mg, Gurley		
MD	172	167
CMD	127	77
Friction Angle, degrees		
MD	13	16
CMD	18	18
AFTER IMPREGNATION IN COSDEN 015SH OIL		
Tensile Strength, lb/in width (kg/cm)		
MD	26.4(4.72)	17.0(3.04)
CMD	12.6(2.25)	7.5(1.34)
Elongation at Break, %		
MD	3.1	3.3
CMD	3.0	4.2
Tearing Strength, gm		
MD	250	211
CMD	328	257
Folding Endurance, double folds		
MD	1000+	1000+
CMD	1000+	1000+
100 Tan δ, at 50 V/mil (1.97kV/mm) & 60 Hz		
25°C	0.02	0.03
80°C	0.05	0.06
100°C	0.07	0.09
Dielectric Constant at 50 V/mil (1.97kV/mm) & 60 Hz		
25°C	2.2	2.2
80°C	2.2	2.2
100°C	2.2	2.2
Dielectric Strength, at 25°C & 60 Hz, V/mil (kV/mm)	920(36.2)-1458(57.4)	741(29.2)-1403(55.2)

Notes: (a) Burlap pattern embossing

(b) See Appendix 3 for references to applicable ASTM Specification Test Methods for individual tests.

Table 2-4

PHYSICAL AND ELECTRICAL PROPERTIES PPP TAPE-
THICKNESS 8 MILS (0.203 mm)

AS RECEIVED (DRY)	PLAIN	EMBOSSED (a)
Thickness, mils, (mm)	7.6(0.19)-7.9(.20)	7.8(0.198)-8.5(.22)
Air Resistance, Gurley Sec.	Infinity	Infinity
Apparent Density, gm/cm^3, range	0.77-0.78	0.77-0.79
Stiffness, mg, Gurley		
MD	511	408
CMD	315	206
Friction Angle, degrees		
MD	15.3	16.3
CMD	15.7	16.7
AFTER IMPREGNATION IN AMERICAN 15H OIL		
Tensile Strength, lb/in width (kg/cm)		
MD	37.0(6.62)	38.0(6.80)
CMD	21.6(3.86)	23.8(4.26)
Elongation at Break, %		
MD	1.1	1.4
CMD	2.2	2.3
Tearing Strength, gm		
MD	80	80
CMD	154	130
Folding Endurance, double folds		
MD	1000+	1000+
CMD	1000+	1000+
100 Tan δ, at 50 V/mil (1.97kV/mm) & 60 Hz		
25°C	0.02	0.03
80°C	0.05	0.06
100°C	0.07	0.08
Dielectric Constant at 50 V/mil (1.97 kV/mm) & 60 Hz		
25°C	2.2	2.2
80°C	2.2	2.2
100°C	2.2	2.2
Dielectric Strength at 25°C & 60 Hz, V/mil (kV/mm)	1476(58.1)-2100(82.7)	1396(55.0)-1795(70.7)

Note: (a) Leather grain pattern by Stauffer Chemical Company

(b) See Appendix 3 for references to applicable ASTM test methods for individual tests.

The results of physical and electrical tests performed on a single sheet of the 5 mil (0.127 mm) plain and embossed samples are given in Table 2-5. The stiffness of the embossed 5 mil (0.127 mm) is signifcantly less than for the plain 5 mil (0.127 mm) material. As expected from previous work, the friction angle is nearly the same for both plain and embossed tapes and comparable to that of cellulose paper. The folding endurance in both the machine and cross-machine directions for both the plain and embossed tapes is very high, more than 1000 double folds. The minimum value of 1400 V/mil (55 kV/mm) for the dielectric strength of the embossed tape is lower than the lower value of 1580 V/mil (62.2 kV/mm) found previously on the 5 mil (0.127 mm) embossed tape. This, most likely, is due to the thicker polypropylene film.

Later in the development program, PPP material having a total thickness of 3 mils (0.076 mm) was investigated for use in the final cable. The results of physical and electrical tests on sheets of this material are given in Table 2-6. At the time of this procurement, high alpha cellulose paper was not available and this tape was made with cellulose paper having a low alpha content. Tan δ of the 3 mil (0.076 mm) is high compared to tan δ of the 8 mil (0.203 mm) PPP tape because of the higher proportion of cellulose to polypropylene.

In order to investigate the ability of the impregnant to flow across the face of a PPP laminate, as will occur in cable, a special oil transmission test was devised. The apparatus is shown in Figure 2-1. A one inch (2.54 cm) wide tape specimen was formed into a continuous loop and placed over a 1/8 inch (0.33 cm) hole at the top of a 7/8 inch (2.22 cm) O.D. metal tube which was mounted horizontally and filled with oil. A one pound (454 grams) weight at the bottom of the looped specimen of tape kept the tape at the top of the loop in close contact with the area around the hole in the oil-filled tube. The time necessary to transmit 5 ml of oil transversely across the face of tape and also transversely through the cellulose paper on the side of the tape in contact with the oil-filled tube was measured as an indication of the oil transmission capability of an oil and tape combination. The results of these tests are given in Table 2-7. Roughly, for both plain and embossed PPP tapes, the transmission capability of DC200-50 silicone oil is at least twice that of the heavier DC200-200 silicone oil.

Table 2-5

PHYSICAL AND ELECTRICAL PROPERTIES OF PPP TAPE-
THICKNESS 5 MILS (0.127 mm)

AS RECEIVED (DRY)	PLAIN	EMBOSSED (a)
Thickness, mils, (mm)	4.6(0.117)-5.1(.13)	5.4(.137)-6.6(.168)
Air Resistance, Gurley Sec.	Infinity	Infinity
Apparent Density, gm/cm^3, range	0.85-0.86	0.85-0.87
Stiffness, mg, Gurley		
MD	335	357
CMD	168	153
Friction Angle, degrees		
MD	16.1	17.1
CMD	17.2	16.8
AFTER IMPREGNATION IN COSDEN 015SH POLYBUTENE OIL		
Tensile Strength, lb/in width (kg/cm)		
MD	33(5.90)	29(5.19)
CMD	17(3.04)	16(2.86)
Tearing Strength, gm		
MD	80	83
CMD	119	132
Folding Endurance, double folds		
MD	1000+	1000+
CMD	501	82
100 Tan δ , at 50 V/mil (1.97kV/mm) & 60 Hz		
25°C	0.05	0.04
80°C	0.04	0.05
100°C	0.06	0.08
Dielectric Constant at 50 V/mil (1.97kV/mm) & 60 Hz		
25°C	1.9	1.7
80°C	1.9	1.7
100°C	1.9	1.9
Dielectric Strength, at 25°C & 60 Hz V/mil (kV/mm)	2270(89.4)-3330(131)	1580(62.2)-2180(85.8)

Note: (a) Leather-grain pattern by Stauffer Chemical Company

(b) See Appendix 3 for references to applicable ASTM test methods for individual tests.

Table 2-6

PHYSICAL AND ELECTRICAL PROPERTIES OF PPP TAPE - THICKNESS 3 MILS (0.076 mm)

	PLAIN
AS RECEIVED (DRY)	
Thickness, mils (mm)	3.0(.076)
Air Resistance, Gurley sec.	Infinity
Apparent Density, g/cm^3	0.79
Stiffness, mg, Gurley	
MD	101
CMD	37
Friction Angle, degrees	
MD	14.7
CMD	15
Ply Separation, lb/in width (kg/cm)	
MD	0.1(17.9)
CMD	0.08(14.3)
AFTER IMPREGNATION IN DC200-50EG OIL	
Tensile, lb/in width (kg/cm)	
MD	35(6.26)
CMD	15(2.68)
Elongation, %	
MD	1.7
CMD	2.7
Tear, gm	
MD	30
CMD	40
Dielectric Constant, avg. at 25°C, 80°C, & 100°C	2.28
Dielectric Strength, at 25°C, 60 Hz V/mil(kV/mm)	2500(98.4)-3000(118.0)
100 Tan δ, at 50 V/mil (1.97kV/mm)	
at 25°C	0.16
80°C	0.13
100°C	0.16

Note: See Appendix 3 for references to applicable ASTM test methods for individual tests.

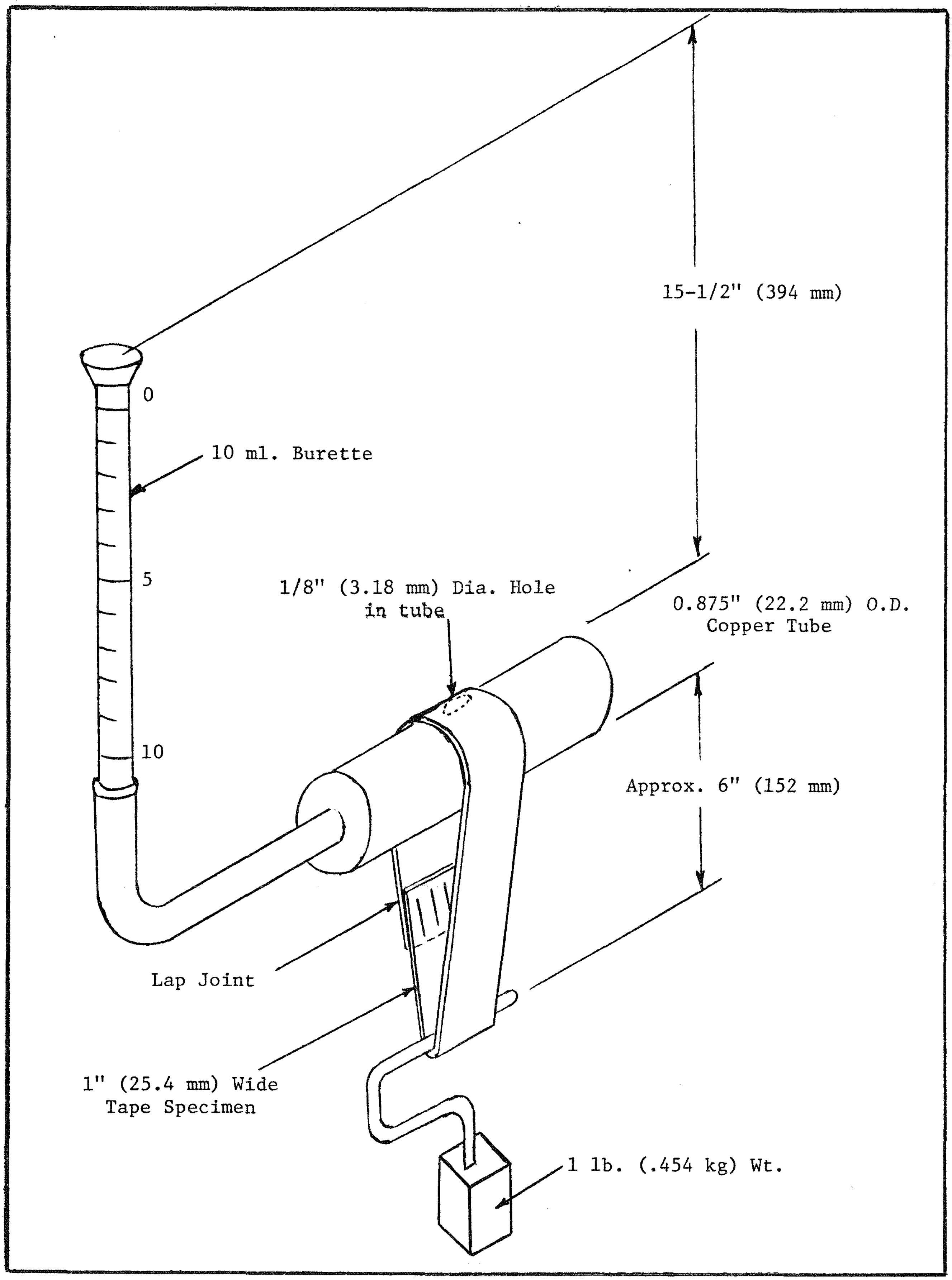


Figure 2-1. Test Set-Up for Oil Transmission Along PPP Tapes

Scale: None

Table 2-7

OIL TRANSMISSION TEST-PPP TAPE

TYPE OF IMPREGNANT	TIME, HOURS TO TRANSMIT 5 ML OF OIL	
	FOR 8 MIL (0.203 mm) TAPE	
	PLAIN	EMBOSSED
DC200-200	18	14
DC200-50	8	1
	FOR 5 MIL (0.127 mm) TAPE	
	PLAIN	EMBOSSED
DC200-200	92	13
DC200-50	9	5

2.3.2 Compatibility Between Insulating Tapes and Impregnants

Two basic tests were used to evaluate compatibility between insulating tapes and impregnants. One test involved immersion of an unrestrained specimen of the material in the impregnant at elevated temperature. At periodic intervals the specimen was removed from the impregnant and changes in the dimensions were measured. In the second test, a cable model was made of six 5 mil (0.127 mm) thick tapes of the material under investigation wound with controlled tension on a 12 inch (30.48 cm) long metal mandrel, the same lay and normal overlay pattern. After drying under heat and vacuum the model was impregnated at a controlled temperature with the impregnant under investigation. During dissection of the model, compatibility was indicated by visual examination for physical distortion and dissolution of the insulating material.

In addition to the two basic compatibility tests an additional test was performed by placing unrestrained insulating papers in impregnants at elevated temperatures to establish the solubility of the insulation in the oil.

Vacuum drying and impregnating procedures performed on cable models, later discussed in detail in Section 2.3.3, also are indicative of compatibility between insulating tapes and impregnants and the results are included in this section.

3M Polypropylene Tape - Compatibility Tests. An investigation was made on the dimensional stability of unrestrained single tapes immersed in oil at 100°C for three weeks. Measurements of tape width, length and thickness were taken every seven days and are given in Figure 2-2. It can be seen that the paraffinic oil caused the least change in length and width, 2.50% and 3.25%, respectively, compared to about 3.50% and 4.50%, respectively, for the other oils. Distortion stabilized for these dimensions in one or two weeks. The change in thickness data are not as consistent. Of particular interest is the apparent shrinkage which occurred in the presence of three of the oils. This shrinkage, which seems to be inversely related to the viscosity of the oils, is probably due to dissolution of the material which affected the thickness measurements. These thickness measurements were made with a constant-pressure, motor-driven, automatic micrometer.

In Table 2-8 are given the data obtained using cable models made of six tapes of either 3M polypropylene paper, plain or embossed to determine compatibility with possible impregnating oils. Also shown are data with PPP tapes used to mechanically support the more fragile polypropylene tapes. These data show that, except for silicone oil, all other impregnants caused wrinkling or longitudinal creases in the 6-tape models of plain or embossed 3M polypropylene paper. Two models were impregnated at reduced temperatures, 50°C and 25°C, but the distortion was unchanged.

The solubility of 3M polypropylene paper was determined for several representative oils at 75°C and 110°C as shown in Table 2-9. These data show that 3M polypropylene is significantly less soluble in the two paraffinic oils, Mohawk 3.5 and Imprego 130-P, than in the polybutene and naphthenic oils. The data for the polybutene oils show that solubility is inversely related to viscosity.

In order to establish suitable factory processing, drying and impregnating conditions for a cable insulated with 3M polypropylene tapes, tests on cable models having an insulation thickness of 1 inch (25.4 mm) were conducted.

The results of these tests, as explained in Section 2.3.3, show that the 3M tapes are not compatible with the polybutene and mineral oils studied because of excessive wrinkling. PPP support tapes used in the insulation structure of 3M tapes did not significantly reduce the wrinkling. When silicone oil was used as the impegnant there was no distortion.

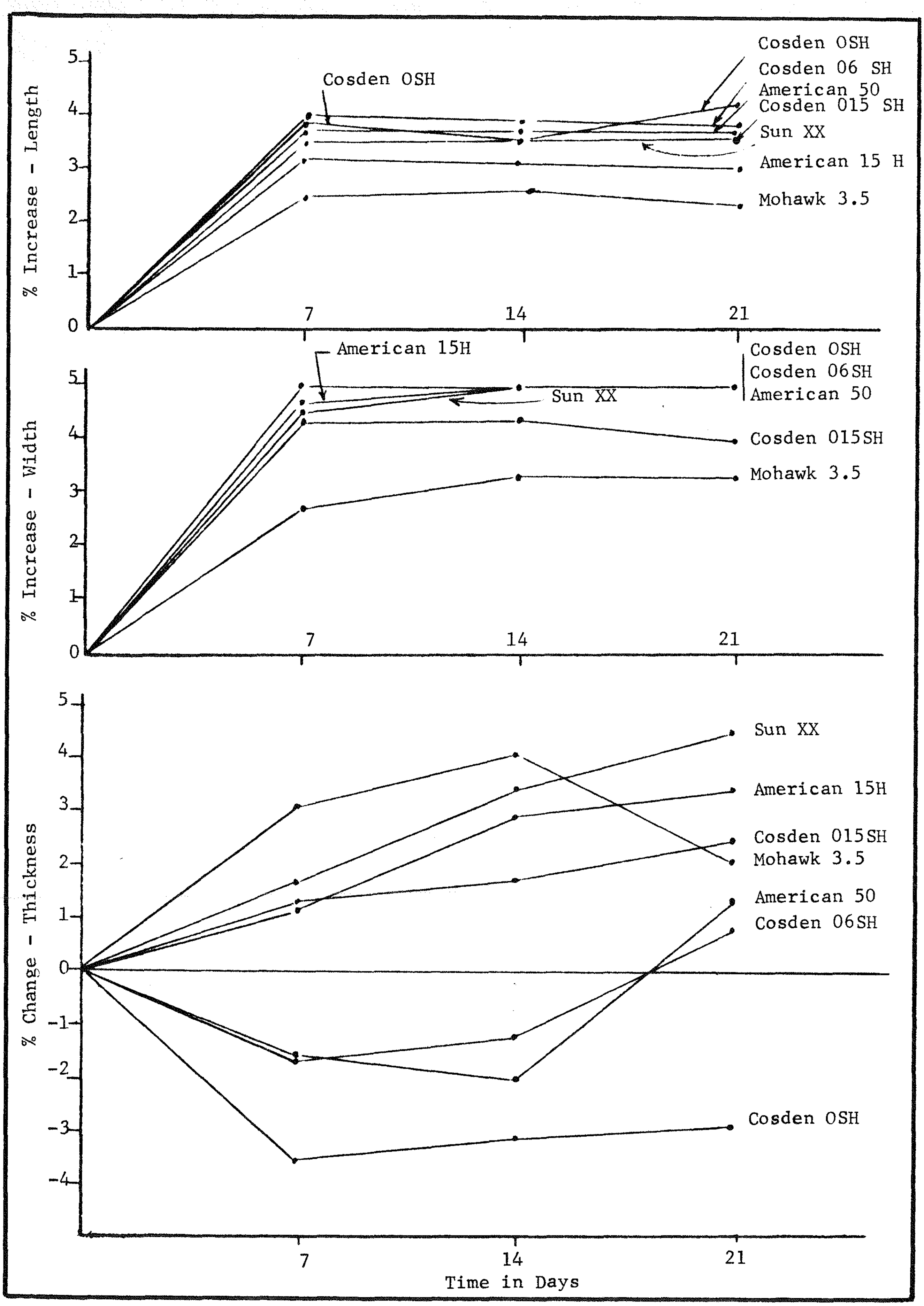


Figure 2-2. Compatibility of 3M Polypropylene Paper in Oils at 110°C

Table 2-8

3M POLYPROPYLENE PAPER TAPES
COMPATIBILITY WITH OILS USING CABLE MODELS

MODEL NO.	IMPREGNANT	VISUAL EXAMINATION
	Plain 3M Polypropylene Paper (a)	
1	Sun XX	Tapes Wrinkled
2	Mobilect A	Tapes Wrinkled
3	Mohawk 3.5	Tapes Wrinkled
4	Mohawk 3.5 (e)	Tapes Wrinkled
5	Imprego 130-P	Tapes Wrinkled
6	American 50 (b)	Tapes Wrinkled
7	Cosden 015SH	Longitudinal Creases
8	Cosden OSH	Tapes Wrinkled, Longitudinal Creases
9	Cosden OSH (c)	Each Tape Collapsed into Butt Space of Adjacent Tape. No Wrinkles
10	Oronite Blend C	Tapes Wrinkled, Longitudinal Creases
11	G.E. SF96-1000	No Wrinkles
12	American 15H (b)	Slight Longitudinal Creases
13	50% American 15H 50% American 50	Longitudinal Creases
	Embossed 3M Polypropylene Paper (a)	
1	Sun XX	Tapes Wrinkled, Longitudinal Creases
2	Mobilect A	Tapes Wrinkled
3	Mohawk 3.5	Tapes Wrinkled, Longitudinal Creases
4	Cosden 015SH	Tapes Wrinkled
	Plain 3M Polypropylene Paper and Tudor Plain PPP Support Tapes (d)	
1	Sun XX	3M Tapes Swell into Butt Spaces of PPP Tapes. Some Wax, No Wrinkles.
	Plain 3M Polypropylene Paper and Tudor Embossed PPP Support Tapes (d)	
1	Sun XX	3M Tapes Swell into Butt Spaces of PPP Tapes. No Wrinkles.

Notes:
(a) Models made with six 1 inch (2.54 cm) tapes wound with 750 gm tension, same lay and normal taping pattern on 12 inch (30.5 cm) metal mandrel of 1-3/8 inch (34.9 mm) diameter. Models vacuum dried at 100°C for 2-1/2 to 3 days and impregnated at 110°C for approximately 20 hours.
(b) Impregnated at 50°C instead of 110°C.
(c) Impregnated at 25°C instead of 110°C.
(d) Same as (a), but constructed of two 3M polypropylene tapes, one PPP tape two 3M polypropylene tapes, and one PPP tape.
(e) On Model 4 the impregnant was same as on Model 3, but clay treated.

Table 2-9

3M POLYPROPYLENE TAPE - SOLUBILITY IN VARIOUS OILS AT ELEVATED TEMPERATURES

TYPE OF OIL	WEIGHT LOSS, PERCENT			
	AFTER AGING AT 75°C		AFTER AGING AT 110°C	
	FOR 7 DAYS	FOR 28 DAYS	FOR 7 DAYS	FOR 28 DAYS
Sun XX	0	0.39	0.59	0.84
Mohawk 3.5	0	0	0	0.18
Imprego 130-P	0	0	0	0.15
American 15H	0.57	0.76	0.76	1.02
Cosden 015SH	0.61	0.75	0.76	0.83
Cosden OSH	0.81	2.00	2.82	2.99

PPP Tape - Compatibility Tests. An investigation was made on the dimensional stability of unrestrained single tapes immersed in oil at 110°C for three weeks. There was no change in either width or length, only a change in thickness. The data were taken every seven days and are given in Figure 2-3. It is evident that the plain PPP tapes swelled about 20 to 30% in thickness, while the embossed specimens expanded only 3 to 9% in the oils used. Apparently, the embossing absorbed some of the distortion. The group of three paraffinic oils used in this investigation produced the least expansion on the embossed PPP tape. Silicone oil produced a slight decrease in thickness of both the plain and embossed PPP specimens.

In Table 2-10 are the results of visual examinations made on cable models composed of either 6 plain or 6 embossed PPP tapes after drying under heat and vacuum and impregnation with various oils. In no case was there any physical distortion of the PPP material. However, when impregnation was performed at 110°C with naphthenic, paraffinic or polybutene oils, the polypropylene component of the PPP laminate dissolved in the impregnant and formed wax. At reduced temperature the effect of dissolution was not detected visually. In the silicone oil there was no formation of wax. The film component of the PPP material is not a polypropylene homopolymer, but a copolymer with about 10% polyethylene. The wax found in the butt spaces of some model cables was identified as dissolved polyethylene.

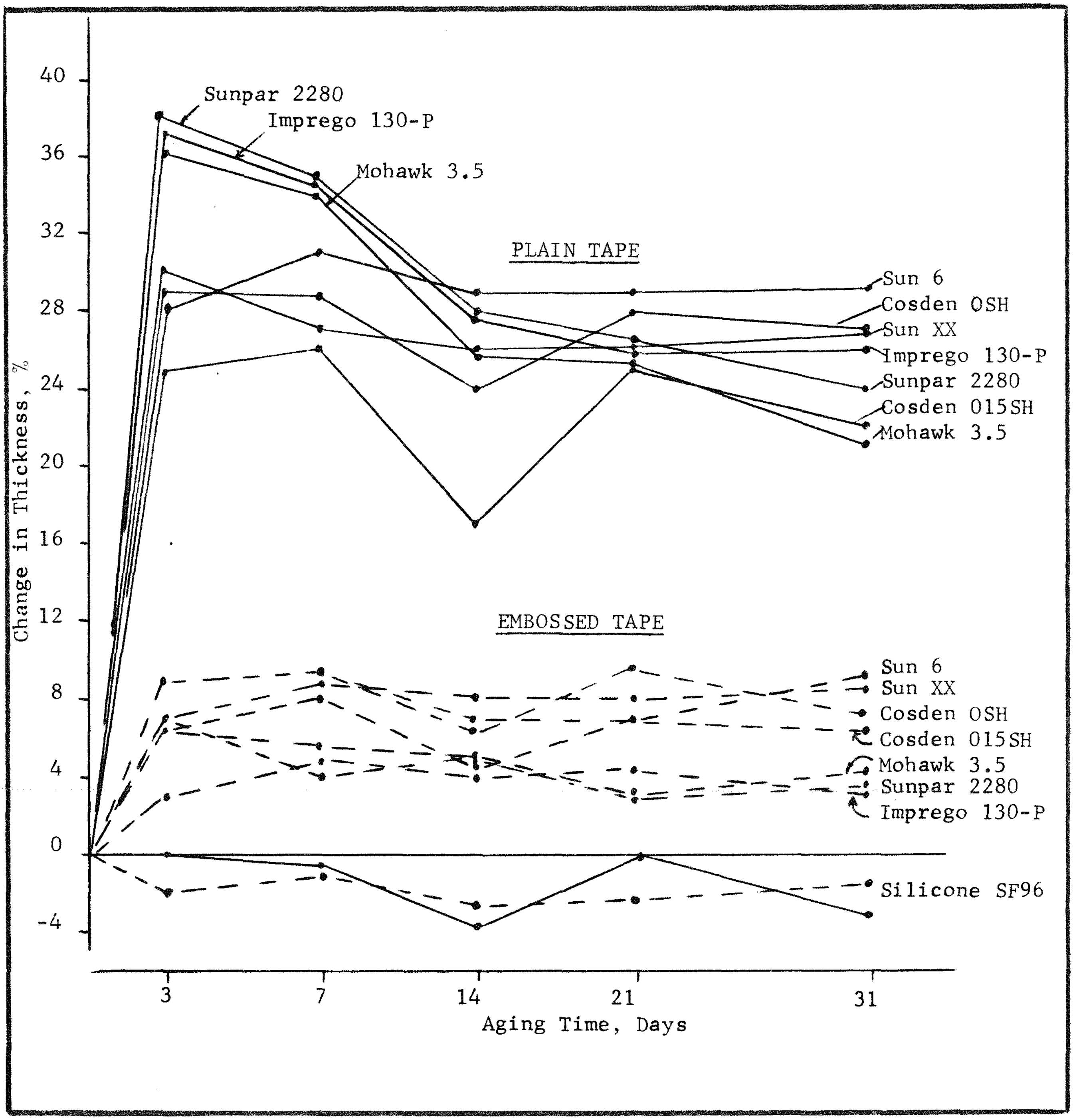


Figure 2-3. Compatibility of PPP Tapes in Oils at 110°C

Table 2-10

PPP TAPES -
COMPATIBILITY WITH OILS USING CABLE MODELS

MODEL NO.	IMPREGNANT	VISUAL EXAMINATION
	Plain PPP	
1	Sun XX	No Wrinkles. Wax in Butt Spaces
	Embossed PPP	
1	Sun XX	No Wrinkles. Wax in Butt Spaces
2	Mohawk 3.5	No Wrinkles. Wax in Butt Spaces
3	Imprego 130-P	No Wrinkles. Wax in Butt Spaces
4	Cosden 015SH	No Wrinkles. Wax in Butt Spaces
5	Cosden OSH	No Wrinkles. Wax in Butt Spaces
6	Cosden OSH (b)	No Wrinkles. No Wax
7	Oronite Blend C	No Wrinkles. Wax in Butt Spaces
8	G.E. SF96-1000	No Wrinkles. No Wax
9	American 15H (c)	No Wrinkles. No Wax
10	50% American 15H- 50% American 50	No Wrinkles. Slight Wax in Butt Spaces

Notes: (a) Models made with six 1 inch (2.54cm) wide tapes wound with 1500 gm tension, same lay and normal taping pattern on 12 inch (30.5 cm) metal mandrel of 1-3/8 inch (34.9 mm) diameter. Models vacuum dried at 100°C for 2-1/2 to 3 days and impregnated at 110°C for approximately 20 hours.

(b) Impregnated at 25°C instead of 110°C.

(c) Impregnated at 50°C instead of 110°C.

Solubility tests were made on samples of PPP tape aged in various oils at 75°C and 110°C with an oil/paper ratio of 5/1 and at 85°C and 110°C with an oil/paper ratio of 1.5/1 by volume. The results of these tests are given in Table 2-11. The oil/paper ratio of 1.5/1 and the temperature of 85°C were chosen to nearly coincide with conditions as they may exist in the wall of an actual cable. At 110°C, the solubility of PPP in polybutene oils is less for an oil/paper ratio of 1.5/1 than for an oil/paper ratio of 5/1 while for Sun XX oil the solubility is about the same. The low viscosity polybutene Cosden OSH oil had the greatest effect on solubility.

On cable models having a 1 inch (25.4 mm) wall of PPP laminate (see Section 2.3.3) polybutene oils dissolved some of the polypropylene and formed wax. When silicone was used as the impregnant no wax was formed.

During preliminary tests, various blends of dodecylbenzene were used with silicone oil, and based on the swelling effect of a 5% mixture on PPP as given in Table 2-12, for example, and the gas-absorption property of several mixtures as given in Table 2-22, a mixture of 5% dodecylbenzene with DC200-50 EG silicone was used in the final cable.

Silicone oil has very little effect on the change in dimensions of the PPP tape. In view of the fact that in later prototype and final cables 5% dodecylbenzene was added to reduce gassing tendencies of the silicone oil, a compatibility test was conducted on this mixture. The results are given in Table 2-12. It is seen that the dodecylbenzene when added to silicone oil has a significant, but acceptable swelling effect on the PPP tape.

Table 2-11

SOLUBILITY OF PPP TAPES IN VARIOUS OILS
AT ELEVATED TEMPERATURES

TYPE OF OIL	PPP Tape			
	WEIGHT LOSS, PERCENT (a)			
	AFTER AGING AT 75°C		AFTER AGING AT 110°C	
	FOR 7 DAYS	FOR 28 DAYS	FOR 7 DAYS	FOR 28 DAYS
Sun XX	0.43	0.80	3.1	6.9
Mohawk 3.5	0.29	0.80	6.0	6.4
Imprego 130-P	0	0.57	1.3	5.5
American 15H	1.0	-	5.2	6.8
Cosden 015SH	0.64	0.96	3.7	8.6
Cosden OSH	1.21	2.10	11.3	17.0
	WEIGHT LOSS, PERCENT (b)			
	AFTER AGING AT 85°C		AFTER AGING AT 110°C	
	FOR 7 DAYS	FOR 28 DAYS	FOR 7 DAYS	FOR 28 DAYS
Sun XX	0.4 (c)	0.4 (c)	3.8	7.6
Cosden 015 OSH	(d)	1.0	1.3	4.4
Cosden OSH	(d)	3.2	4.1	13.4

Notes: (a) Oil/paper ratio = 5/1 by volume
(b) Oil/paper ratio = 1.5/1 by volume
(c) This apparent discrepancy is within the accuracy of the measurement.
(d) Trace amount of polymer dissolved in oil.
(e) Weight loss related to polymeric component only.

Table 2-12

CHANGE IN THICKNESS OF
PLAIN PPP TAPES IMPREGNATED WITH
MIXTURE OF SILICONE OIL AND DODECYLBENZENE

	95% DC200-50 5% DODECYLBENZENE (ALKYLATE 21) INCREASE IN THICKNESS DURING AGING AT 100°C, PERCENT OF ORIGINAL THICKNESS					
Measured After Days:	1	2	4	7	14	21
5 mil (0.127 mm)	-0.7	-0.9	-0.2	-0.9	-2.4	-0.7
8 mil (0.203 mm)	1.8	2.4	2.7	2.6	1.4	1.9

Notes:
1. Samples aged under unrestricted conditions.
2. Sample size 3-1/2 inches (8.8 cm) x 1 inch (2.54 cm).
3. All measurements made at room temperature.
4. There was no increase in width or length of the tapes.

Assessment of Compatibility Tests. Normal impregnants such as polybutene oil and mineral oil caused swelling of the 3M polypropylene tapes which resulted in distortion of the insulation when applied to cable models. For the PPP tapes, normal impregnants such as polybutene oil and mineral oil caused dissolution of the polypropylene film which made the impregnant more viscous and formed wax in the butt spaces of cable models. Silicone oil has no significant swelling effect on either the 3M polypropylene paper or the PPP laminate.

2.3.3 Laboratory Preliminary Trials of Vacuum-Drying and Impregnation Using Cable Models

In order to investigate the problems related to vacuum-drying and impregnation, 18 inch (45.7 cm) long cable models having an insulation wall thickness of 1 inch (25.4 mm) were made with 1 inch (25.4 mm) wide tapes applied with controlled tension and normal taping patterns to a 1-3/8 inch (34.9 mm) diameter hollow copper tube having numerous holes to simulate the effect of a stranded conductor. The ends of the model were sealed to insure radial drying and impregnation and to reproduce the factory process at the center of a long length of cable. During drying and impregnation, capacitance and tan δ were monitored to insure satisfactory completion of each step. Each model was installed in a steel container with suitable electrical and hydraulic fittings, and the container was placed in an air oven. During impregnation, the oil pressure was increased in steps according to the type of oil and temperature, but for each model the maximum pressure was 70 psig.

Two typical examples of distortion observed on the 1 inch (25.4 mm) wall models made with 3M polypropylene tapes are included in Figure 2-4.

3M Polypropylene Tape. In Table 2-13 is a summary of data obtained on one inch (25.4 mm) wall cable models made with 3M polypropylene tapes.

The drying time for Model No. 1 made with plain tapes was four days. This time was established by capacitance measurements and is considered reasonable. The impregnation time was 1 day, but the innermost 26 tapes of a total of 200 were not impregnated. In the impregnated portion of the insulation wall there were several severe longitudinal creases approximately 1/4 inch (6.4 mm) deep. These creases are related to the swelling of the 3M tapes by the 015 SH polybutene oil. The inner 26 dry tapes were not distorted. A similar type of distortion appeared in the compatibility tests on a cable model having 30 mils (0.76 mm) of insulation and impregnated with the same oil.

Model No. 2 made with plain tapes developed longitudinal creases approximately 1/4 inch (6.4 mm) deep as a result of swelling of the 3M polypropylene tape in the American 50 polybutene oil which was at 25°C when applied to the cable model maintained at 110°C.

Model No. 3 made with plain 3M tapes was impregnated at 90°C with General Electric SF97-100 silicone oil. There were no longitudinal creases in this model. There was, however, a slight longitudinal ridge which may have resulted from raising the pressure too quickly at some point in the impregnation process. The absence of longitudinal creases indicates that the silicone oil is more compatible with 3M tapes than the other oils tested. This confirms data taken on models having a thickness of 30 mils (0.76 mm). However, the silicone oil in the simulated hollow conductor of the model, was cloudly and the 100 tanδ of the oil at 100°C increased from a value of 0.01, as received, to 0.70. Radial power factor measurements on the tapes in this model showed a gradual increase in 100 tanδ from 0.12 for the outermost tape to a high of 0.90 for the 190th tape from the outside. Obviously, the oil became contaminated during impregnation. An infrared analysis of the oil from the simulated hollow conductor of the cable model revealed that the contaminant was likely an additive (such as in antioxidant or stabilizer) to the 3M polypropylene tape.

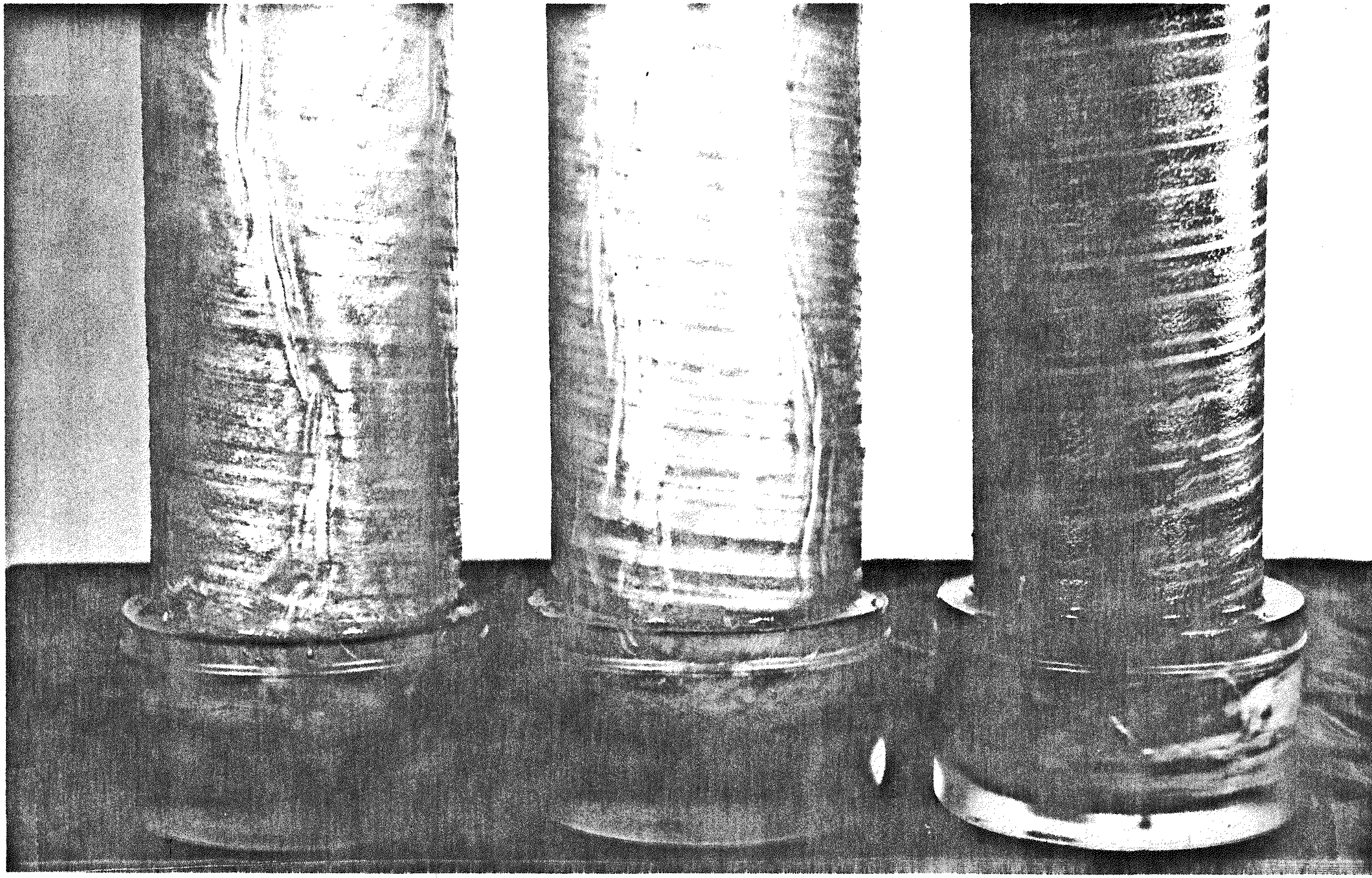


Figure 2-4. Effects of Impregnation on Cable Models with Insulation Thickness of 1 Inch (25.4 mm)

Left: Embossed 3M Polypropylene Paper Impregnated with American 15H at 90°C
Center: Plain 3M Polypropylene Paper Impregnated with Cosden 015SH at 90°C
Right: Embossed PPP Impregnated With Cosden 0SH at 90°C

Table 2-13

DRYING AND IMPREGNATION TIMES OF CABLE MODELS
HAVING ONE INCH (25.4 mm) OF 3M POLYPROPYLENE TAPE INSULATION

	Vacuum Drying		Impregnation				
			Oil				
Model No.	Temp. °C	Time Days(b)	Type	Viscosity SUS at 98.9°C	Temp. °C	Time, Days(c)	Remarks
			Plain 3M Polypropylene Tape (a)				
1	100	4	Cosden 015SH	165	90	1	Longitudinal Crease. Inner 26 Tapes Dry.
2	110	5	American 50	550(d)	25	4	Longitudinal Creases
3	110	4	G.E. SF97-100	140	90	3	Slight Ridge.
			Plain 3M Polypropylene Tape With Support Tapes (a)				
1(e)	110	2	American 15H	165	90	2	3M Tapes Swollen Into Butt Spaces of Adjacent Tapes
2(e)	110	2	50% American 15H-50% American 50	95	50	3	3M Tapes Swollen Into Butt Spaces of AdjacentTapes
3(f)	110	1	Imprego 130-P	125	50	3	Longitudinal Creases or Ridge
			Embossed 3M Polypropylene Tape (g)				
1	110	4	American 15H	165	90	3	Longitudinal Creases

Notes:
(a) Each model consisted of 200 tapes, 5 mils (0.13mm) thick and 1 inch (25.4mm) wide, wound in a normal taping pattern on a 1-3/8 inches (35mm) diameter perforated copper tube. Winding tension was 750 grams. The direction of the tape lay was reversed every 10 tapes.
(b) Determined by stabilization of capacitance measurements. Time is in 24 hour days and includes weekends in some cases.
(c) Determined by stabilization of capacitance measurements. Time is in 8 hour days. Changes in impregnation pressure were made during working hours only.
(d) Viscosity at 37.8°C.
(e) 1st, 5th, 6th and 10th tape of each lay group was a 6 mil (0.15mm) embossed PPP support tape.
(f) 1st and 10th tape of each lay group was a 6 mil (0.15mm) embossed PPP support tape.
(g) Same as note (a) except 165 tapes, 7 mils (0.18mm) thick and 1 inch (25.4mm) wide, were used.
(h) Drying and impregnation were performed in a suitable steel container.

The model made with embossed 3M tapes and impregnated at 90^{o}C with American 15H polybutene oil developed longitudinal creases, 1/4 inch (0.64 cm) deep, as a result of swelling of the 3M tapes in the presence of that oil.

Three models were tested having one inch (25.4 mm) walls made with 3M tapes and support tapes. The results from these models are included in Table 2-13. When a support tape was used as the 1st and 10th tapes of each group of ten tapes applied with alternate lay, longitudinal creases were present through the insulation wall of the model. This is similar to the distortion observed on models made without support tapes. When a support tape was used as the 1st, 5th, 6th and 10th tape of each lay group composed of 10 tapes, the swelling of each 3M tape was concentrated at the butt space of the radially adjacent tapes. Each 3M tape had a ridge, or two, that was along the length of the tape.

PPP Tape. A summary of data obtained on one inch (25.4 mm) wall cable models made with PPP tape is given in Table 2-14. Plain PPP tapes were used in three models having one inch (25.4 mm) wall thickness. Model No. 1 was dried and impregnated at normal temperature using Amoco 15H polybutene which is a normal saturant for high pressure oil filled cable. Model No. 2 was impregnated with a polybutene oil having much lower viscosity and the impregnation time was significantly reduced. Model No. 3 was dried at a lower temperature initially, to reduce swelling of the composite paper, but this did not lessen drying time. During dissection of these cable models after impregnation with polybutene oil, a viscous fluid was found in the tape butt spaces and within the simulated hollow conductor. This viscous material was analyzed by infra-red spectrophotometer and found to be a combination of degraded and oxidized polypropylene and polybutene oil. This wax was formed through partial solution of the polypropylene component of the laminate in the 90^{o}C polybutene impregnating oil as it moved radially into the cable by way of the tape butt spaces. As the wax formed, it was pushed toward the simulated conductor, where its concentration was greatest. The 100 tanδ of the wax from Model No. 1 of the plain PPP full-wall series of models was measured and found to be 0.05 at 50 V/mil (2.0 kV/mm) and 100^{o}C. In other words, the wax does not have high tan δ .

Table 2-14

DRYING AND IMPREGNATION TIME OF CABLE MODELS
HAVING ONE INCH (25.4 mm) OF PPP TAPE INSULATION USING POLYBUTENE OIL

Plain PPP Tape (a)

	Vacuum Drying		Impregnation				
			Oil				
Model No.	Temp., °C	Time, Days(c)	Type	Viscosity SUS at 98.9°C	Temp, °C	Time, Days(d)	Remarks
1	110	12	Amer. 15H	165	90	11	Wax
2	125	11	Amer. 50	60	90	3	Wax
3	60&110(b)	14	Amer. 15H	165	90	12	Wax
			Embossed PPP Tape (e)				
1	110	7	Amer. 15H	165	90	3	Pressure Ridge Slight Wax
2	110	5	Cosden OSH	40	90	3	No Wax
3	110	9	Amer. 15H	165	50	8	Pressure Ridge No Wax
4	110	4	50% Amer. 15H- 50% Amer. 50	95	90	21 Hours(f)	No Ridge No Wax
			Embossed PPP Tape (g)				
1	110	2	Amer. 50	60	90	14 Hours(f)	No Ridge No Wax

Notes:
(a) Each model consisted of 200 tapes, 5 mils (0.13mm) thick and 1 inch (25.4mm) wide, wound in a normal taping pattern on a 1-3/8 inch (35mm) diameter perforated copper tube. Winding tension was graded from 800 to 1500 grams. The direction of the tape lay was reversed every 10 tapes.
(b) The drying began at 60°C, later increased to 110°C when it was found that drying was not effective at 60°C.
(c) Determined by stabilization of capacitance measurements. Time is in 24 hour days and includes weekends in some cases.
(d) Determined by stabilization of capacitance measurements. Time is in 8 hour days.
(e) Same as note (a) except 180 tapes, 6 mils (0.15mm) thick and 1 inch (25.4mm) wide were used and tension graded from 800 to 1200 grams.
(f) Impregnation performed continuously.
(g) Same as note (a) except 80-6 mil (0.15mm) and 70-8 mil (0.20mm) tapes were used.
(h) Drying and impregnation were performed in a suitable steel container.

Model No. 1 made with embossed PPP tapes was treated at the same temperatures for vacuum drying and impregnation and the same oil as used in Model No. 1 with plain PPP tapes. The vacuum drying time was reduced from 12 to 7 days and the impregnation time from 11 to 3 days. It is apparent that embossing is an effective means of reducing both the drying and impregnation times. There was no heavy concentration of wax in the tape butt spaces of this model as for each of the identical models with plain PPP tapes. However, inside the hollow tube that simulated the conductor, the oil was very viscous. The viscosity of the oil in the tube was 301 SUS at 98.9°C compared to 165 SUS for the impregnating oil at the same temperature. The 100 tanδ of the heavy oil was measured and found to be 0.01 at 50 V/mil (2.0 kV/mm) and 100°C. There was a slight longitudinal ridge in the insulation wall of the embossed PPP full-wall model that appeared at about mid-wall and persisted to within 10 tapes of the conductor. This was, most likely, due to raising oil pressure too rapidly.

Model No. 2 made with embossed tapes was treated in the same manner as No. 1 except that a polybutene oil of lower viscosity was used. No visible wax was produced by the low viscosity oil.

For embossed Model No. 3, which was impregnated with American 15H polybutene at 50°C over a period of 8 days, there was no wax.

The same result was obtained on embossed Model No. 4 which was impregnated with a blend of 50% American 15H and 50% American 50 at 90°C in 21 hours. This impregnation was carried out on a continuous basis (rather than during normal working hours only) to evaluate an impregnation process that would be suitable for commercial processing.

A model composed of both 6 mil (0.15 mm) and 8 mil (0.20 mm) embossed PPP tapes, was impregnated with American 50 oil at 90°C in 14 hours on a continuous basis. There was no wax present in this model.

Because silicone oil was found to be the only oil which did not swell polypropylene cable models were prepared for use with different silicone fluids.

In Table 2-15, it may be seen that a temperature of at least 125°C is necessary to vacuum-dry a full-wall cable composed of plain PPP tapes in a reasonable time of 4 days. Reduced taping tensions (Model No. 2) and the use of an embossed tape for every fifth tape in the insulation wall (Model No. 3) had no significant effect on the drying time. The influence of the viscosity of the silicone impregnating fluid and temperature during impregnation are also evident.

Model No. 4, which had 5 mil (0.127 mm) and 8 mil (0.203 mm) plain PPP tapes and was impregnated with DC200-200 silicone oil, represented a conventional cable construction where the inner tapes are normally used in the high voltage stress area at the conductor.

The oil from the simulated hollow conductor of each model was either cloudy or slightly discolored, and very viscous. This contamination is very likely the result of the antioxidant being leached from the film of the PPP tape. However, this dissolution did not adversely affect the tanδ of the silicone oil or the radial power factor of the tapes.

2.3.4 Cable Models for Mechanical Bend Tests

In order to investigate the bending characteristics of a cable made with different materials, mechanical cable models were made with tapes wound on a flexible mandrel. The models were bent over cylindrical forms of selected diameters and the results observed visually. The flexible mandrel was composed of a 7 foot (182.9 cm) long 500 kcmil (253 mm^2), 37 wire concentric copper conductor insulated with rubber to an outside diameter of 1.7 inches (43.2 mm). Over this mandrel, 8 tapes were applied with right hand lay followed by 8 more with left hand lay. All tapes were applied with typical tensions and overlay patterns. In actual practice, after taping, the dry cable would experience only one bend around the take-up reel. In the model tests, however, four reverse bends were made to insure pessimistic results.

Table 2-15

DRYING AND IMPREGNATION TIMES OF CABLE MODELS HAVING ONE INCH (25.4 mm) OF PPP TAPE INSULATION USING SILICONE OIL

Plain PPP Insulating Tapes

			Impregnation				
	Vacuum Drying		Oil				
Model No.	Temperature, °C	Time, Days (f)	Dow Corning Silicone, Type	Viscosity, SUS at 98.9°C	Temperature, °C	Time Hours, (g)	Remarks
1(a)	110(e)	14	200-50	75	90	20	Oil at conductor cloudy
	125	3					
2(b)	110(e)	6	200-350	540	90	48	Impregnation incomplete. Longitudinal ridge in insulation.
	125	10					
	130	4					
3(c)	125	4	200-350	540	125	49	Oil at conductor discolored.
4(d)	125	4	200-200	290	125	48	Oil at conductor discolored.

Notes: (a) Model consisted of 200 tapes, 5 mil (0.127 mm) thick and 1 inch (25.4 mm) wide, wound in a normal taping pattern on a 1-3/8 inch (35 mm) diameter perforated copper tube. Winding tension was graded from 800 to 1500 grams. The direction of the tape lay was reversed every 10 tapes.

(b) Same as (a) but 800-1000 gram tension.

(c) Same as (a) but 5th and 10th tape in each lay group was embossed.

(d) Same as (a) but 100-5 mil (0.13 mm) and 62-8 mil (0.20 mm) tapes were used.

(e) Drying began at lower temperature, later increased to higher level for better effect.

(f) Determined by stabilization of capacitance measurements. Time is in 24 hour days and includes weekends in some cases.

(g) Determined by stabilization of capacitance measurements. Changes in impregnation pressure were made continuously.

(h) Drying and impregnation were performed in a suitable steel container.

3M Polypropylene Tape. The results shown on Table 2-16 for models made with plain 3M polypropylene paper having a thickness of 5 mils (0.13 mm) show that in order to prevent tape buckling, the taping tension must be less than 700 grams and the ratio of bending diameter (D) to the cable diameter (d) must be 30 or more. The substitution of 3/4 inch (19 mm) wide tapes in place of the one inch (25.4 mm) wide tapes was ineffective in preventing distortion. For the border-line case of a plain 3M tape model made with 750 gm tension and bent with four reverse bends over a mandrel having a diameter 30 times that of the mandrel, a less severe test was conducted. Only one bend, rather than four reverse bends was made. Examination indicated no buckling. The bend ratio of 30 is significant because this is approximately the condition that would be experienced in the factory.

Two models were made using 7 mil (0.18 mm) thick embossed 3M tapes, The bending characteristics of these embossed 3M models were the same as for the 5 mil (0.13 mm) plain 3M models made and bent under the same conditions.

Bending tests were made on cable models taped with the 8 mil (0.20 mm) 3M and the 10 mil (0.25 mm) embossed 3M PP tapes. The thicker tapes are inherently stiffer than the thinner tapes. This permits higher taping tensions to be used with the thicker tapes for the same degree of buckling when the cable models are bent over a given mandrel.

In Table 2-17 are shown the results of bending tests performed on cable models made with 3M tapes plus support tapes. A comparison between these results and those previously given on bending models having only 3M tapes, Table 2-16, indicates that the addition of up to 50% PPP support tapes provided only slight improvement in the bendability of models made with 3M tapes for the same conditions of taping tension and bending mandrel diameter.

PPP Tapes. Three cable models were made using 6 mil (0.15 mm) embossed PPP tapes applied with controlled taping tensions and bent over selected mandrels. These data are given in Table 2-18. The results are comparable to what may be expected with cellulose paper.

For the same taping tension and bending mandrel diameter as used for a 5 mil (0.127mm) embossed PPP model, the model made with 8 mil (0.203mm) embossed PPP tapes produced less severe tape buckling.

Table 2-16

MODEL CABLE BENDING TESTS-
3M POLYPROPYLENE TAPES

Taping Tension, grams	Bend Ratio (a), D/d	Result
Plain 3M Polypropylene Tape, 5 Mils, (0.13mm)		
1500	20	Severe buckling
1000	20	Moderate buckling
500	20	Slight buckling No buckling of outer tapes
1000	30	Moderate buckling
750	30	Slight buckling. No buckling of outer tapes.
750	30	Slight buckling. No buckling of outer tapes. 3/4 inch (19mm) wide tapes used.
750	30	No buckling. Single bend made rather than four reverse bends.
1500	42	Moderate buckling.
500	42	No buckling.
Embossed 3M Polypropylene Tape, 7 Mils (0.18mm)		
1000	30	Moderate buckling.
750	30	Slight buckling. No buckling of outer tapes.
Plain 3M Polypropylene Tape, 8 Mils (0.20mm)		
1500	30	Moderate buckling.
1000	30	No buckling.
750	30	No buckling.
Embossed 3M Polypropylene Tape, 10 Mils (0.25mm)		
1200	30	No buckling.

Notes:
(a) Bend Ratio = $\frac{\text{Diameter of mandrel over which model is bent}}{\text{Outside diameter of model cable}}$
(b) Sample Cable Construction: Rubber insulated cable "core". Eight 1 inch (25.4mm) tapes applied with right hand lay and normal taping pattern plus eight 1 inch (25.4mm) tapes applied with left hand lay and normal taping pattern.
(c) Bending Program: Four reverse bends in same plane.
(d) All buckling was on inside of final bend and was composed of individual ridges at about right angle to the cable model axis.
(e) Buckling created a crease along the center of an individual tape, which was very often coincident to the butt space of an over or underlying tape.

Table 2-17

MODEL CABLE BENDING TESTS -
3M POLYPROPYLENE TAPES WITH PPP SUPPORT TAPES

Plain 3M Polypropylene Tape, 5 Mils, (0.13mm) With PPP Support Tapes

Taping Tension, grams	Bend Ratio (a), D/d	Results
1000	30	Moderate buckling. A plain 5 mil (0.13mm) PPP support tape was used as the last tape of the inner and first tape of the outer lay group.
1000	30	Slight buckling. No buckling of outer tapes. An embossed 6 mil (0.15mm) PPP support tape was used as the 1st, 4th, 5th and 8th tape of each lay group.
1000	30	Slight buckling. An embossed 6 mil (0.15mm) PPP support tape was used for every other tape.

Notes:
(a) Bend Ratio = $\frac{\text{Diameter of mandrel over which model is bent}}{\text{Outside diameter of model cable}}$
(b) Sample Cable Construction: Rubber insulated cable "core". Eight 1 inch (25.4mm) tapes applied with right hand lay and normal taping pattern plus eight 1 inch (25.4mm) tapes applied with left hand lay and normal taping pattern.
(c) Bending Program: Four reverse bends in same plane.
(d) All buckling was on inside of final bend and was composed of individual ridges at about right angle to the cable model axis.
(e) Buckling created a crease along the center of an individual tape, which was very often coincident to the butt space of an over or underlying tape.

Table 2-18

MODEL CABLE BENDING TESTS - EMBOSSED PPP TAPES

Taping Tension, grams	Bend Ratio (a), D/d	Result
	Embossed PPP Tape, 6 Mils (0.15mm)	
1500	20	Moderate buckling.
1500	30	Moderate buckling.
1500	30	No buckling. Single bend made rather than four reverse bends.
1000	30	No buckling of outer tapes. Very slight buckling of innermost tapes.
	Embossed PPP Tape 8 Mils (0.20mm)	
1500	30	Slight buckling. No buckling of outer tapes.
	Commercial Cellulose Paper, Tape 5 Mils (0.13mm)	
1500	30	Slight buckling

Notes:
(a) Bend Ratio = $\frac{\text{Diameter of Mandrel over which model is bent}}{\text{Outside diameter of model cable}}$

(b) Sample Cable Construction: Rubber insulated cable "core". Eight 1 inch (25.4mm) tapes applied with right hand lay and normal taping pattern plus eight 1 inch (25.4mm) tapes applied with left hand lay and normal taping pattern.

(c) Bending Program: Four reverse bends in same plane.

(d) All buckling was on inside of final bend and was composed of individual ridges at about right angle to the cable model axis.

(e) Buckling created a crease along the center of an individual tape, which was very often coincident to the butt space of an over or underlying tape.

2.3.5 Cable Models for Voltage Soak Tests

In order to evaluate the aging characteristics of insulating systems under accelerated conditions of heat and electrical stress, cable models were made with six 1 inch (25.4 mm) x 5 mil (0.13 mm) tapes wound with controlled tension on a 1/2 inch (13.0 mm) diameter x 24 inch (61 cm) long stainless steel mandrel. The center 8 inch (20.3 cm) section of the model was the active length. It was guarded on each end by the grounded metallic covering on stress relief cones. Each model was vacuum dried, impregnated and tested while mounted within a pyrex tube sealed with teflon gaskets and fitted with stainless steel hardware. A bellows maintained 5 psi (0.35 kg/cm^2) oil pressure during accelerated aging. Testing was conducted in an oven at 100°C while the model was simultaneously subjected to a stress of 500 V/mil (19.7 kV/mm), or more.

3M Polypropylene Tapes. In Table 2-19 a summary is given of voltage-soak data obtained on cable models made with 3M polypropylene tapes.

In Model No. 1 made of plain 3M polypropylene tapes the high voltage electrode was covered with two layers of carbon black tape. This contributed to the high power factor of this model. Upon failure, after being on test for 23 days, dissection revealed that the tapes were wrinkled and on the innermost tape there was a dark stress line coincident to the butt space of the underlying carbon black tape.

After failure of the first model, a re-test was made with essentially the same set-up except that aluminum foil was used in place of lead as the outer shield. The second model had an initial 100 tan δ of 2.37 at 500 V/mil (19.7 kV/mm) and 100°C compared to 4.70 for the first model at the same time and conditions. As for the first model, the tan δ of the second model decreased as aging continued. After 42 days on test, the 100 tan δ of the second model was 0.07 at 500 V/mil (19.7 kV/mm) and 100°C. This tan δ is comparable to the tan δ measured on unaged single sheets at the same temperature. The improvement in tan δ as aging progressed on both models is believed due to the "clean-up" effect of the carbon black paper tape over the high voltage electrode. Representative data taken during these tests are included in Table 2-19.

A third voltage-soak model using plain 3M tapes was tested with stainless steel as the high voltage electrode and aluminum as the low voltage electrode. A similar model was made using embossed 3M tapes. Each of these models remained on test at 100°C and 500 V/mil (19.7 kV/mm) for more than 52 days before being removed from test.

Table 2-19

VOLTAGE SOAK TESTS AT 500 V/MIL, (19.7 kV mm) AND 100°C USING CABLE MODELS WITH 30 MILS (0.76 mm) OF 3M POLYPROPYLENE INSULATION

Model No.	Shield Material Condr.	Shield Material Ins.	Impregnant	Aging Time, Days	100 Tan δ at 100°C 300 V/mil (11.8 kV/mm)	100 Tan δ at 100°C 500 V/mil (19.7 kV/mm)	Dielectric Strength at 25°C AC or Impulse(e), V/mil (kV/mm)	Remarks
				Plain 3M Polypropylene Tapes (a)				
1(b) (c)	Carbon Black	Lead	Cosden 015SH	0	2.1	4.7		Model failed after 23 days. Tapes wrinkled. Stress mark on innermost tape.
				7	0.29	0.69		
				21	0.52	0.57		
2(c)	Carbon Black	Alum.	Cosden 015SH	0	0.95	2.37	666 (26.2) ac	Removed from test after 45 days. Tapes wrinkled. Stress mark on innermost tape.
				14	0.16	0.30		
				28	0.12	0.17		
				42	0.06	0.07		
3(d)	Stain-less Steel	Alum.	Cosden 015SH	0	0.34	0.47	875 (38.9) ac	Removed from test after 60 days. Tapes wrinkled.
				10	0.16	0.21		
				28	0.15	0.18		
				56	0.08	0.09		
4(d)	Stain-less Steel	Crepe Carbon Black	Cosden 015SH	0	1.17	1.52	2500 (98.4) Impulse	Removed from test after 7 days. Tapes wrinkled.
				7	0.52	0.82		
				Embossed 3M Polypropylene Tapes (a)				
1(d)	Stain-less Steel	Alum.	Cosden 015SH	0	0.50	0.78	710 (28.0) ac	Removed from test after 52 days. Tapes wrinkled.
				11	0.28	0.35		

Notes:
(a) Models consisted of six 1 inch (25.4 mm) tapes wound with same lay and normal taping pattern on 1/2 inch (13 mm) diameter x 24 inch (61 cm) long stainless steel mandrel. Taping tension 750 gm. Eight inch (20.3 cm) test length guarded by stress cones. Vacuum dried and impregnated at approximately 100°C. Operated at 5 psig (0.35 kg/cm^2).
(b) Impregnated at 50°C.
(c) Two carbon black tapes over stainless steel high voltage electrode.
(d) Carbon black tapes omitted over stainless steel high voltage electrode.
(e) 60 Hz or 1-1/2 x 40 microsecond wave shape.

The initial tan δ of these models, without carbon black in the electrical field, was lower than those models having carbon black in the electrical field and, as for those with carbon black, tan δ became lower during aging.

After being removed from test, the models which had not failed were subjected to an ac or impulse test to determine dielectric strength. These data are included in Table 2-19 along with remarks related to evidence revealed during dissection. In each case incompatibility with the 015SH polybutene impregnant was evident by the presence of wrinkled tapes.

PPP Tapes. In Table 2-20 and 2-21 are data derived from voltage-soak cable models made with PPP tapes.

Each model listed in Table 2-20 was made with embossed PPP tapes. Because of carbon black in the electrical field tan δ was greater than anticipated from the data on single sheets. For the Cosden polybutene oils and the Sun XX naphthenic oil used, there was no distortion of the embossed PPP tapes. However, for the more viscous oils, Cosden 015SH and Sun XX, dissolved polypropylene, or wax, was present in the tape butt spaces after removal of the model from test. For the lower viscosity blend of 50% American 15H and 50% American 50 polybutenes, thickening of the impregnant by dissolved polypropylene was not evident.

In Table 2-21, the models listed, which were made with no carbon black in the electrical field and an improved power factor guard assembly, exhibit low initial power factor. One model was taped with embossed PPP and impregnated with a mixture of 50% American 15H and 50% American 50 polybutene. The other two were taped with plain PPP and impregnated with Dow Corning silicone fluids. After aging for 36 days or more at 500 V/mil (20 kV/mm) the stress was increased to higher levels to induce failure. For the model impregnated with polybutene, there was slight wax in the butt spaces of the tapes.

Table 2-20

VOLTAGE SOAK TESTS AT 500 V/MIL (19.7 kV/mm) AND 100°C
USING CABLE MODELS WITH 30 MILS (0.76 mm) OF EMBOSSED PPP TAPE INSULATION

					Embossed PPP Tape (a)			
	Shield Material			Aging	100 Tan δ at 100°C During Aging		Dielectric Strength at 25°C AC or Impulse (d),	
Model No.	Condr.	Ins.	Impregnant	Time, Days	300 V/mil (11.8 kV/mm)	500 V/mil (19.7 kV/mm)	V/mil (kV/mm)	Remarks
1 (b)	Carbon	Lead	Cosden 015SH	0	0.22	0.47	(e)	Removed from test after 23
	Black			7	0.16	0.18		days. Wax in butt spaces.
	Paper			21	0.14	0.16		
2 (b)	Carbon	Alum.	Cosden 015SH	0	0.14	0.15	1233 (48.5)	Removed from test after 59
	Black			14	0.07	0.07	ac	days. Slight wax in butt
	Paper			56	0.07	0.07		spaces.
3 (b)	Carbon	Alum.	Sun XX	0	0.40	0.78	1133+ (f) (44.6)	Removed from test after 21
	Black			10	0.21	0.23	ac	days. Slight wax in butt
	Paper			21	0.22	0.25		spaces.
4 (c)	Carbon	Alum.	50% Amer.	0	0.19	0.30	3200 (126)	Removed from test after 35
	Black		15H-50%	7	0.20	0.19		days. No wax.
	Paper		Amer. 50	35	0.17	0.17		

Notes: (a) Models consisted of six 1 inch (25.4 mm) tapes wound with same lay and normal taping pattern on 1/2 inch (13 mm) diameter x 24 inch (61 cm) long stainless steel mandrel. Taping tension 1500 gm. Eight inch (20.3 cm) test length guarded by stress cones. Vacuum dried and impregnated at approximately 100°C. Operated at 5 psig (0.35 kg/cm^2).

(b) Two carbon black tapes over stainless steel H.V. electrode.

(c) One carbon black tape plus one duplex carbon black-paper tape over stainless steel H.V. electrode.

(d) 60 Hz or 1-1/2 x 40 microseconds wave shape.

(e) No measurement made of dielectric strength.

(f) End flashover.

Table 2-21

VOLTAGE SOAK TESTS AT 100°C AND 500-900 V/MIL (19.7-35.4 kV/mm) OF PPP TAPE INSULATION

Model No.	Impregnant	Aging Time, Days	100 Tan δ at 100°C During Aging: 300 V/mil (11.8 kV/mm)	500 V/mil (19.7 kV/mm)	700 V/mil (27.6 kV/mm)	900 V/mil (35.4 kV/mm)	Remarks
			Embossed PPP Tapes 5 Mil (0.13 mm)				
1	50% Amer.15H	0	0.08	0.08	-	-	
	50% Amer.50	33	0.06	0.07	-	-	
		48	0.06	0.07	0.10 (b)	-	
		76	0.06	0.07	0.08	-	
		103	0.10	0.11	0.12	-	
		130	0.12	0.14	0.16	0.19 (c)	Failed after 133 days.
			Plain PPP Tapes, 5 Mil (0.13 mm)				
1	DC200-50	0	0.06	0.07	-	-	
		33	0.06	0.06	-	-	
		40	0.06	0.06	0.06 (b)	-	Failed after 47 days.
		47	0.06	0.06	0.06		
2	DC200-350	0	0.07	0.08	-	-	
		29	0.07	0.07	-	-	
		36	0.07	0.07	0.07 (b)	-	
		57	0.07	0.07	0.07	-	End failure (d) after 109 days.
		88	0.09	0.09	0.09	-	
		109	0.09	0.09	0.09	0.13 (c)	

Notes: (a) Models consisted of six 1 inch (25.4 cm) tapes wound with same lay and normal taping pattern on 1/2 inch (13 mm) diameter x 24 inch (61.0cm) long stainless steel mandrel. Taping tension 1500 gm. Six inch (15.2cm) test length guarded by stress cones. Vacuum dried and impregnated at approximately 100°C. Operated at 5 psi (0.35 kV/cm^2). Aluminum foil used as low voltage electrode.

(b) Continuous stress during aging changed from 500 to 700 V/mil (19.7 to 27.6 kV/mm).

(c) Continuous stress during aging changed from 700 to 900 V/mil (27.6 to 35.4 kV/mm).

(d) Fault at edge of measuring electrode.

2.3.6 Physical and Electrical Tests on Impregnants

Physical Tests. In Table 2-2, which lists the oils investigated as possible impregnants, are included the viscosity at 37.8°C and 98.9°C of each oil.

Electrical Tests. When it became evident that silicone oil having a low viscosity is desirable for use in a cable made with PPP laminate to avoid incompatibility and to lessen oil-starvation, the propensity for silicone oil to generate gas under electrical stress was investigated. In Table 2-22 are data obtained by using an ASTM gassing test on various oils, including silicones and different mixtures of a silicone fluid DC200-50 and dodecylbenze. Under the conditions of the test, silicone DC200-200 and silicone DC200-50 generate gas while under electrical stress; and Sun XX and Amoco 15H both of which are commonly used as cable impregnants, absorb gas while under electrical stress. An addition of as little as 2% dodecylbenzene to DC200-50 resulted in a mixture which absorbed gas while under electrical stress.

During the evaluation of prototype cable samples it was observed during dissection of the failure in Prototype Cable No. 3 that there were incipient radial fault paths that penetrated approximately the first 10 PPP tapes at the conductor. This pattern indicated that the oil in the butt spaces of the PPP tapes had been over stressed. In order to investigate this further, a program was initiated to determine the dielectric strength of thin oil films. A set of data was acquired on DC200-50 silicone oil and Amoco 15H polybutene using 3/4 inch (19 mm) diameter electrodes at a spacing of 10 mils (0.25 mm). For these tests, each specimen was dried by vacuum treatment at 100°C. In Table 2-23 the dielectric strength results are given at 25°C as a function of pressure. The rate of voltage rise was 10 V/mil (0.39 kV/mm) every 30 seconds in order to approach the dielectric strength at steady state. By this test, the dielectric strength of DC200-50 silicone oil, is seen to be approximately 20% less than Amoco 15H from 0 psi (0 kg/cm^2) to 200 psi (14.1 kg/cm^2).

Table 2-22

GASSING OF OILS AND MIXTURES UNDER ELECTRICAL STRESS

Silicone 200-50 and Alkylate 21 Composition of Blend % DC200-50	Alkylate 21	Gassing Rate Microliters/Minute
100	0	+ 20.5
98	2	- 6.95
95	5	- 20.13
90	10	- 29.34
80	20	- 50.4
Type of Oil		
DC 200-200, silicone		+ 15.6
Sun XX, mineral		- 1.1
Amoco 15H, polybutene		- 14.5

Note: Tests performed according to ASTM D2300 Procedure B, using hydrogen gas, 10 kV, and 65°C.

Table 2-23

DIELECTRIC STRENGTH OF OILS AS A FUNCTION OF PRESSURE

Sample	Pressure psi(kg/cm^2)	Dielectric Strength Volts/mil (kV/mm)
DC200-50, Silicone	0 (0)	660 (26.0)
	105 (7.40)	700 (27.6)
	175 (12.3)	720 (28.3)
Amoco 15H, Polybutene	0 (0)	780 (30.7)
	100 (7.05)	850 (33.5)
	220 (15.5)	860 (33.9)

Note: (1) Tests performed on dry and degassed oil samples at 25°C using 3/4 inch (19.1mm) diameter chrome-plated electrodes with 10 mil (0.25mm) spacing. Initial voltage: 200 V/mil (7.9kV/mm), then increased in steps of 10 V/mil (0.39 kV/mm) each 30 seconds.

A second set of dielectric strength data are given in Table 2-24 for various silicone oils and Cosden 015EG at 25°C. Each datum in this table is the 99% probability value derived from a Weibull distribution. The electrode system consisted of two 1/2 inch (13 mm) diameter steel balls, with micrometer adjustment. Each 99% probability point was determined for 10 to 15 breakdowns performed with a slow rate of rise of 12.5 V/mil/30 sec. (0.49 kV/mm/30 sec.) at 25°C and 0 psi (0 kg/cm^2) on oil specimens which had been degassed and dried. From these data, it can be seen that the electrical grade of silicone oil has more than 100 V/mil (3.94 kV/mm) higher voltage breakdown than the commercial grade, both as-received and after degassing, and drying. Also, the addition of 3% dodecylbenzene to DC200-50 EG, in order to reduce the tendency for gas generation by the silicone under electrical stress, does not significantly degrade the dielectric strength, as a result of degassing and drying.

In Table 2-25 are given the results of dielectric strength tests at 100°C on basically the same oils as listed in Table 2-24. Compared to the results given in Table 2-24, the dielectric strength of Cosden 015EG polybutene oil and Dow Corning 200-50 EG silicone oil is greatly affected while the dielectric strength of the blend of 97% DC200-50 EG silicone oil and 3% Alkylate 21 oil is virtually unchanged by the increase in temperature from 25°C to 100°C.

Compatibility of Oils. As a check on the compatibility of silicone oil and dodecylbenzene (Alkylate 21) intended for use as the impregnant in the final cables, various blends of Alkylate 21 with DC200-200 and DC200-50 were aged in air at 115°C. As given in Table 2-26, tan δ measurements made after aging for 96 hours indicate that the silicone fluids and Alkylate 21 are compatible. During the aging, which was conducted in an air oven, some of the Alkylate 21 evaporated. In Table 2-26 a datum is included where an aging test was performed at elevated temperature and dodecylbenzene which "boiled-off" was condensed and refluxed. The tan δ of the dodecylbenzene became lower during aging under this condition as it did in the other tests where the volume of dodecylbenzene was reduced due to evaporation. This indicates that dodecylbenzene is inherently antioxidant and it is not the loss of low vapor pressure components that improves the aged dissipation factor.

Table 2-24

60 Hz DIELECTRIC STRENGTH OF OILS AT 25°C AND 0 PSI (0 kg/cm^2)

Sample	Dielectric Strength Volts/mil (kV/mm) 99% Weibull Probability	Moisture Content, ppm	Effect of Degassing and Drying: % Increase in Dielectric Strength	% Decrease in Moisture Content
Cosden 015EG				
As-Received	830 (32.7)	24	-	-
Degassed and Dried	1025 (40.4)	20	18	16.5
DC200-50 Commercial Grade				
As-Received	640 (25.2)	30	-	-
Degassed and Dried	730 (28.7)	25	14	16.5
DC200-50EG				
As-Received	820 (32.3)	26	-	-
Degassed and Dried	840 (33.1)	24	2.5	7.7
97% DC200-50 EG + 3% Alkylate 21				
Degassed and Dried	820 (32.3)	-	-	-

Notes: (1) Electrodes: 1/2 inch (13 mm) diameter steel spheres, 10 mil (0.254 mm) gap.

(2) Voltage Schedule: start at 200 V/mil (7.87 kV/mm), raise in steps of 12.5 V/mil (0.49 kV/mm) each 30 seconds.

(3) Each Weibull number is the result of 10 to 15 tests on a sample. See Appendix 4.

Table 2-25

60 Hz DIELECTRIC STRENGTH OF OILS AT 100°C and 0 psi (0 kg/cm^2)

Type Oil Sample	Dielectric Strength Volts/mil (kV/mm) (99% Weibull Probability)
Cosden 015EG	510 (20.1)
DC200-50EG	575 (22.6)
97% DC200-50EG + 3% Alkylate 21	810 (31.9)

Notes: (1) All samples degassed and dried.

(2) Electrodes: 1/2 inch (13 mm) diameter steel spheres, 10 mil (0.254mm) gap.

(3) Voltage Schedule: Start at 200 V/mil (7.87 kV/mm), raise in steps of 12.5 Volt/mil (0.49 kV/mm) each 30 seconds.

(4) Each Weibull number is the result of 10 to 15 tests on a sample. See Appendix 4.

Table 2-26

COMPATIBILITY TEST
SILICONE OIL AND DODECYLBENZENE

	100 Tanδ at 100°C				
	100% DC200-200	90% DC200-200 10% A21 (3)	80% DC200-200 20% A21 (3)	100% A21 (4)	(5)
Unaged	0.02	0.10	0.12	0.08	0.09
After Aging, in Air for 96 hrs. at 115°C	0.02	0.02	0.02	0.04	0.03
	100% DC200-50	90% DC200-50 10% A21	80% DC200-50 20% A21	100% A21	
Unaged	0.03	0.06	0.07	0.08	
After Aging, in Air for 96 hrs. at 115°C	0.03	0.03	0.03	0.03	

Notes:
(1) A21 is Alkylate 21, a dodecylbenzene supplied by Chevron Chemical Corporation.

(2) Dodecylbenzene is miscible with DC200-200 and DC200-50.

(3) During aging approximately 1/3 of dodecylbenzene component in blends evaporated. Samples aged in glass beakers with watch glass covers.

(4) During aging approximately 1/10 of dodecylbenzene in the 100% samples evaporated. Samples aged in glass beakers with watch glass covers.

(5) There was no evaporation of dodecylbenzene for this sample. Aging performed using a reflux condenser.

(6) This test performed according to ASTM D1934A.

Section 3

MANUFACTURE AND EVALUATION OF PROTOTYPE CABLES

3.1 DESIGN AND MANUFACTURE

Three prototype full-size cables were evaluated to establish feasibility and basic properties of an insulation structure made with PPP tapes. Silicone oil was used as the impregnant because it was the only oil commercially available found compatible with the PPP tapes as judged by compatibility tests, Section 2.3.2. The constructions of the prototype cables manufactured are given in Table 3-1. The copper strands of the conductor were tinned to reduce the effect of copper on the aging of the oil. The PPP tapes were either plain or embossed with the same leather-grain pattern as used previously in the studies of cells and models reported in Section 2.

A zinc covering was placed over the insulation shield to permit the cables to be pulled into the impregnating pipe and was perforated to facilitate drying and impregnation.

The impregnation of the cables was performed in a 6 inch (14.24 cm) pipe approximately 70 feet (21.3 meters) long rather than factory impregnation tanks to (1) reduce the consumption of silicone oil required because of its expense and (2) to avoid mixing this experimental oil with regular factory processing oils. The degassing of the oil and the impregnation process followed normal procedures except both the vacuum drying and the impregnation periods were significantly lengthened. The extruded polypropylene center component of the PPP tape is impervious, and this makes it more difficult to remove moisture from the insulation structure and to fill with oil. Preliminary trials to establish vacuum-drying and oiling times and procedures were conducted on cable models as explained in Section 2.3.3. The impregnant was DC200-200 silicone oil having a viscosity of 200 centistokes which at 25°C is close to the viscosity of mineral oil used in commercial production of pipe-type cable.

Prototype Cable No. 1 was made with plain PPP tapes.

Table 3-1

CONSTRUCTIONS OF PROTOTYPE CABLES

PROTOTYPE NUMBER	1	2	3
Conductor Size, kcmil (mm^2) Type Material	2000 (1011) Segmental Tinned Copper	2000 (1011) Segmental Tinned Copper	2000 (1011) Segmental Tinned Copper
Conductor Shield	1 Carbon Black & 1 Duplex Tape	1 Carbon Black & 1 Duplex Tape	1 Carbon Black & 1 Duplex Tape
Insulation Thickness Inches (mm)	1.025 (26)	1.025 (26)	1.025 (26)
Insulation Structure Tapes 1 Inch (2.54 cm) Wide	78-5 mil (0.127 mm) & 78-8 mil (0.203 mm) Plain PPP Tapes	78-6 mil (0.152 mm) & 68-8 mil(0.203mm) Embossed PPP Tapes	78-5 mil (0.127 mm) & 78-8 mil(0.203mm) Plain PPP Tapes
Impregnant	Silicone Oil DC200-200	Silicone Oil DC200-50 (5% Dodecylbenzene by volume added)	Silicone Oil DC200-50
Insulation Shield	2 Perforated Aluminum Foil- Backed Paper Tapes	2 Perforated Aluminum Foil- Backed Paper Tapes	2 Perforated Aluminum Foil- Backed Paper Tapes
Covering	Perforated Zinc Alloy Tape	Perforated Zinc Alloy Tape	Perforated Zinc Alloy Tape

Prototype Cable No. 2 was made with embossed tapes rather than plain tapes. The purpose of the embossing is to facilitate the flow of oil through the insulation structure during rapid cooling cycles in order to avoid oil-starvation in local areas between tapes which causes gaseous ionization. This prototype was impregnated with a less viscous silicone oil, DC200-50, to further facilitate the flow of oil through the insulation structure. This oil has a viscosity of 50 centistokes at 25°C. Five percent by volume of dodecylbenzene oil was added to the oil to reduce its tendency to evolve gas when subjected to electrical discharges as would be the case if ionization occurs. The addition of the dodecylbenzene oil transformed the oil to be a gas absorbing oil without significantly affecting its other properties. As indicated in Section 2.3.2 the addition of dodecylbenzene slightly increased the swelling effect of the silicone oil on the PPP tapes.

Prototype Cable No. 3 was made with plain PPP tapes because, during handling, Prototype Cable No. 2 developed excessive soft-spots and therefore was considered to have an insulation structure too soft for commercial cable. The less viscous silicone oil DC200-50 was used as the impregnant and the dodecylbenzene was not added to the silicone oil in this case to permit studies of the cable insulation structure without the admixture. The PPP tapes, because their center component is an extruded film do not permit radial transmission of oil except at butt spaces and it is felt that the less viscous oil is required to avoid oil-starvation during the cooling portion of a load cycle.

3.2 EVALUATION OF PROTOTYPE CABLE NO. 1

Mechanical integrity, cold bend, radial power factor, dielectric loss, physical properties of insulating tapes, aging at continuous thermal loading, cyclic loading, impulse and miscellaneous special tests were conducted on this sample.

The mechanical structure of this prototype was satisfactory, and adequately oiled and the sample passed the AEIC Specification No. 2-73 cold bend test without any torn tapes.

Radial power factor data taken on this sample are shown in Figure 3-1. The data, taken on a short piece the sample removed from one end prior to the dielectric loss, cyclic loading and surge testing is as anticipated, based on previous data taken on single tapes in the cell tests. The data indicate that the cable was adequately dried. The lower tan δ of the tapes 8 mils (0.203 mm) in thickness is due to the higher ratio of the thickness of the polypropylene to cellulose paper components of the composite PPP tape. The higher tan δ values of both 5 mil (0.127 mm) and 8 mil (0.203 mm) tapes after aging indicate a significant deterioration due to ionization which occurred during the cyclic loading tests.

Physical properties and 60 Hz voltage breakdown of the insulating tapes taken on this sample are shown in Table 3-2.

The dielectric loss at rated operating voltage to ground for cable rated 500 kV of Prototype Cable No. 1 prior to any testing is shown in Table 3-3.

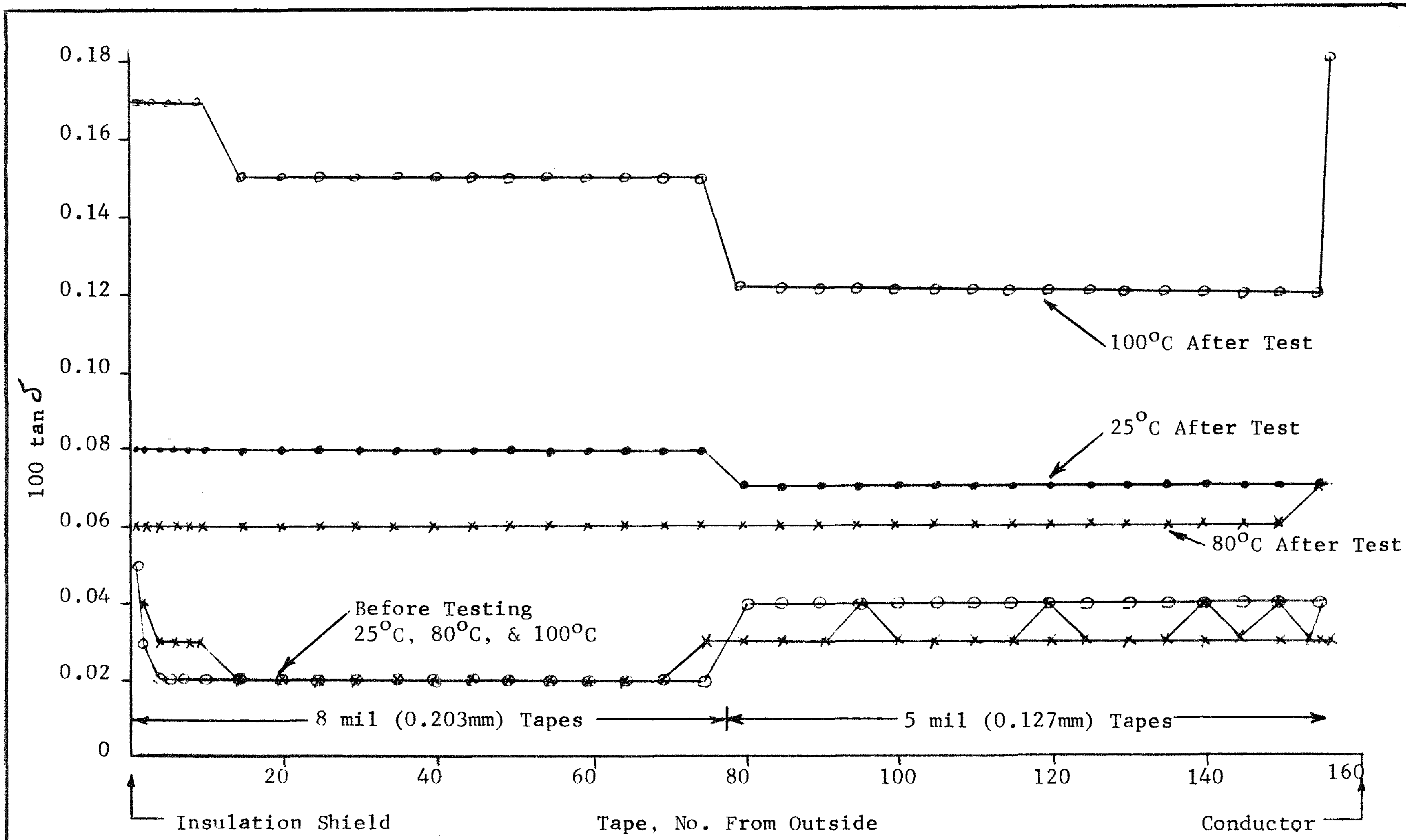


Figure 3-1. Prototype Cable No. 1. - Radial Power Factor

Table 3-2

PROTOTYPE CABLE NO. 1

TESTS ON INSULATION TAPES

PROPERTY	BEFORE TESTING		AFTER TESTING	
Thickness, mils (mm)	8 (0.203)	5 (0.127)	8 (0.203)	5 (0.127)
Avg. Tensile Strength, lb/inch width (kg/cm)	52.4 (9.38)	33.4 (5.98)	44.3 (7.9)	37.1(6.64)
Avg. Tearing Strength, grams	109	76	117	73
Folding Endurance, double folds	1,000+	1,000+	1,000+	1,000+
Avg. Voltage Breakdown, volts/mil (kv/mm) at 25°C and 60 Hz				
In Oil	1850 (74)	2560 (102)	1830 (73)	2560 (102)
In Air	-	-	1490 (60)	2050 (82)

Note: 1. See Appendix 3 for references to applicable ASTM test methods
2. Improvement in physical properties compared to those shown in Tables 2-4 and 2-5 is probably due to sampling from different lots.

Table 3-3

PROTOTYPE CABLE NO. 1
DIELECTRIC LOSS

TEMPERATURE, °C	CAPATITANCE, pF PER FOOT (pF/m)	100 TAN δ	DIELECTRIC LOSS, WATTS PER FOOT (W/m)
30	54.0 (177)	0.034	0.57 (1.87)
60	53.3 (175	0.032	0.47 (1.54)
70	53.2 (174	0.026	0.44 (1.44)
90	52.6 (173)	0.030	0.50 (1.64)

Prototype Cable No. 1 was aged at steady conditions of conductor temperature and voltage in accordance with the schedule indicated in Table 3-4. Periodically during the 6 week aging period tanδ was measured at the hot temperature indicated and at voltages up to the maximum voltage shown at each step. There was no significant change in tan δ during this period as indicated in Figure 3-2. There was no development of ionization in the sample as would be indicated by an abrupt change to a higher tanδ during measurements of tan δ vs. voltage.

Table 3-4

PROTOTYPE CABLE NO. 1
CONTINUOUS LOAD AGING
PROGRAM

STEP NO.	TIME, WEEKS	CONDUCTOR TEMPERATURE, °C	VOLTAGE TO GROUND KV	X RATED
1	1	25	346	1.2
2	1	25	433	1.5
3	1	60	346	1.2
4	1	60	433	1.5
5	1	90	346	1.2
6	1	90	433	1.5

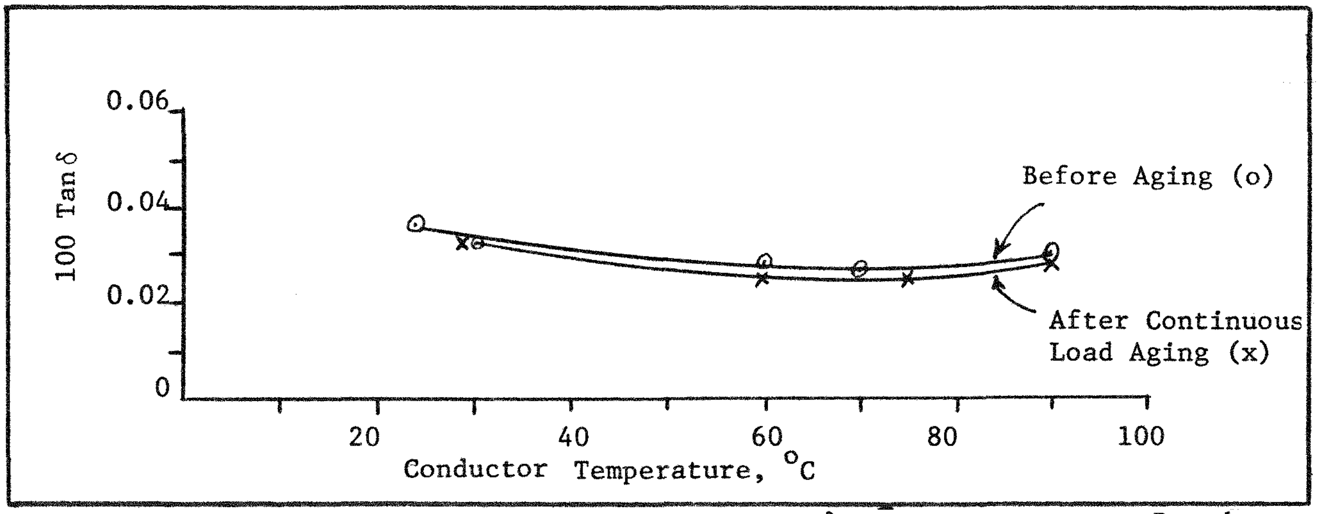


Figure 3-2. Prototype No. 1. – Tan δ vs. Temperature at Rated Voltage and 200 psi (14 kg/cm^2)

A summary of the cyclic loading testing conducted on Prototype Cable No. 1 is shown in Table 3-5. Current was passed through the conductor and through the pipe containing the cable to provide a temperature drop across the cable insulation representative of service conditions. The design value of rated conductor temperature of the cable is 85°C so that the higher temperatures shown in Table 3-5 are overload conditions.

In order to study in detail if ionization existed in Prototype Cable No. 1 a special test was devised. This test consisted of continuously monitoring tan δ at the test voltage during a thermal decay after the conductor and pipe heating currents were reduced to zero. Thermal decay tests were conducted at each step indicated in Table 3-5. Beginning at Step No. 3, where the conductor temperature was 60°C, ionization was observed, as indicated by abrupt significant changes in tanδ, approximately 1 to 3 hours after the current was turned off and the cable was cooling. This test was repeated many times during Steps Nos. 3, 4 and 5 and ionization was present during a portion of the thermal decays. Typical thermal decay data are shown in Figure 3-3 which were taken during Step No. 5. At cycle Number 5 the tan δ vs. time curve was a smooth curve and at cycle Number 6 there were only insignificant changes in tan δ.

Table 3-5

PROTOTYPE CABLE NO. 1
SUMMARY OF CYCLIC LOADING TESTING

STEP NO.	NO. OF CYCLES	VOLTAGE X RATED	TEMPERATURE, $^{\circ}$C CONDUCTOR	SHIELD
1	4	1.2	40	35
2	5	1.2	50	43
3	4	1.2	60	49
4	11	1.2	70	64
5	6	1.2	90	70
6	32	(2)	100	84

Notes: (1) Current loading, conductor and pipe, on 12 hours and off 12 hours each cycle. Voltage stress applied continuously.

(2) This aging performed without voltage stress in order to "condition" cable insulation against oil-starvation.

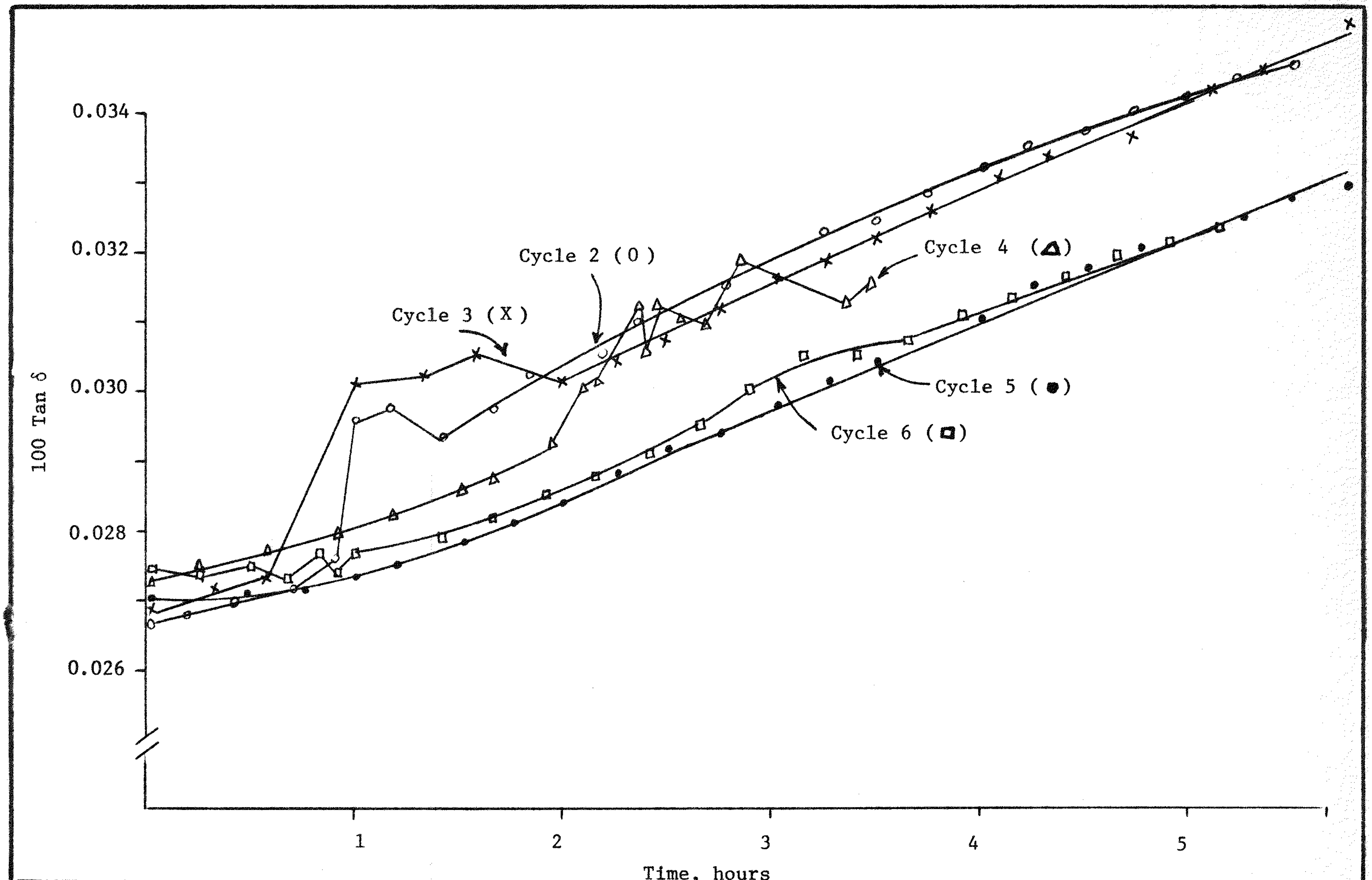


Figure 3-3. Prototype Cable No. 1. Thermal Decay from Conductor Temperature of $90^{\circ}C$ at 1.2 Rated Voltage and 200 psi (14 kg/cm^2)

In order to further study oil-starvation in Prototype Cable No. 1, the pressure was reduced from 200 psi (14 kg/cm^2) down to 15 psi (1.05 kg/cm^2). Past experience with pipe-type cable insulated with cellulose paper tapes has given no indication of oil-starvation at 15 psig. However, abrupt changes in tan δ were observed during a thermal decay from a conductor temperature of 90°C at 1.5 x rated voltage and 15 psig. Attempts were made to eliminate the abrupt change in tan δ by raising the oil pressure to 200 psig and subjecting the cable to additional heat cycles from 100°C to 25°C at 200 psig without voltage, but it was not possible to eliminate ionization in the sample during thermal decays from a conductor temperature of 100°C. During this testing it was observed that 100 tan δ was slowly increasing and finally reached a recorded value of 0.055 during a thermal decay from 100°C. This indicates that the ionization had finally made a permanent change in tan δ . It was decided, therefore, to discontinue further thermal decay studies on this sample.

An impulse test at 25°C using a 1.5 x 40 microsecond wave shape was then conducted on Prototype Cable No. 1. The sample withstood seven impulses at 1625 kV with negative polarity on the conductor. The sample withstood fifteen impulses at 1365 kV with positive polarity on the conductor. Higher voltages could not be placed on the sample because of flashover to nearby test equipment which was permanently installed. Prototype Cable No. 1 was, therefore, removed from test and dismantled. Radial power factor and physical tests on the tapes of the insulation structure were conducted with the results shown in Figure 3-1 and Table 3-2.

Assessment of Prototype Cable No. 1. The evaluation of Prototype Cable No. 1 indicates that cable made in accordance with this design is unsatisfactory because of a tendency towards oil-starvation during the cooling portion of the load cycle. Oil-starvation at local areas within the insulation structure may cause gaseous ionization at operating stresses. In the process additional gases are evolved which are not obsorbed by the impregnant and the condition may worsen, perhaps eventually leading to insulation breakdown. The by-products of the electrical discharges during ionization significantly increases tanδ which may lead to an intolerable run-away condition.

3.3 EVALUATION OF PROTOTYPE CABLE NO. 2

Prototype Cable No. 2 differed from Prototype Cable No. 1 in that the PPP tapes were embossed and the impregnant was changed from DC200-200 to DC200-50 oil with an additive of 5% dodecylbenzene. DC200-50 oil has a viscosity of 50 centistokes rather than 200 centistokes at 25°C and thereby is significantly less viscous. The low viscosity of the oil will permit easier flow between tapes of the insulation structure and reduce the tendency to create oil-starvation during the cooling portion of the load cycle. The embossing of the tapes creates more space between layers and permits an easier flow of oil. The addition of 5% dodecylbenzene to the silicone oil improves its gassing properties and makes the mixture gas absorbing under voltage stress. See Section 2.2 for test results on oil samples. The dodecylbenzene used is Alkylate 21, a product of Chevron Chemical Division of Oronite. The addition of dodecylbenzene to silicone oil has the disadvantage that the mixture increases the swelling of the PPP tapes, however, this does not appear to be significant if the amount of additive is below 5% by volume.

Mechanical integrity, insulation softness, radial power factor, dielectric loss, high-voltage-time, impulse, cyclic loading, and miscellaneous special tests were conducted on Prototype Cable No. 2. The mechanical integrity tests indicated that the insulation structure is too soft for commercial cable. Soft spots developed in the cable due to handling during transport from the impregnating pipe to the pipe used to house the sample when tested for electrical properties. The softness is aggravated by the fact that the embossing pattern is not permanent and is reduced when exposed to the drying and impregnating temperatures. Although this is good from the standpoint that oil can flow more freely between tapes, it has the practical disadvantage that the insulation structure loses its mechanical integrity when long lengths of cables are pulled into pipes. The results of the deformation test conducted on Prototype Cable No. 2 are given in Table 3-6. The data in Table 3-6 indicate that the deformation is approximately 3 times normal for commercial 345 kV cable of the same conductor size and insulation thickness and what is more dangerous, the deformation increases significantly during cyclic heat aging. Such looseness could cause excessive shifting of tapes during and after installation.

Physical properties and voltage breakdown at 60 Hz of the embossed insulating tapes taken from this sample are shown in Table 3-7. The physical properties of the tapes are adequate and did not change due to cyclic loading. However, the lower tensile strength indicates that the embossing process damaged a significant number of cellulose fibers. The voltage breakdown data indicate that the embossing operation reduced the dielectric strength of the PPP tape significantly. These voltage breakdown data may be compared to those data of Table 3-2 because the tapes used on Prototype Cables Nos. 1 and 2 differ only in the embossing feature.

Radial power factor data taken on this sample are shown in Figure 3-4. The data was taken on a short piece of cable removed from one end prior to the dielectric loss, high-voltage-time, impulse and cyclic loading tests and is slightly higher than expected based on previous data taken on single tapes in the cell tests. This may be due to some contamination of the sample and tape handling during measurements. The data indicate that the cable was adequately dried and impregnated.

Table 3-6

PROTOTYPE CABLES NOS. 2 AND 3
GCC SOFTNESS TEST

	DEFORMATION, PERCENT
Prototype No. 2	
As Manufactured	3.8
After Cyclic Aging	5.0
Prototype No. 3	
As Manufactured	1.2
After Cyclic Aging	1.2

Notes: (1) A 10 lb. (4.57 kg) force is applied to the cable insulation at 25°C with a 1 inch (2.54 cm) diameter pressure plate. The deformation is measured after 5 minutes.

(2) A typical value for deformation on 345 kV commercial pipe-type cable is 1.2%.

Table 3-7

PROTOTYPE CABLE NO. 2
TESTS ON INSULATION TAPES

PROPERTY	BEFORE TESTING		AFTER TESTING	
Thickness, mils (mm)	8 (0.203)	5 (0.127)	8 (0.203)	5 (0.127)
Avg. Tensile Strength, lb/inch width (kg/cm)	51(9.1)	44(7.9)	45(8.1)	36(6.4)
Avg. Tearing Strength, grams	100	77	110	63
Folding Endurance, double folds	1000 +	1000 +	1000 +	1000 +
Avg. Voltage Breakdown, volts/mil (kV/mm), at 25°C and 60 Hz, In Air	1370(54.8)	1780(7.12)	1430(57.2)	1970(78.8)

Note: See Appendix 3 for references to applicable ASTM test methods

The electrical tests conducted on Prototype Cable No. 2 did not significantly change the values of radial power factor. The higher values of the tapes on the outside and next to the conductor are perhaps due to some contamination from the pipe-filling oil and from processing oil in the conductor strands.

The dielectric loss at rated operating voltage to ground for 500 kV cable of Prototype Cable No. 2 prior to any testing is shown in Table 3-8. These data are very similar to the dielectric loss data obtained on Prototype Cable No. 1.

Prototype Cable No. 2 was load cycled as summarized in Table 3-9. Current was passed through the conductor and through the pipe containing the cable to provide a temperature drop across the insulation representative of service conditions. Periodically during the cyclic loading test, thermal decay runs were made with the conductor temperature at 90°C or 100°C, the voltage up to 1.5 x rated and the oil pressure at 200 psi (14 kg/cm^2). No evidence of oil-starvation during these decays was detected as no abrupt change in tanδ was observed which would indicate the presence of ionization in the cable. A typical thermal decay curve is shown in Figure 3-5 taken starting at 90°C conductor temperature and 1.2 x rated voltage continuously on the cable sample.

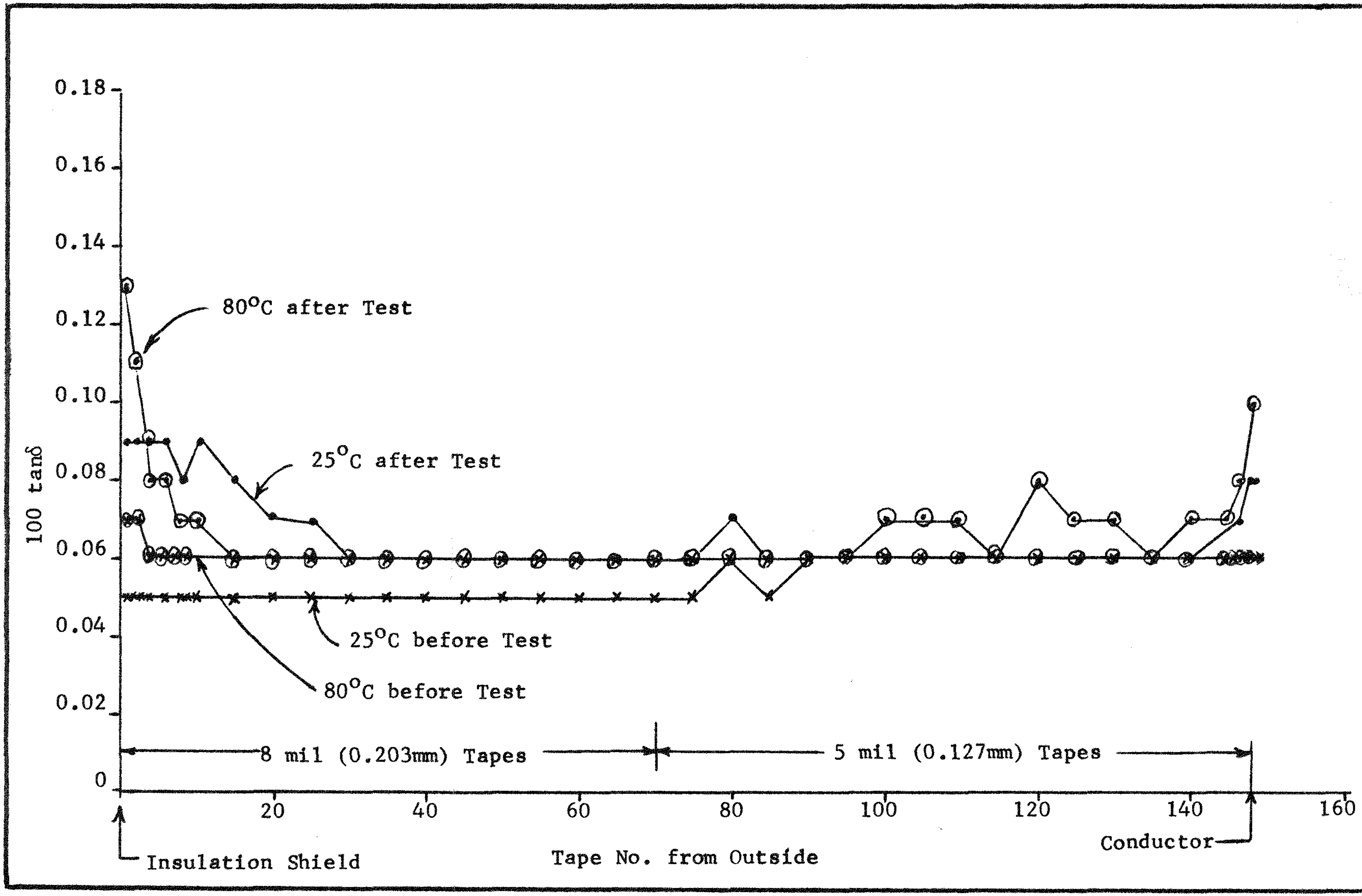


Figure 3-4. Prototype Cable No. 2. - Radial Power Factor

Table 3-8

PROTOTYPE CABLE NO. 2
DIELECTRIC LOSS

TEMP. °C	CAPACITANCE, pF PER FT. (pF/m)	100 TANδ	DIELECTRIC LOSS, WATTS PER FOOT (W/m)
26	52.8 (173)	0.034	0.57 (1.87)
60	51.8 (170)	0.032	0.53 (1.74)
75	51.6 (169)	0.033	0.54 (1.77)
90	51.2 (168)	0.036	0.59 (1.94)

Table 3-9

PROTOTYPE CABLE NO. 2

SUMMARY OF CYCLE LOADING CONDITIONS

STEP NO.	NO. OF CYCLES	VOLTAGE TO GROUND kV	X RATED	TEMPERATURE, °C CONDUCTOR	SHIELD
1	3	346	1.2	90	76
2	8	346	1.2	100	86
3	21	433	1.5	100	86

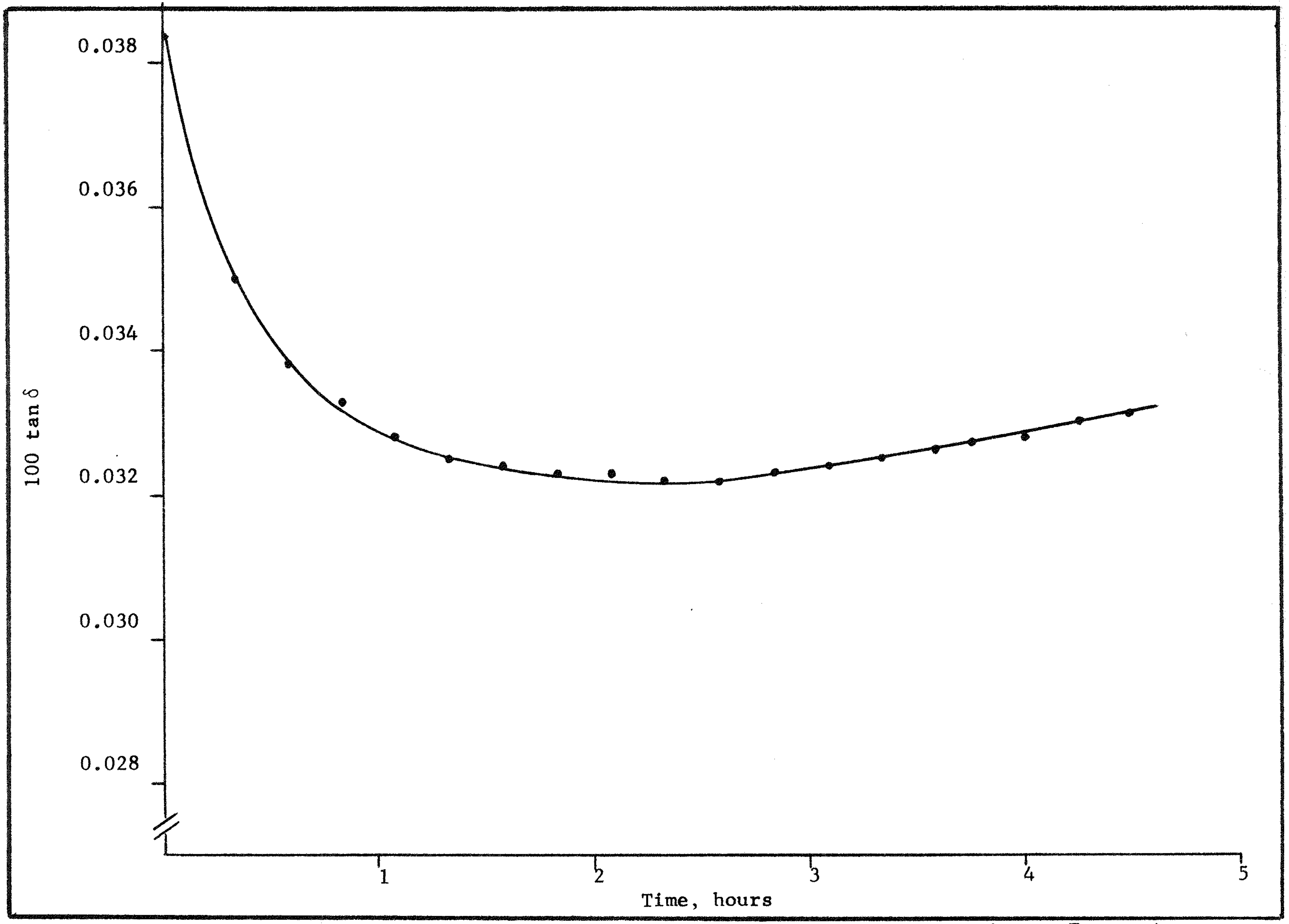


Figure 3-5. Prototype Cable No. 2. - Thermal Decay from Conductor Temperature of 90°C at 1.2 x Rated Voltage and 200 psi (14 kg/cm2)

Upon completion of the cyclic loading test, a high-voltage-time test was performed at 1.85 x rated voltage for 24 hours at 25°C. The dissipation factor of the sample was measured before and after the high-voltage-time test. The data obtained are plotted in Figure 3-6 and show no significant change in dissipation factor due to the test.

An impulse test at 25°C using a 1.5 x 40 microsecond wave shape was then conducted on Prototype Cable No. 2. The sample withstood 10 impulses at 1250 kV with negative voltage on the conductor. Higher voltage could not be placed on the sample because of proximity to other equipment. Prototype Cable No. 2 was removed from test and dismantled. Radial power factor tests and physical tests on the tapes of the insulation structure were conducted with the results shown in Figure 3-4 and Table 3-7, respectively. There is no significant change in the properties of the tapes due to the electrical tests to which Prototype Cable No. 2 was subjected.

The cold bend test in accordance with AEIC 2-73 was performed on this sample with satisfactory results.

A sample 20 feet (6.1 meters) long was installed in a special pipe for determination of the thermal resistivity of the insulation structure. The value of thermal rho was found to be 500°C-cm/watt from 25°C to 85°C.

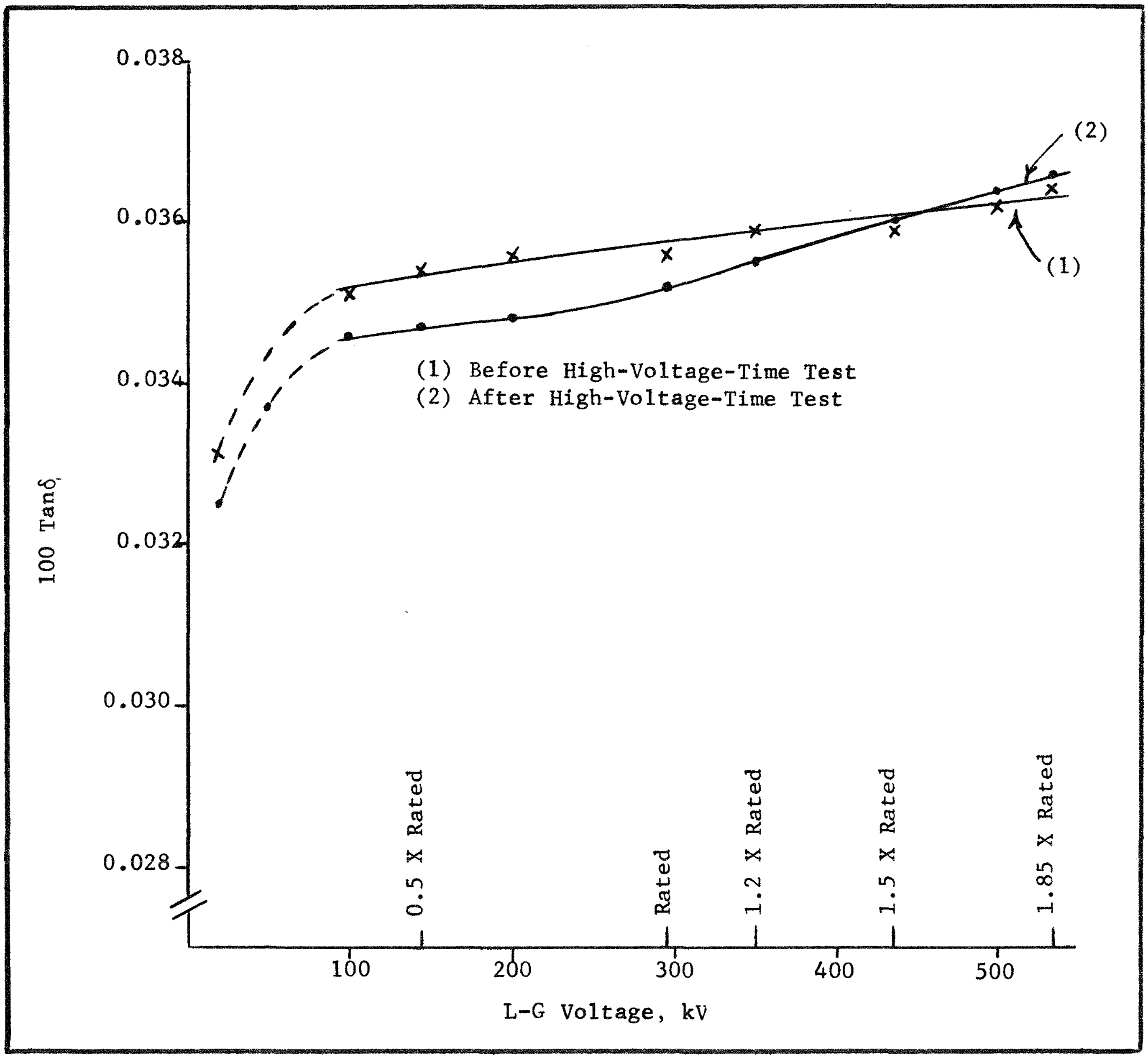


Figure 3-6. Prototype Cable No. 2. - Tan δ vs. Voltage at at 25°C and 100 psi (7 kg/cm^2)

Assessment of Prototype Cable No. 2. The evaluation of Prototype Cable No. 2 indicates that the cable made in accordance with this design is unsatisfactory because of excessive softness of the insulation structure. This softness is due to the fact that the embossing pattern creates looseness between tapes. The embossing disappears with time which further loosens the insulation structure.

On the other hand, this looseness of the insulation structure combined with the lower viscosity oil apparently eliminated any tendency towards oil-starvation during the cooling portion of the load cycle as encountered in Prototype Cable No. 1.

3.4 EVALUATION OF PROTOTYPE CABLE NO. 3

Because Prototype Cable No. 2 had excessive soft spots in the insulation structure which are unacceptable for commercial cable and the voltage breakdown of the insulating tapes was significantly reduced by the embossing process, the use of embossed tapes was abandoned. The use of higher tensions at the taping machine heads to make the cable harder is not practicable because this also reduces the effect of the embossing. Therefore, Prototype Cable No. 3 was made with plain PPP tapes. The dry insulation core was removed from the same factory length as Prototype Cable No. 1. Prototype Cable No. 3 was impregnated with the less viscous DC200-50 silicone oil because of the encouraging results obtained with this oil in Prototype Cable No. 2 insofar as oil-starvation prevention is concerned. No dodecylbenzene was added to the impregnant for this prototype as this sample would then differ from Prototype Cable No. 1 only in the viscosity of the impregnating oil.

Mechanical integrity, radial power factor, dielectric loss, physical properties of insulating tapes, cyclic loading, and miscellaneous special tests were conducted on this sample.

The mechanical structure of this prototype was satisfactory and the cable could be adequately oiled. There was no evidence of soft spots. The percent deformation was 1.2% which is very low compared to Prototype Cable No. 2. These data are presented in Table 3-5.

Physical properties and 60 Hz voltage breakdown of the insulating tapes removed from this prototype are shown in Table 3-10. There was no change in the physical properties due to the testing of Prototype Cable No. 3. The increase in voltage breakdown of the tapes may be due to the effects of absorbed impregnant in the PPP tapes.

Table 3-10

PROTOTYPE CABLE NO. 3

TESTS ON INSULATION TAPES

PROPERTY	BEFORE TESTING		AFTER TESTING	
Thickness, mils (mm)	8(0.203)	5(0.127)	8(0.203)	5(0.127)
Avg. Tensile Strength, lb/inch width (kg/cm)	51.4(5.20)	37.7(6.75)	49.4(8.84)	36.5(6.53)
Avg. Tearing Strength, grams	104	72	101	64.5
Folding Endurance, double folds	1000+	1000+	1000+	1000+
Avg. Voltage Breakdown, volts/mil, (kv/mm) at 25°C and 60 Hz in Air	1540(61.6)	2230(89.2)	1950(78.0)	2520(100.8)

Note: See Appendix 3 for references to applicable ASTM test methods.

Radial power factor data taken on this sample are shown in Figure 3-7. The data, taken on a short piece of the sample removed from one end prior to the dielectric loss and cyclic load testing indicate the cable was adequately dried. A visual examination indicated the sample was completely oiled during impregnation.

The dielectric loss at rated voltage to ground for 500 kV operation of Prototype Cable No. 3 prior to any testing is shown in Table 3-11. The dielectric loss of this sample is substantially the same as for Prototype Cables No. 1 and No. 2.

Thermal decay tests were conducted from conductor temperatures up to 100°C at oil pressures of 200 psi (14 kg/cm^2) to 15 psi (1.05 kg/cm^2) and at a continuous voltage of 1.5 x rated. Typical thermal decay curves are shown in Figure 3-8. In no case was any abrupt change in tan δ observed during these thermal decay tests which indicates no ionization took place at 1.5 x rated voltage as a result of oil-starvation. The curve of Figure 3-8 may be compared to the curves of Figure 3-3 of Prototype Cable No. 1 where oil-starvation did occur. The reason for the improvement in performance of Prototype Cable No. 3 over Prototype Cable No. 1 is attributed to the lower viscosity of the DC200-50 impregnating oil used in Prototype Cable No. 3. This low viscosity oil moves more freely between the tapes compared to the more viscous oil DC200-200 used in Prototype Cable No. 1.

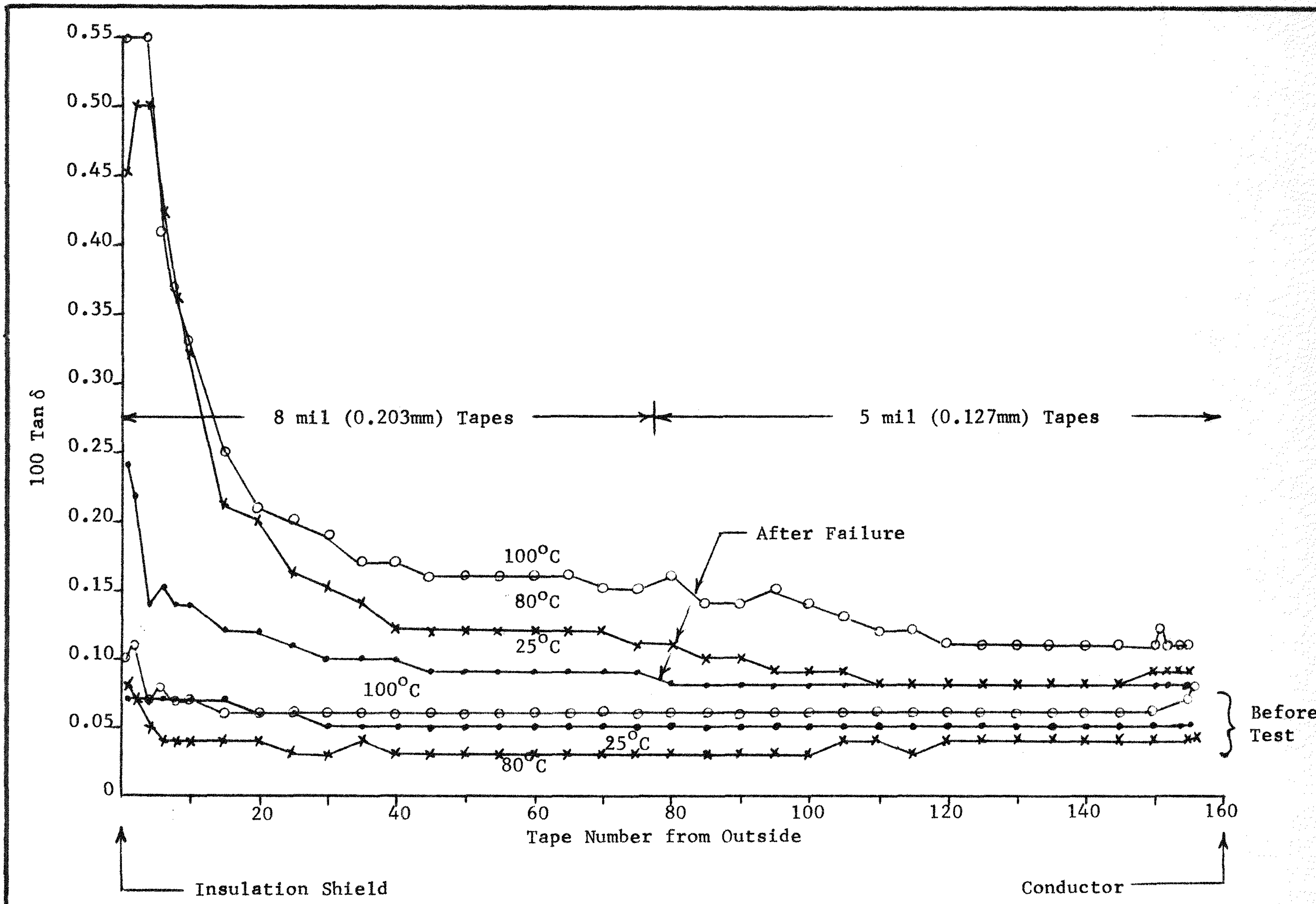


Figure 3-7. Prototype Cable No. 3. - Radial Power Factor

Table 3-11

PROTOTYPE CABLE NO. 3
DIELECTRIC LOSS

TEMPERATURE, ^{o}C	CAPACITANCE, pF PER FT. (pF/m)	100 TAN δ	DIELECTRIC LOSS, WATTS PER FOOT (W/m)
25	54.1(177)	0.036	0.63(2.07)
60	53.4(175)	0.031	0.53(1.74)
75	52.9(174)	0.031	0.51(1.67)
90	52.5(172)	0.031	0.52(1.71)

A summary of the cyclic loading test conducted on Prototype Cable No. 3 is shown in Table 3-12. As for previous samples, current was passed through the conductor and through the pipe containing the cable to provide a temperature drop across the cable insulation representative of service conditions.

For the first 23 cycles the temperature drop across the insulation was approximately $10^{o}C$, for all subsequent cycles this temperature drop was maintained at $15^{o}C$, as was done during cyclic aging of Prototype Cables No. 1 and No. 2.

During the cooling of the cable at cycle 26, 4 hours after the heating currents were turned off, Prototype Cable No. 3 failed. Tan δ of the sample had been periodically determined up to 1.5 x rated voltage, and there was no indication of an increase which may be the case if ionization or other thermal deterioration was taking place. In addition to the periodic tanδ readings, thermal decay data was taken during cycles 14 and 19 and there were no signs of ionization or oil-starvation in the insulation structure. These data are plotted in Figure 3-8.

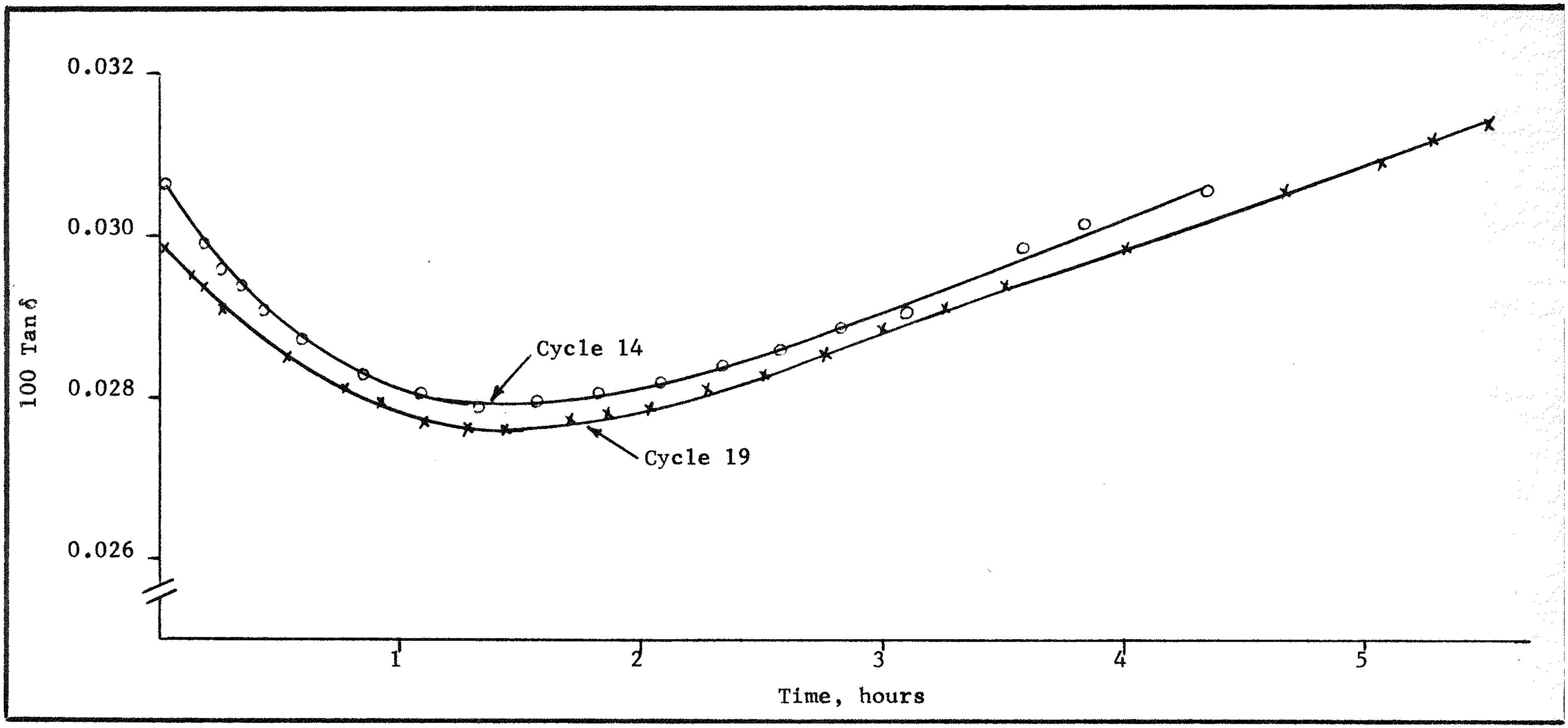


Figure 3-8. Prototype Cable No. 3. Thermal Decay from Conductor Temperature and 100°C at 1.5 x Rated Voltage and 100 psi (7 kg/cm^2).

Table 3-12

PROTOTYPE CABLE NO. 3

SUMMARY OF CYCLIC LOADING CONDITIONS

STEP NO.	NO. OF CYCLES	VOLTAGE X RATED	TEMPERATURE, °C CONDUCTOR	SHIELD
1	1-23	1.5	100	90
2	24-26	1.5	100	85

Note: Current loading, conductor and pipe, on 12 hours and off 12 hours each cycle.

Examination and Tests of Cable Components After Failure of Prototype Cable No. 3. The failure of Prototype Cable No. 3 was unexpected. The most likely cause is over-stressing of the impregnating oil in several spots in the insulation structure near the conductor.

A diagram of the fault paths is shown in Figure 3-9. The main fault path was a radial hole approximately 3/4 inch in diameter that eminated from the conductor at a point 12 inches below the terminal base plate on one end of the set-up. The PPP tapes were fused together around the edges of the main fault path.

Through most of the cable insulation wall, there was a longitudinal burned track up to 6 inches (15.24 cm) long connected to the main fault path and directed toward the termination. The longitudinal burns were not present at the extreme ends of the main fault path near the conductor and the insulation shield.

There was a secondary fault which began as a radial puncture at the conductor at a position about 6 inches (15.24 cm) above the main fault path (or 6 inches (15.24 cm) below the terminal base plate). At a diameter of about 1.9 inches (4.83 cm) a longitudinal burned track from the main fault made contact with the secondary fault. From this junction, the secondary fault path had a strong longitudinal component and as it gradually progressed outward through the cable insulation wall, it moved toward the termination.

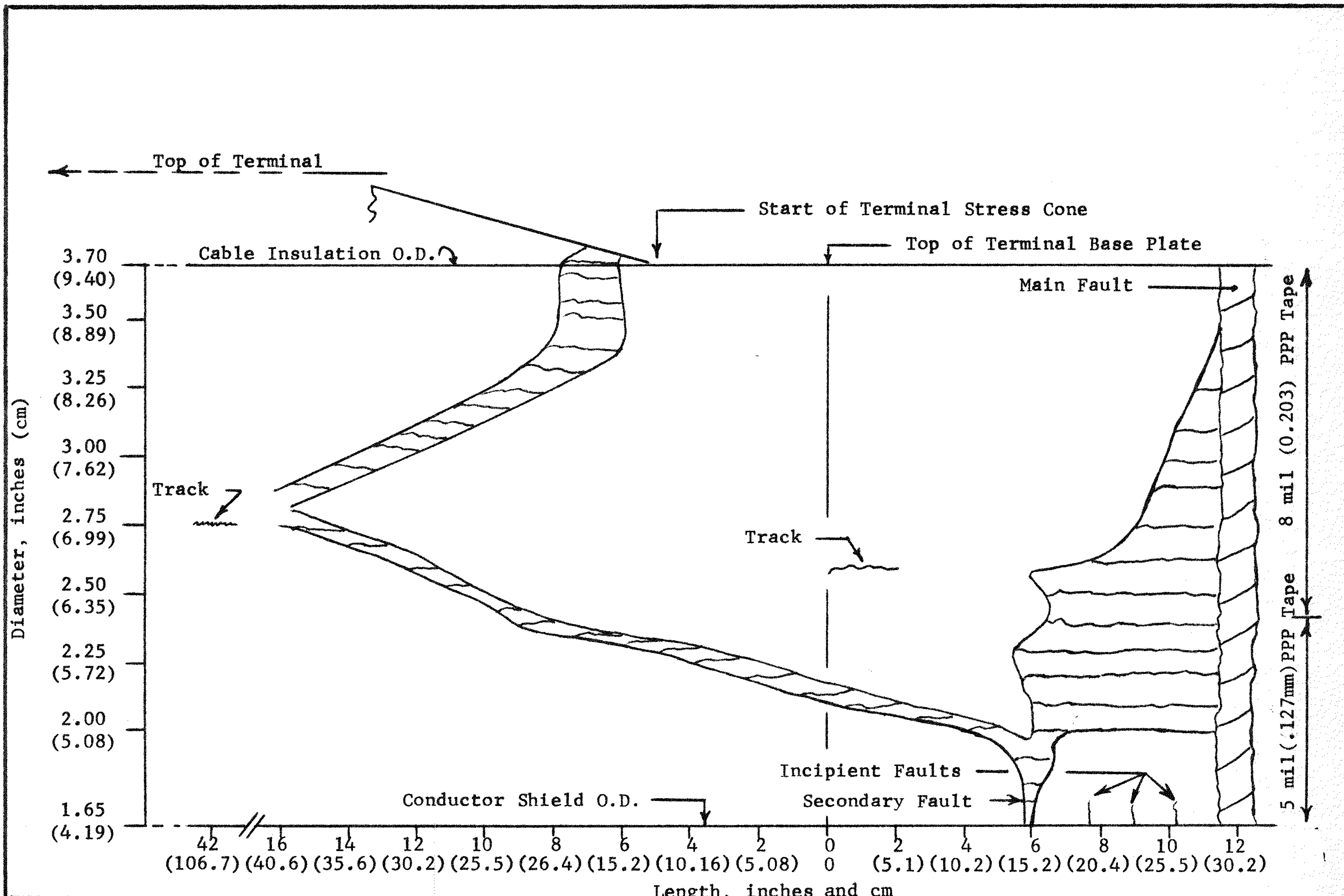


Figure 3-9. Prototype Cable No. 3. - Diagram of Fault Paths.

At about half way through the cable insulation wall, an apparently isolated track was found at a point 42-1/2 inches (1.08 meters) above the base plate.

A branch of the secondary fault path progressed in a generally radial direction until contact was made with the outer shield on the stress relief cone at a location about 1-1/2 inches (3.81 cm) above the base of the stress cone.

In the area between where the main and secondary fault paths made contact with the cable conductor, there were three incipient faults which had progressed radially through about the 10 innermost PPP tapes.

In the cable length and paper build-up rolls beyond the track 42 inches (1.05 meters) above the terminal base plate and for at least 3-1/2 feet (1.07 meters) in the cable below the location of the main fault path, no further evidence of disturbance was noted.

Along the entire test length of the cable sample there were burn marks in the insulation shield assembly. The burns were particularly prevalent along the edges of the two intercalated perforated aluminum foil-backed paper tapes; and along the edges of the intercalated perforated zinc and plain paper tape. The burning was also evident on the outermost PPP tape. These burns are believed due to the fault current which passed through the cable insulation shield assembly. The cable shield was insulated from the pipe enclosure and made contact with the grounded pipe at the end of the 30 foot (9.15 meters) pipe remote from the fault.

Additional tests were conducted on the insulation structure in order to establish the cause of failure. As previously indicated by the data presented in Table 3-10 physical tests and voltage breakdown tests indicate no deterioration of the insulation tapes during the cyclic aging testing. The radial power factor data taken on selected samples of Prototype No. 3 after failure and presented in Figures 3-7 and 3-10 indicate a significant increase in tan δ near the insulation shield and in some, but not all cases near the center of the insulation wall. For representative tapes with high values of tan δ the oil was extracted and replaced with new oil. In all cases the tan δ returned to initial low values. This demonstrates that there was no deterioration of the tapes tested as far as the cellulose and polypropylene components are concerned which would be the case if ionization was present during the cyclic loading test. This points out the highly localized deterioration which precipitated failure. The oil was removed from the PPP tapes having high tan δ and the 100 tan δ of this oil found to be in the range of

0.11-0.15 which demonstrates a deterioration or contamination of the oil tested. Infra-red and ultraviolet analysis of the oil did not reveal any oxidation or any other deterioration or contaminant to explain the higher tan δ .

Special Oil-Starvation Tests on Models. To further assess the possibility of oil-starvation in a PPP cable during thermal decay, 18 inch (45.7 cm) models of Prototype Cable No. 1 and Prototype Cable No. 3 were prepared. On each end, these models were fitted with epoxy seals. On one end a copper tube was imbedded in the seal and fitted with a compound gauge to measure pressure at the conductor. The models were placed in separate containers which were evacuated and filled with the appropriate oil. When the models had been pressurized, they were placed in a 100°C oven. The thermal decay imposed on the full-sample lengths of Prototypes 1 and 3 was simulated with the models by removing them from the oven, maintaining the container (pipe) pressure at the prescribed level while cooling to room temperature and monitoring the conductor pressure as a function of time.

The results for the 18 inch (45.7 cm) full-wall model of Prototype Cable No. 1 are given in Figure 3-11. During thermal decays from 100°C with different pressures, the pressure at the conductor was up to about 25 psi (1.7 kg/cm^2) less than the container pressure.

For the model of Prototype Cable No. 3 which has plain PPP tapes (as had Prototype Cable No. 1) and DC200-50 oil (rather than the more viscous DC200-200 for Prototype Cable No. 1), during thermal decay from 100°C, there was no measurable difference between the pressure at the conductor and the pressure in the container at container pressures as low as 25 psi.

Assessment of Prototype Cable No. 3. The evaluation of Prototpye Cable No. 3 indicates that the use of the lower viscosity silicone oil DC200-50 provided a means to eliminate oil-starvation during the cooling portion of the cyclic loading even when the plain PPP tapes are used in the insulation structure.

The failure of Prototype Cable No. 3 is attributed to the fact that the maximum voltage stress at the conductor during the cyclic aging test, when the voltage between the conductor and shield was 1.5 x rated, was excessive and caused local ionization in the butt spaces next to the conductor. With continued load cycling this precipitated voltage breakdown of the cable without creating a general deterioration of the insulation structure. In the design of the final cables it was, therefore, decided to reduce the voltage stress at the conductor by (1) increasing the conductor size from 2000 kcmil (1013 mm^2) to 2500 kcmil (1266 mm^2), (2) increasing the wall thickness from 1.025 inches (26 mm) to 1.200 inches (30.5 mm) and (3) using 3 mil (0.076 mm) thick tapes next to the conductor in place of 5 mil (0.127 mm) thick PPP tapes.

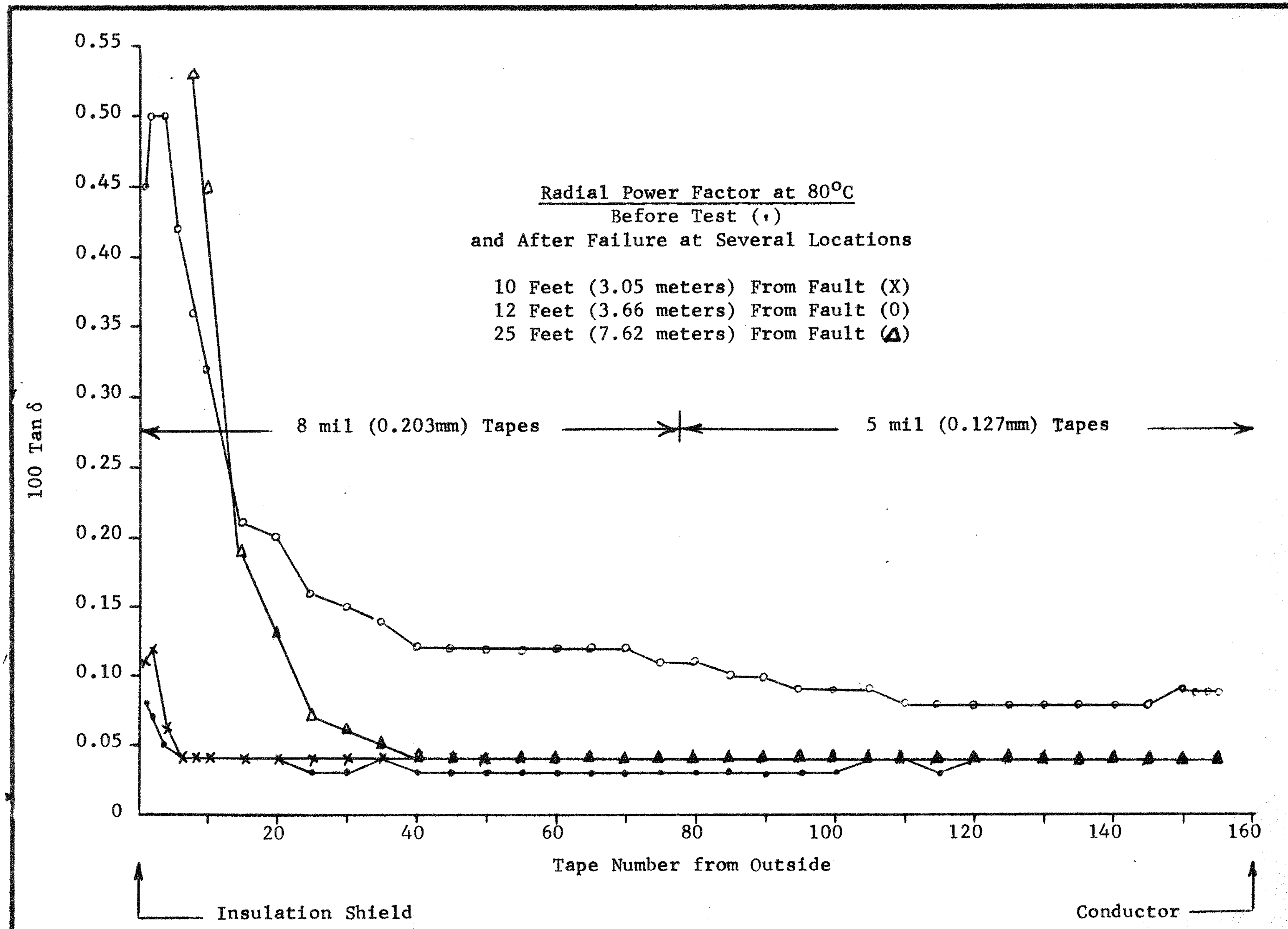


Figure 3-10. Prototype Cable No. 3. - Radial Power Factor After Failure

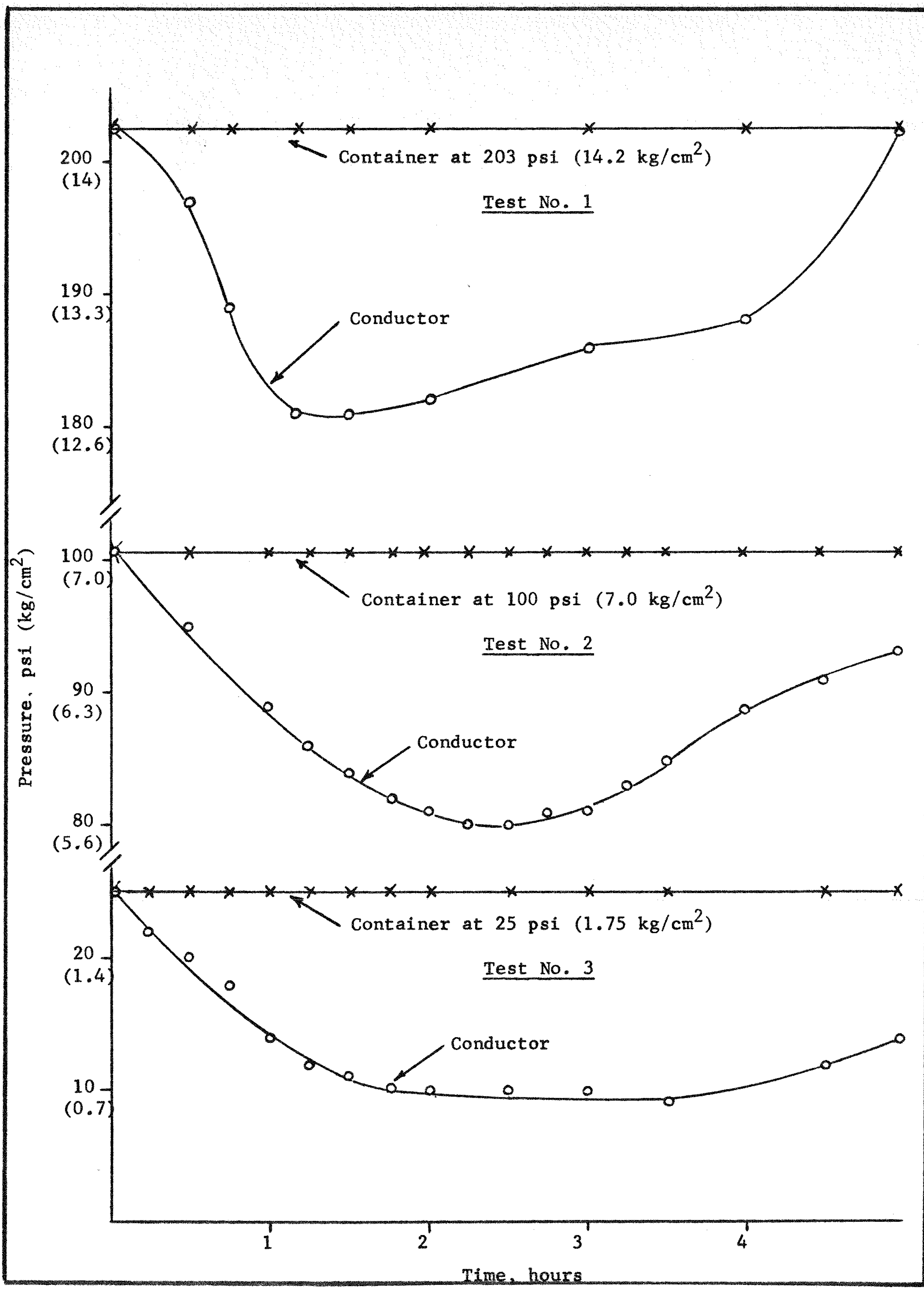


Figure 3-11. Conductor Pressure vs. Time During Thermal Decay - Special Oil-Starvation Test

Section 4

MANUFACTURE AND EVALUATION OF FINAL CABLE AND JOINT FOR TESTING AT WALTZ MILL TEST SITE

4.1 DESIGN AND MANUFACTURE

The design of the final cable is described in Table 4-1. In order to reduce the voltage stress in the insulation structure the conductor size was increased to 2500 kcmil (1266 mm^2) in place of 2000 kcmil (1013 mm^2), and the insulation thickness increased to 1200 mils (30.48 mm) in place of 1025 mils (26.04 mm) as was the case for the prototype cables. To increase the voltage breakdown strength of the oil in the butt spaces near the conductor, the thickness of the insulating tapes was reduced from 5 mils (0.127 mm) to 3 mils (0.076 mm). To provide additional filtering effect of the impregnant near the insulation structure surface, cellulose paper insulation and several carbon black cellulose tapes were used at both the inner and outer boundaries of the insulation wall.

To lower the impedance to oil flow through the insulation wall and thereby lessen the possibility of oil-starvation during thermal decay, the width of the PPP tapes was reduced from 1 inch (2.54 cm) to 1/2 inch (1.27 cm) and 3/4 inch (1.90 cm) as indicated in Table 4-1. The estimated oil flow impedance of the final cable is 25% less than Prototype Cable No. 3.

The impregnant used for the final cable is DC200-50 EG with an additive of 5% by volume of dodecylbenzene. The EG grade of oil is so designated because the supplier, Dow Corning Corporation, subjects the oil to additional filtering prior to shipment. The data presented in Table 2-27 indicates the higher voltage breakdown of the EG grade of oil compared to the commercial grade used in the prototype cables.

Final cables were dried and impregnated in a 400 foot (121.9 meter) length of 6 inch (15.24 cm) steel pipe to allow the manufacture of 4 lengths of cable for the present Waltz Mill test configuration. This allows for 3 cables to be installed for test and for one spare length in case of damage of one length during installation or if it becomes necessary to replace one length during testing.

Table 4-1

DESIGN OF FINAL 500 KV CABLE

Conductor:	
Type - Tinned Copper Compact Segmental 4 Segments, 2 Insulated with Paper	
Size - 2500 kcmil (1266 mm^2)	
Binder - Tinned Bronze Tape Intercalated with Cellulose Paper Tape	
OD, Inches (cm)	1.82 (4.62)
Insulation Structure:	
(Impregnant - Silicone Oil DC200-50 EG with 5% Dodecylbenzene Additive)	
Conductor Shield	
4 - 5 mil (0.127 mm) Carbon Black + 1 - 5 mil (0.127 mm) Carbon Black/Paper Duplex Tape	
Insulating Tapes	
2 - 3 mil (0.076 mm) x 1/2 Inch (1.27 cm) Cellulose Paper Tapes 13 - 3 mil (0.076 mm) x 1/2 Inch (1.27 cm) PPP Tapes 20 - 5 mil (0.127 mm) x 1/2 Inch (1.27 cm) PPP Tapes 20 - 5 mil (0.127 mm) x 3/4 Inch (1.90 cm) PPP Tapes 100 - 8 mil (0.203 mm) x 3/4 Inch (1.90 cm) PPP Tapes 18 - 8 mil (0.203 mm) x 1 Inch (2.54 cm) PPP Tapes 2 - 8 mil (0.203 mm) x 1 Inch (2.54 cm) Cellulose Paper Tapes	
Insulation Thickness, Nominal, Inches (mm)	1.20 (30.5)
Insulation OD, Inches (cm)	4.28 (10.9)
Insulation Shield	
1 - 5 mil (0.127 mm) Carbon Black/Paper Duplex Tape 2 - 5 mil (0.127 mm) Carbon Black Tape 2 - 5 mil (0.127 mm) Perforated Aluminum Foil Backed Carbon Black Tape	
Moisture Seal, Skid-Wire Assembly	
2 - 2.5 mil (0.064 mm) Aluminum Foil Back Intercalated Polyester Tapes 2 - 5 mil (0.127 mm) Tinned Copper Tapes Intercalated with 2 mil (0.051 mm) Polyester Tapes 2 - 0.150 Inch (0.38 cm) x 0.300 Inch (0.76 cm) Black High Density Polyethylene Skid Wires	
OD, Inches (cm)	4.67 (11.9)

After the manufacture of the first final cable a full reel dissipation factor test was performed up to 75 kV. Beyond this voltage, ionization appeared due to drainage of the impregnant. Therefore, the AEIC Specification Ionization Test was not performed on the remaining 3 lengths of final cable. Approximately 70 feet of cable was cut from final lengths No. 1 and No. 3 for full laboratory evaluation. The cables, with pulling eyes on each end are available for further testing at Waltz Mill are as follows:

Final Cable No. 1 - 315 feet (96 meters)
Final Cable No. 2 - 375 feet (114 meters)
Final Cable No. 3 - 335 feet (101 meters)
Final Cable No. 4 - 378 feet (115 meters)

These 4 lengths are stored under nitrogen-filled blankets.

4.2 DESIGN AND MANUFACTURE OF FINAL JOINT

A joint was installed in Sample No. 1 of the final cable made for evaluation at the Waltz Mill Test Site. A diagram of the joint and the principal dimensions are given in Figure 4-1.

The average design stress along the longitudinal creepage path from the connector, along the pencil in the cable insulation and beneath the stress cone to the outer shield is 5.0 Volt/mil (0.2 kV/mm). This value is comparable to what is employed in EHV joints made of cellulose paper insulation and is dictated by the construction of the PPP insulation which offers no advantage over cellulose paper in the longitudinal direction.

At the connector, the maximum design radial stress is 280 Volt/mil (11.0 kV/mm) and the average design radial stress is 159 Volt/mil (6.3 kV/mm). These values are less than the maximum stress at the cable conductor of 370 Volt/mil (14.6 kV/mm) and an average stress in the cable of 240 Volt/mil (9.4 kV/mm).

The build-up tapes within the joint matched the thickness of the cable tapes. One half inch (1.27 mm) x 3 mil (0.076 mm) thick PPP tapes were used in the joint up to the same diameter as the 1/2 inch (12.7 mm) x 3 mil (0.076 mm) tapes in the cable. Three quarter inch (19.1 mm) wide x 5 mil (0.127 mm) thick PPP tapes were used in the joint to match the 1/2 inch (12.7 mm) and 3/4 inch (19.1 mm) x 5 mil (0.127 mm) PPP tapes in the cable. One inch (25.4 mm) wide x 8 mil (.203 mm) thick PPP tapes were used in the joint to match the 3/4 inch (19.1 mm) and 1 inch (25.4 mm) wide x 8 mil (0.23 mm) PPP tapes in the cable and also in the "belt"which is that part of the joint with diameter greater than the cable. Pads of splicing tapes were wound from the same PPP material as used in the cable. The pads were vacuum dried and impregnated with the same mixture of silicone and dodecylbenzene oils used for the cable. The jointing operation was performed in a controlled atmosphere of approximately 15% relative humidity. Interruptions in the cable shield were made on each side of the joint in order to permit determination of the dissipation factor of the joint separate from that of the cable.

4.3 EVALUATION OF SAMPLE NO. 1, FINAL CABLE AND FINAL JOINT

After removing 10 feet (30.5 m) from one end of the first length of the final cable for tests on its components, an additional 70 feet (21.3 m) was removed for installation of the final joint in its center and full-scale electrical testing of the joint and cable.

Mechanical integrity, cold bend, radial power factor, dielectric loss, physical properties of insulating tapes, cyclic loading, and high-voltage-time tests were conducted on this cable. The joint was fabricated in a special housing maintained at 15% relative humidity.

The mechanical structure of this cable is satisfactory and was adequately oiled. The sample passed the AEIC Specification No. 2-73 cold bend test.

Physical properties and 60 Hz voltage breakdown of the insulating papers taken from this sample are shown in Table 4-2. The physical properties are satisfactory. The voltage breakdown values are satisfactory and the slight decrease after testing is not significant.

Radial power factor data taken on this sample are shown in Figure 4-2. These data, taken on a short piece of cable removed prior to testing indicate the cable was dried adequately. The data taken on a short sample after testing indicate that the high-voltage-time test and the cyclic aging testing did not significantly affect tan δ .

The dielectric loss at rated operating voltage to ground for 500 kV cable of Sample No. 1 of the final cable and final joint are given in Table 4-3. The data on the cable are consistent with previous data taken on the prototype cables and the data on the joint are consistent with past experience when fabricating joints at the low-humidity condition of 15%.

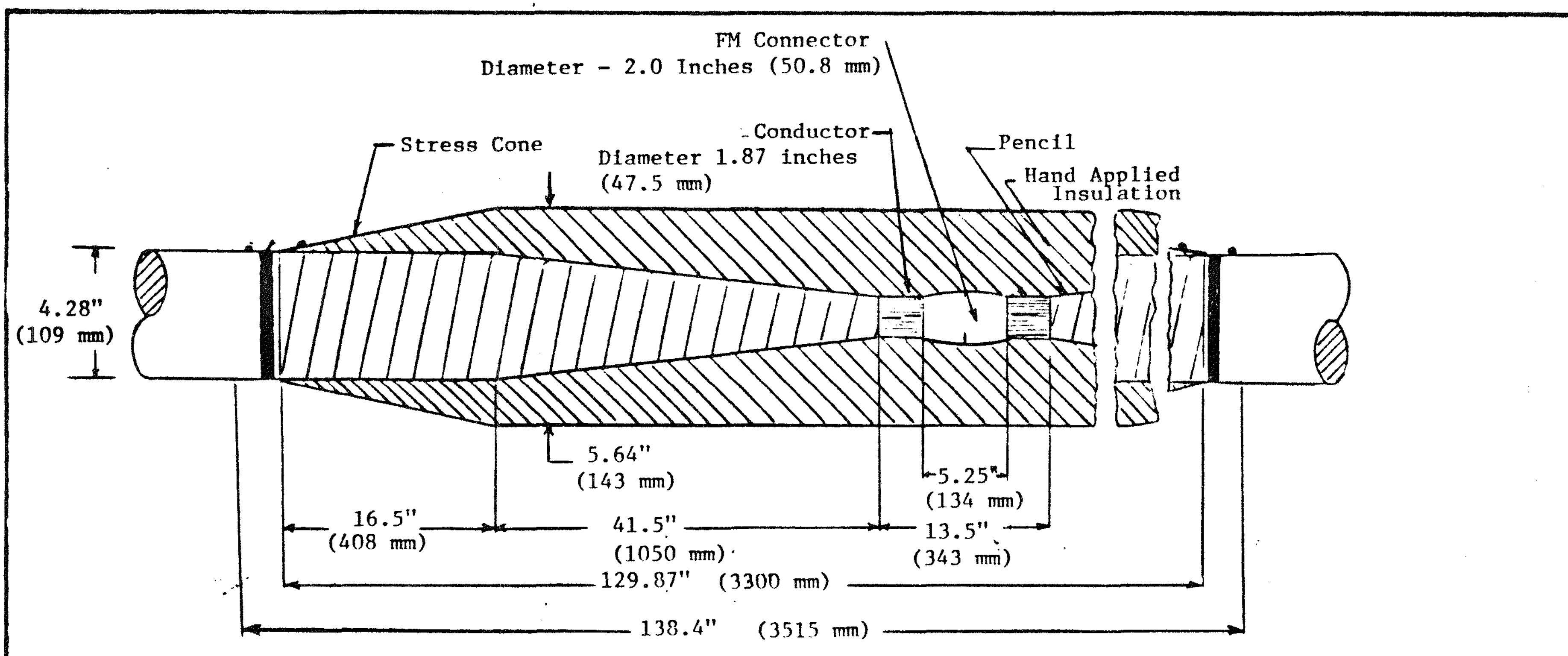


Figure 4-1.- Final Joint for 500 kV Cable, 2500 kcmil (1266 mm^2) Conductor, 1.2 Inch (30.5 mm) Insulation Thickness

Table 4-2

SAMPLE NO. 1 - FINAL CABLE
TESTS ON INSULATION TAPES

PROPERTY	BEFORE TESTING			AFTER TESTING		
Thickness, mils (mm)	8(0.203)	5(0.127)	3(0.076)	8(0.703)	5(0.07)	3(60.6)
Avg. Tensile Strength, lb/inch width (kg/cm)	34(6.1)	23(4.1)	24(4.3)	32(5.7)	27(4.8)	30(5.4)
Avg. Tearing Strength, grams	111	70	54	116	76	63
Folding Endurance, double folds	500+	500+	77	500+	500+	211
Avg. Voltage Breakdown, 60 Hz, Volts/mil (kV/mm) at 25°C, in Oil, In Air	1760 (70.4)	2230 (89.2)	2140 (85.6)	1580 (63.2)	1990 (79.6)	2040 (81.6)

Note: See Appendix 3 for references to applicable ASTM Test Methods.

Table 4-3

SAMPLE NO. 1 FINAL CABLE AND FINAL JOINT
DIELECTRIC LOSS
AT 200 PSI (14 kg/cm^2) OIL PRESSURE AND 289 KV CONDUCTOR SHIELD

TEMPERATURE, °C	CAPACITANCE, pF/FOOT, (pF/m)	100 TANδ	DIELECTRIC LOSS, WATTS/FOOT, (Watts/m)
Final Cable			
20	53.0(174)	0.040	0.67(2.20)
40	52.0(171)	0.033	0.54(1.77)
60	51.8(170)	0.032	0.52(1.71)
80	51.6(169)	0.034	0.55(1.81)
Final Joint			
20	-	0.055	-
40	-	0.050	-
60	-	0.052	-
80	-	0.055	-

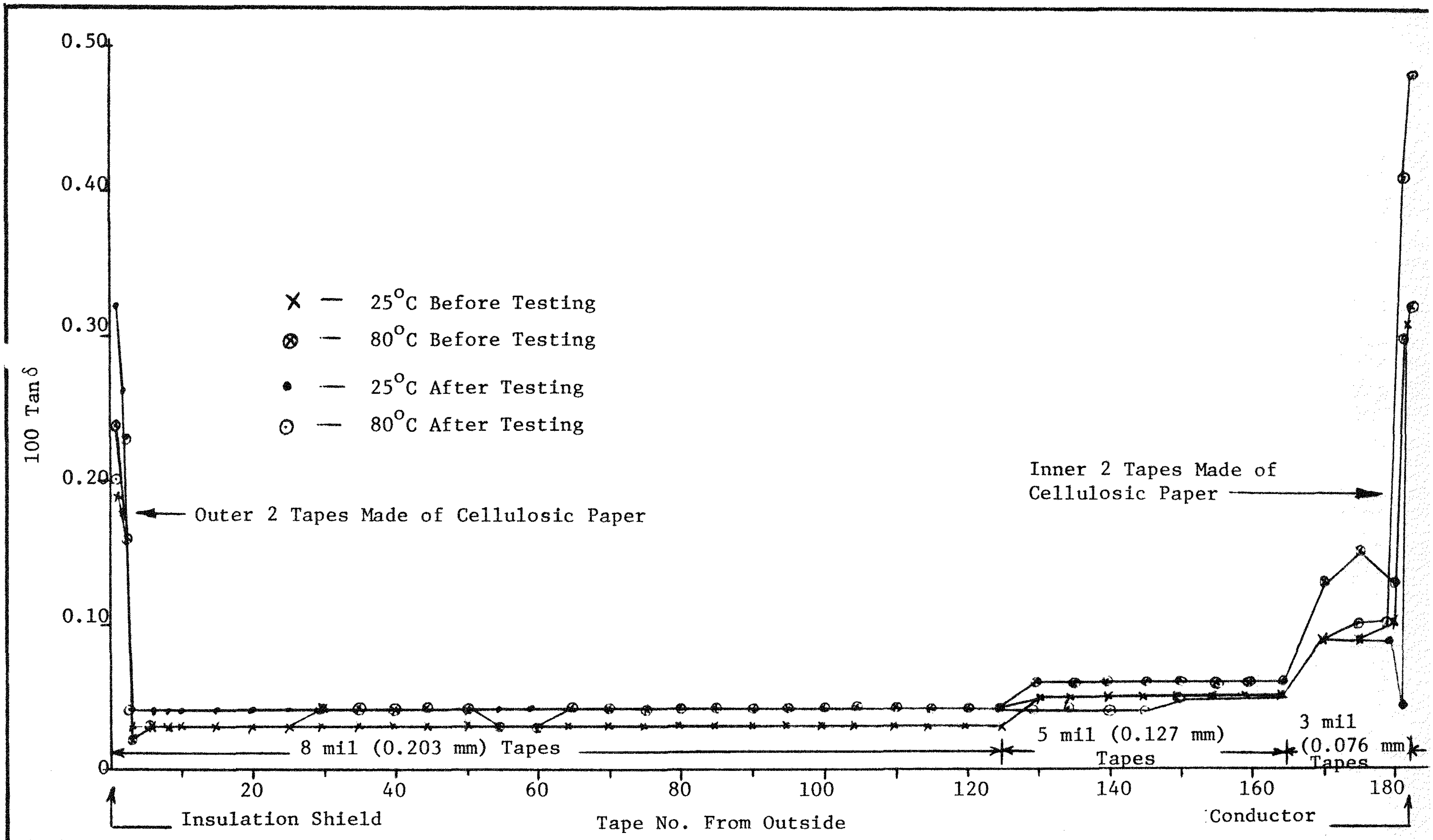


Figure 4-2. Final Cable Sample No. 1 - Radial Power Factor

Sample No. 1 of the final cable with joint was subjected to numerous thermal decays to judge if there was any evidence of oil-starvation in either the cable or joint. None was found. Tan δ was monitored continously during these decays because an abrupt and significant change in tan δ would indicate ionization was present. The most likely cause of this ionization would be oil-starvation. Thermal decays were conducted at temperatures up to $80^{o}C$ and voltages as high as 1.5 x rated voltage. Tan δ data obtained during a thermal decay is shown in Figure 4-3. The conductor and the pipe are heated so that the shield temperature reaches values representative of service conditions. When the thermal decay test is conducted both conductor and pipe currents are removed at time zero so that the maximum rate of cooling is effected.

After completion of the dielectric loss and thermal decay testing, the sample and joint were subjected to the AEIC Specification No. 2-73 High-Voltage-Time Test. A voltage of 516 kV or 1.8 x rated was applied on the sample and joint for 6 hours at an oil pressure of 150 psi (10.5 kg/cm^2) and at ambient temperature. After the High-Voltage-Time Test, tan δ was measured at $25^{o}C$ and $80^{o}C$ at voltages up to 516 kV and an oil pressure of 175 psi (12.2 kg/cm^2). No significant change in tan δ was found in the cable or joint and no evidence of ionization was present.

The sample and joint were then cyclic loaded at 1.25 x rated voltage to ground, at a conductor temperature of $80^{o}C$ and oil pressure of 175 psig (12.2 kg/cm^2). However, this test was aborted in daily load cycle No. 11 because an oil pressure pump was inadvertently disconnected and this lowered the oil pressure in the sample to atmospheric, and precipitated failure. There was no deterioration found in the cable or joint except at the fault paths which were localized in the vicinity of the stress cone at one terminal. Because of this incident, it was decided to subject another sample of the final cable to extensive testing.

4.4 EVALUATION OF SAMPLE NO. 2, FINAL CABLE

After removing a small section for tests on the cable components, a 70 foot (21.3 meters) section of the third length of the final cable was removed from the cable for testing in the laboratory. Mechanical integrity, radial power factor, dielectric strength and physical properties of the insulating tapes were tested and found to be substantially similar to the data established for Sample No. 1 from the first length of the final cable. Physical properties and 60 Hz voltage breakdown of the insulating tapes taken from Sample No. 2 are shown in Table 4-4. The radial power factor data are given in Figure 4-4.

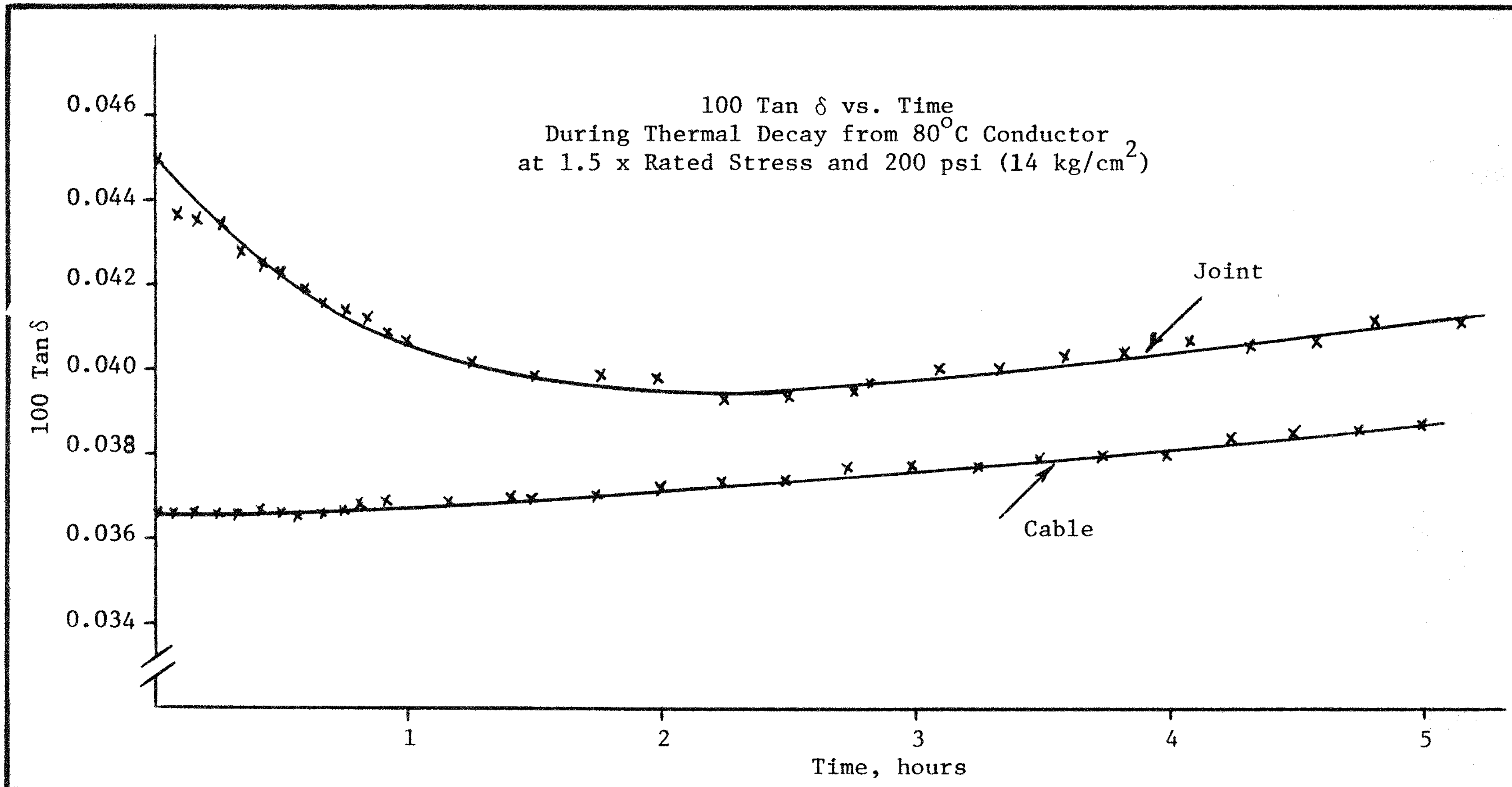


Figure 4-3. Final Cable Sample No. 1 with Joint - Thermal Decay

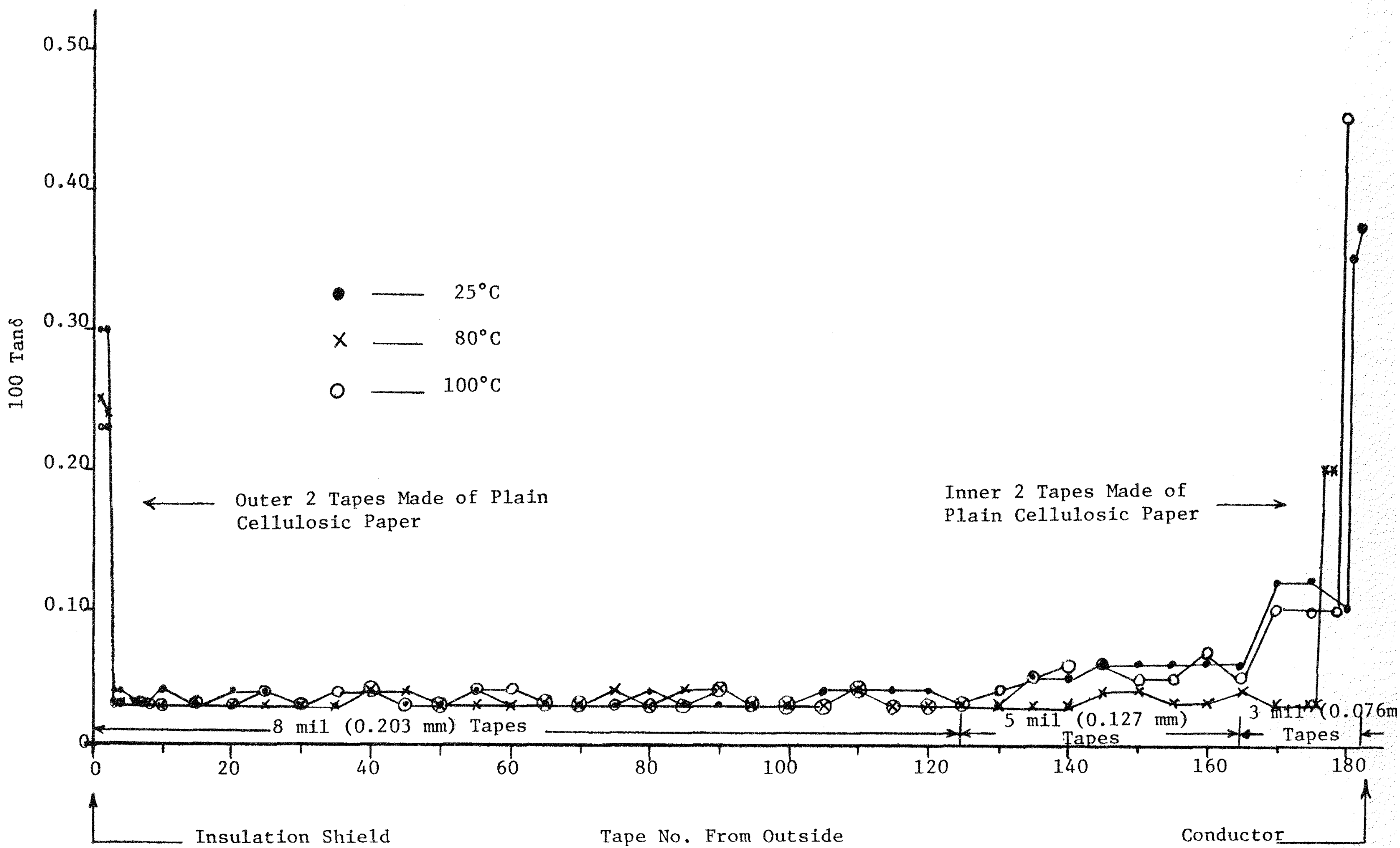


Figure 4-4. Final Cable Sample No. 2 - Radial Dissipation Factor Before Testing

Table 4-4

SAMPLE NO. 2 - FINAL CABLE
PHYSICAL AND ELECTRICAL TESTS ON PPP TAPES
PRIOR TO TESTING

Thickness, mils (mm)	8(0.203)	5(0.127)	3(0.076)
Avg. Tensile Strength, lb/inch width (kg/cm)	36(6.4)	28(5.0)	32(5.7)
Avg. Tearing Strength, grams	132	76	72
Avg. Folding Endurance, double folds	500+	500+	500+
Avg. Dielectric Strength, Volts/mil, (kv/mm) at 25°C and 60 Hz, In Air	1730 (69.2)	2470 (98.8)	2830 (113.2)

Note: See Appendix 3 for references to applicable ASTM methods.

Similar data were taken on short samples from the second and fourth lengths of final cable and the data was substantially similar to that established for Sample No. 1 from the first length.

Sample No. 2, taken from the third length of the final cable, was tested in the GCC EHV outdoor laboratory and initial tan δ data taken are given in Figure 4-5. The sample was first tested in an ambient temperature of 4°C. Since the tan δ increased with voltage, indicating ionization could be present, the partial discharge of the sample was determined using a bridge-type partial-discharge detector. This allows any discharge in the termination to be separated from discharge on the cable sample. No partial discharge was found in the cable up to 300 kV, the maximum voltage at which the noise level did not exceed 50 picocoulombs. Discharges up to approximately 1000 picocoulombs were present in one of the two terminals. The sample was raised in temperature to 20°C and at this temperature tan δ did not change significantly with voltage. The sample was load cycled without voltage at a conductor temperature of 80°C and tan δ data obtained after 5 and 12 daily cycles are shown in Figure 4-4. It appears that tan δ had significantly decreased at the higher voltages after this load cycling.

Thermal decays from a conductor temperature of 80°C at 300 psi (21 kg/cm^2) oil pressure and at 300 kV were conducted and the partial discharge was monitored.

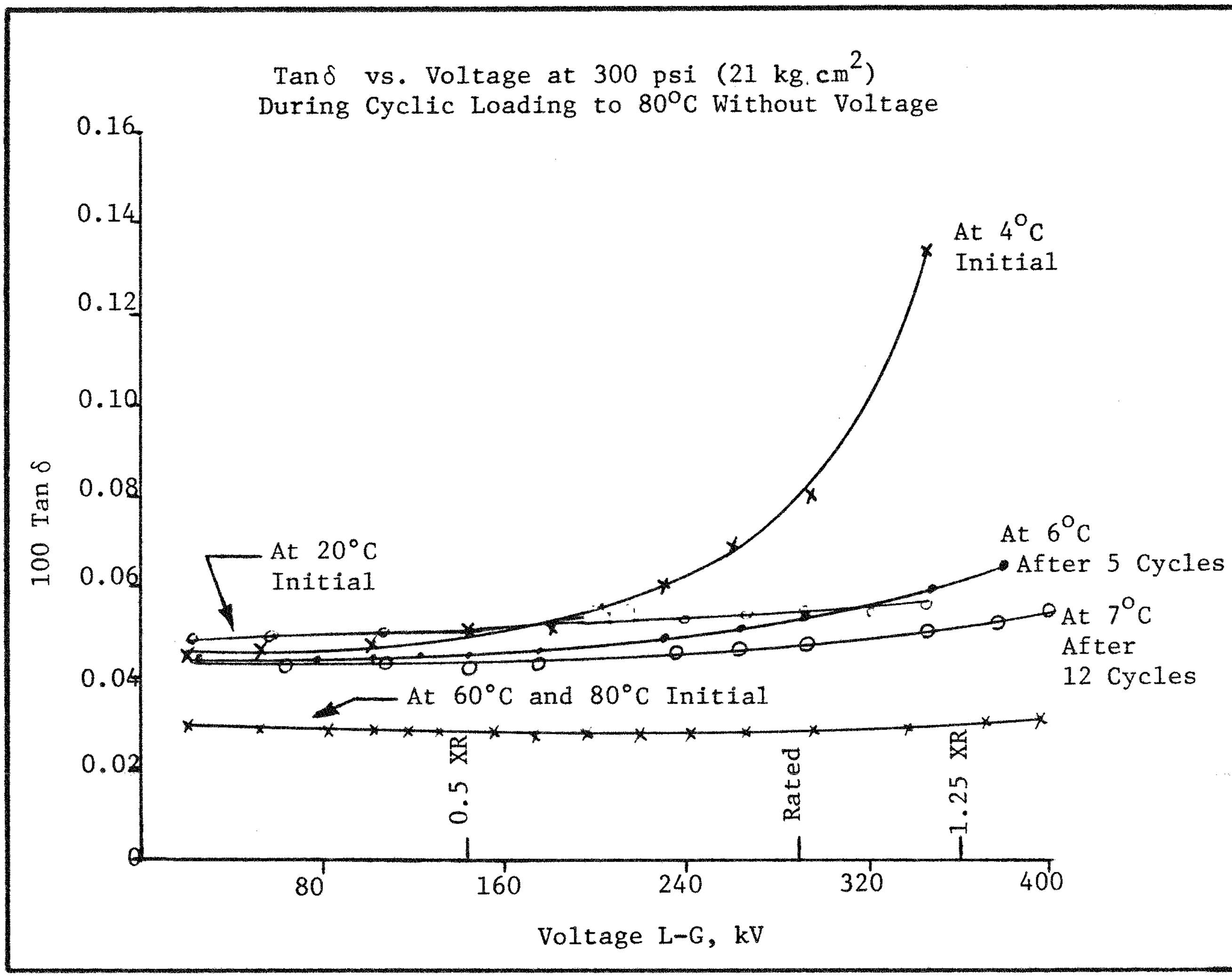


Figure 4-5. Final Cable Sample No. 2 - Tan δ vs. Voltage

No discharge of the cable at ambient temperatues down to 7°C was detected at 300 kV after 12 load cycles. A summary of the partial discharge (corona) measurements on Sample No. 2, including thermal decays, is presented in Table 4-5. The terminals were interchanged on the test sample and the fact that the partial discharge exists in the same terminal after removal from one end of the test cable to the other is a further demonstration that the partial discharge exists in the termination and not in the cable, the stress cones or the paper build-ups in the terminal. Shield interrupts were in place at each end of Sample No. 2 to enable separation of the discharges in the terminals from those in the cable.

Sample No. 2 was load-cycled following the program indicated in Table 4-6 with satisfactory results. Upon completion of the load-cycling, a thermal decay test was conducted and no indication of ionization was found. There was no change in tan δ of the sample during the load-cycle test as revealed by the data in Table 4-7.

Table 4-5

SAMPLE NO. 2 OF FINAL CABLE
SUMMARY OF CORONA MEASUREMENTS

LOCATION	TEMP. °C	VOLTAGE kV L-G	PARTIAL DISCHARGE, PICOCOULOMBS: WEST END TERMINAL	CABLE	EAST END TERMINAL
Outdoor	-5	260	None	None	700
	Potheads removed from set-up and tested at 0 psig without cable				
Indoor	25	315	None	-	None
	Potheads interchanged and reinstalled on same test cable				
Outdoor	7	260	500	None	None
Outdoor	80 (3)	300	None	None	None

Notes: (1) All measurements made at 300 psi (21 kg/cm^2), unless stated otherwise.
(2) All measurements made using bridge-type detector.
(3) Measurements made continously for 5 hours during thermal decay from 80°C conductor temperature.

Table 4-6

SAMPLE NO. 2 FINAL CABLE
SUMMARY OF CYCLIC LOADING CONDITIONS

At 300 psi (21 kg/cm^2) Oil Pressure

STEP NO.	NO. OF CYCLES	VOLTAGE TO GROUND KV	VOLTAGE TO GROUND X RATED	CONDUCTOR TEMPERATURE, °C
1	10	290	1.0	80
2	10	360	1.25	80
3	30	360	1.25	90

Table 4-7

SAMPLE NO. 2 FINAL CABLE
DISSIPATION FACTOR DURING CYCLIC LOADING

Time	Conductor Temperature, °C	Dissipation Factor at 289 kV 100 Tanδ
Initial	20	0.05
	80	0.03
End Step No. 1	50	0.04
	80	0.04
End Step No. 2	90	0.05
After 11 Cycles During Step No. 3	90	0.04

Section 5
ECONOMIC COMPARISON

An economic comparison was made between self-cooled 500 kV cable systems using plain PPP tapes as insulation having an insulation wall thickness of 1.04 inches (26.0 mm) or 1.2 inches (30.5 mm), and a cable system employing cellulose cable insulation having an insulation wall of 1.34 inches (34.0 mm) thickness.

In order to simplify the comparison, the same conductor size 2500 kcmil (1266 mm^2), the same pipe size 10 inches (25.4 mm), and cost $225,000/mile ($140,625/km) for pipe installation were used in each case. Also, it was assumed that for each system there will be two joints/mile (1.61 km), two sets of terminals/10 miles (16 km), and that the cost of these joints or terminals will be the same in each case. The prices are based on the results of the Electric Research Council Research Project 78-8. For each cable the conductor temperature is 85°C, the earth temperature is 25°C and the thermal rho for the soil is 65°C-cm/W.

For the cables insulated with PPP tapes, silicone oil (at a projected price of $10 per gallon) ($2.64/1) was used as both the cable impregnant and the pipe-filling fluid. A price of $1.45/lb ($3.22/kg) was used for the PPP tapes having a S.I.C. of 2.6 and a 100 tan δ of 0.06.

For the cellulose cable, mineral oil (at a price of $0.91 per gallon) ($.24/1) was used as the impregnant and pipe-filling oil.

A price of $0.48/lb ($1.07/kg) was used for the cellulose paper having an S.I.C. of 3.5 and a 100 tan δ of 0.16.

The results of the economic comparison are given in Table 5-1. The system cost, on a $/MVA-mile ($/MVA-km) basis, is virtually identical for the two cables insulated with PPP tapes. As shown, the system cost of the PPP cable system is approximately 9% more than the cost of the cellulose cable system. However, this will be mitigated by the additional cost (not included in this comparison) of the larger amount of compensating reactance required by the cellulose cable system compared to the PPP cable system. Since the amount of required KVAR is directly proportional to the cable capacitance, the cost of compensation will be 25% greater for the cellulose cable system than for the system utilizing the final design of PPP cable. This follows from the fact that the capacitance of the 500 kV cable insulated with PPP tapes is 25% less than conventional cable insulated with cellulose paper tapes. Dielectric losses are lower with the PPP insulation structure and with the increased interest in this parameter, it may be very significant.

Table 5-1

ECONOMIC COMPARISON OF 500 KV CABLES
USING PLAIN PPP TAPES AND DEIONIZED WATER
WASHED CELLULOSE PAPER TAPES

	PPP CABLES (1)		
	PROTOTYPE CABLE	FINAL DESIGN	CELLULOSE CABLE (2)
Conductor Size, kcmil (mm^2)	2,500 (1266)	2,500 (1266)	2,500 (1266)
Insulation Wall, mils (mm)	1,025 (26.0)	1,200 (30.5)	1,340 (34.0)
Pipe Size, inches (mm)	10 (254)	10 (254)	10 (254)
Pipe/Cable Fill Ratio, %	40.4	43.5	43.9
Amperes	1,132	1,125	932
MVA, Self-Cooled	980	974	807
Pipe Oil, gal/mile (l/km)	13,100 (30,820)	11,300 (26,585)	9,523 (22,404)
	Costs, $/circuit mile ($/circuit km)		
Cable	462,200	481,000	368,323
Pipe	26,400	26,400	26,400
Pipe Oil	131,000	113,000	8,666
Installation	225,000	225,000	225,000
Accessories	46,000	46,000	46,000
TOTAL	890,600 (553,500)	891,400 (554,000)	674,389 (419,140)
	System Cost, $/MVA mile ($/MVA km)		
	909 (565)	915 (569)	836 (520)

Notes: (1) Silicone oil DC200-50 EG used as impregnant and pipe oil.

(2) Sun XX oil used as impregnant and Sun No. 4 used as pipe oil.

Section 6

DISCUSSION OF RESULTS AND CONCLUSIONS

6.1 DISCUSSION OF RESULTS

6.1.1 3M Polypropylene Paper Tape

Studies by the 3M Company during an earlier project indicated that their polypropylene paper appeared to be a very promising material for laminar dielectric power cables. The principal deficiency found in this material during this project is the lack of compatibility with available impregnants of the tapes when applied in insulation thicknesses of about 1 inch (25.4 mm). Although no fully compatible impregnant was found in this project, it is conceivable that future investigations could develop compatible impregnants and pipe-filling oils. Other deficiencies were found such as excessive variability in air resistance, density and dielectric strength which most likely, can be corrected if additional experience is gained in processing. The most promising use of the 3M paper for application to EHV cables is to laminate it between two thin cellulosic papers. This composite tape is likely to have satisfactory mechanical stability with impregnating oils and have air resistance comparable to high density insulating grade cellulosic papers. Thus, the impregnating oil would penetrate radially through the composite tape which is not possible with the extruded polypropylene film when sandwiched between two cellulosic papers. Such a composite tape would have sufficiently low dissipation factor and dielectric constant for cables rated 500 kV and higher, would have adequate voltage breakdown strength, be compatible with impregnants and pipe-filling oils and transmit these oils radially as required by the cable cooling periods, in service. Preliminary trials were made by 3M to produce such a tape, but were abandoned because PPP tapes showed greater promise.

6.1.2 PPP Cellulosic Paper-Polypropylene Film-Cellulosic Paper Tape

As explained in Section 1 of this report the PPP tape evolved after extensive investigations at the General Cable Research Center. The present state-of-the-art indicates this tape to be the most promising available tape for power cables rated 500 kV ac and higher.

In order to utilize the PPP tape in its present form it is necessary to use a lower viscosity impregnant than currently used in pipe-type cables and it is necessary to use an insulation structure with low impedance to oil flow during thermal cycling. The latter requirement presents no handling or fabrication problems. However, the lower viscosity oil has more tendency to drain from the insulation structure. It is believed that this oil drainage can be minimized by optimized design of the shield/moisture seal assembly.

It is also possible to reduce the permeability of the present PPP tape from infinity to a value similar to cellulose paper tape by perforating the polypropylene film with small holes randomly placed. The proper placement, number and size of these holes would not be expected to reduce the dielectric strength in the entire insulation structure sufficiently to rule out this concept. Some preliminary investigations have been conducted along these lines, but are beyond the scope of the present project.

The silicone oil used to impregnate the prototypes and final cables in this project requires the addition of 3 to 5% dodecylbenzene to provide an oil which absorbs small quantities of gas during ionization. The silicone oil with this additive appears to be satisfactory for 500 kV ac cables and can be processed and handled in the factory utilizing conventional equipment now used with polybutene and mineral oils.

The full-reel ionization factor of the final cables could not be measured at voltages as high as now specified by AEIC for pipe-type cables. This was due to the drainage of the low viscosity impregnant. As previously mentioned, proper designs of the insulation shield/moisture seal assembly can partially, and may completely, remedy this situation. Further studies are required to determine the solution to this drainage problem. Another possible solution to this problem could be to pressure-cycle the pipe oil over a period of time after the cable is installed in the final pipe to replace the impregnant which has drained.

6.2 APPLICATION OF SYNTHETIC CABLES DEVELOPED IN THIS PROJECT

The pipe-type cables developed in this project appear to be satisfactory for self-cooled and forced-cooled rated 500 kV ac. Further studies are required to establish their suitability above 500 kV. Their application at 500 kV has advantages over cellulosic insulated cables because less compensating reactance is required and the dielectric loss is less. Another advantage of the synthetic insulated cables at this voltage is that less cooling would be required in forced cooled applications. However, the synthetic insulated cables developed in this project are more expensive than conventional cellulosic insulated cables as pointed out in Section 5. Consequently, the savings in compensating reactance and savings due to less dielectric loss must be balanced against the extra cost of the synthetic cables for each specific transmission line.

The insulation structure of the synthetic cables developed in this project is suitable for self-contained oil-filled cable systems operating at reasonably high pressure for the same voltages as pipe-type cables. When so used, the impregnating oil drainage problem is eliminated because self-contained cables are impregnated under a metallic sheath and positive oil pressure is maintained during installation. No additional studies are required concerning drainage as indicated for pipe-type cables. In addition, the low viscosity silicone oil is satisfactory for most transmission circuit lengths. Should a lower viscosity silicone oil become desirable because of transmission line length, only minimum verification tests are considered necessary to verify the slightly lower viscosity oil.

6.3 CONCLUSIONS

6.3.1 Insulation tape made of polypropylene fibers manufactured by the 3M Company was found unsuitable for use in EHV power cables because:

- lack of dimensional stability in impregnating oil
- lack of uniformity in the fiber distribution
- low taping tensions are required to avoid wrinkling of tapes when cable is handled which leads to excessive softness in the insulation structure

6.3.2 Insulation tape made of a cellulosic paper-polypropylene film-cellulosic paper composite (PPP) made by Tudor Pulp & Paper Company was found suitable for use in EHV power cables.

6.3.3 Silicone oil is the only impregnant found compatible with PPP tape. Polybutene, naphthenic and paraffinic mineral oils cause excessive swelling of the polypropylene component of the tape.

6.3.4 Full-size 500 kV pipe-type cable manufactured with PPP tapes in commercial factory equipment are considered satisfactory based on extensive short-time electrical tests and cyclic aging tests. The dielectric loss of the cable is 20% of conventional cable made with cellulosic paper insulation.

6.3.5 Cable made with PPP tapes must be designed to prevent oil-starvation during cooling. This can be accomplished by:

- selection of tape widths and thicknesses throughout the insulation structure to reduce the impedance to radial oil flow
- using low viscosity impregnant rather than the high viscosity impregnant used in pipe-type cables having cellulose paper tape insulation
- operating the cable at an oil pressure 1.5 times that now used on pipe-type cables

6.3.6 The higher costs of PPP tapes compared to cellulosic paper tapes and of the silicone impregnant and pipe-filling oils compared to mineral or polybutene oils combine to increase the estimated installed cost by 10% over conventional cable. However, the cost of compensating reactance for conventional cable is higher because of a 25% higher capacitance. During operation, the lower losses of a PPP cable will result in lower operating costs than a conventional cellulosic paper cable.

6.3.7 Ionization may occur in the insulation wall of a PPP pipe-type cable at low temperature, approximately 4°C or less, after installation because of drainage of the impregnant. It was demonstrated that heat cycling will correct the problem. Ionization at low temperature may warrant additional investigations not only on cables insulated with PPP tapes, but also on conventional cables insulated with cellulosic tapes.

Section 7

APPENDICES

7.1 APPENDIX 1 - STUDIES ON OTHER MISCELLANEOUS INSULATION TAPES

7.1.1 Insulations Other Than 3M Polypropylene and Tudor PPP Tapes

At the beginning of this project. when investigations were being conducted on insulating materials, two materials in addition to 3M polypropylene paper and the Tudor Pulp & Paper Company PPP laminate were evaluated. One material was a polypropylene paper made by the Riegel Paper Company and the other was Tenax supplied by AKZO Laboratories, Arnheim, Holland. Tenax is the AKZO trade name for poly-2, 6-diphenyl-para-phenylene oxide film.

Riegel Polypropylene Paper. The sample lots of polypropylene paper provided by Riegel were actually from a pilot plant operated by Exxon. Riegel had a license from Exxon to use the Exxon "melt-blown" process and was in the process of setting up their own equipment at the beginning of this project. However, there was no advantage of the polypropylene paper provided by Riegel compared to the polypropylene paper made by the 3M Company and it was decided to evaluate the 3M material completely rather than wait for Riegel to have their own manufacturing facility.

In Table 7-1 are the results of physical and electrical tests performed on sheets of Riegel polypropylene tape. In spite of very high air resistance (3,800-11,000 Gurley seconds), the dielectric strength ranged from 526 (Volts/mil(20.7 kV/mm) to 1667 Volts/mil (85.6 kV/mm) and in this respect was comparable to 3M tape.

A six tape cable model was made with Riegel polypropylene tape and impregnated with Sun XX oil at 110°C. The longitudinal crease which resulted in the insulation of the model confirmed that the Riegel polypropylene tape was no more compatible with normal impregnants than the 3M tape.

7.1.2 Tenax Tape

The Tenax material is very expensive; approximately \$11.00/lb (\$24.2/kg), but nevertheless has some promising properties:

- it is chemically inert
- it has high air resistance that could be controlled during manufacture
- it has reasonable dielectric properties of S.I.C. (2.4), 100 tan δ (0.05 at 80°C) and dielectric strength (1,000 Volts/mil) (39.4 kV/mm)

Unfortunately, before evaluation of this material could be completed, it was withdrawn from the market due to a lack of demand in the chemical industry which was the principal area of application.

In Table 7-2 are the results of physical and electrical tests performed on sheets of Tenax. At temperatures greater than 80°C, the 100 tan δ increased greatly. The stiffness of Tenax tape is about the same as for 3M paper tape of the same thickness, but the friction angle of 25 to 29 degrees for the Tenax tape is considerably greater than a value of about 11 to 18 degrees for 3M tape.

Bending tests were performed on two cable models made with 5 mil (0.127 mm) Tenax tapes. For a D/d ratio of 30, anticipated in factory production for the final cable in this project, low taping tensions, close to the 500 gm minimum, must be used in order to avoid buckling of the Tenax tapes. These results are about the same as obtained on the 5 mils (0.127 mm) 3M tapes and poorer than the results obtained using the 6 mils (0.152 mm) embossed PPP tapes. The high coefficient of friction, undoubtedly, influenced these results.

Table 7-1

TYPICAL PHYSICAL AND ELECTRICAL PROPERTIES
RIEGEL POLYPROPYLENE PAPER

AS RECEIVED (DRY)		
Thickness, mils (mm)		4.2(.107)-4.9(.124)
Air Resistance, Gurley Sec., range		3810-10990
Apparent Density, gm/cm^3, range		0.74-0.75
Stiffness, mg, Gurley		
MD		72
CMD		69
Friction Angle, degrees		
MD		22.6
CMD		(a)
AFTER IMPREGNATION	COSDEN 015SH, POLYBUTENE	MOHAWK 3.5, PARAFFINIC
Tensile Strength, lb/inch width (kg/cm)		
MD	16.6 (2.97)	24.6 (4.40)
CMD	9.9 (1.77)	15.8 (2.83)
Elongation at Break, %		
MD	2.1	2.1
CMD	2.2	2.1
Tearing Strength, gm		
MD	84	45
CMD	97	62
Folding Endurance, double folds		
MD	1000+	1000+
CMD	1000+	1000+
100 Tan δ at 50 V/mil (1.97 kV/mm) and 60 Hz		
25°C	0.02	0.02
80°C	0.04	0.05
100°C	0.07	0.08
Dielectric Constant at 50 V/mil (1.97 kV/mm) and 60 Hz		
25°C	2.0	1.9
80°C	2.1	2.0
100°C	2.1	2.2
Dielectric Strength, at 25°C and 60 Hz, V/mil (kV/mm)	526(20.7)-1667(65.6)	697(27.4)-1563(61.5)

Notes: (a) Insufficient material.
(b) See Appendix 3 for references to applicable ASTM test methods for individual tests.

7.2 APPENDIX 2 - REHABILITATION OF WALTZ MILL 500 KV TERMINALS

Reconditioning at G&W Electric Specialty Company

Two 500 kV terminals previously used during the evaluation of 500 kV cellulose paper insulated cables at the Waltz Mill Test Site were reconditioned by G&W Electric Specialty Company, the manufacturer, for use in testing the final cables developed during this project at Waltz Mill.

As a part of this reconditioning, G&W performed a long-term cyclic heating test with voltage stress on terminal capacitor elements immersed in DC200-50 silicone oil. The elements were originally impregnated with Sun XX (normally used by G&W to impregnate the capacitors) and a polybutene oil (of the type normally used by G&W to impregnate the support rolls). During 190 daily temperature cycles up to 60^{o}C conducted at stresses up to 2.2 x rated voltage, there was no adverse effect on either power factor or voltage withstand capability. Examination after test revealed a wax-like formation in the capacitors impregnated with polybutene along the foil edge where the electrical stress is greatest. This formation, which is derived from the silicone oil, is not considered significant.

A compatibility test between pothead components and silicone oil revealed that varnished dacron glass used in the semi-stop became brittle. Creped cellulose paper was substituted.

Table 7-2

PHYSICAL AND ELECTRICAL PROPERTIES OF TENAX TAPE

AS RECEIVED (DRY)		
Thickness, mils (mm)		4.8(.122)-5.2(.132)
Air Resistance, Gurley Sec., range		2703-3765
Apparent Density, gm/cm^3		0.80
Stiffness, mg, Gurley		
	MD	89.5
	CMD	70.1
Friction Angle, degrees		
	MD Smooth on Rough Surface	29
	Smooth on Smooth Surface	28
	Rough on Rough Surface	28
	CMD Smooth on Rough Surface	25
	Smooth on Smooth Surface	25
	Rough on Rough Surface	25
AFTER IMPREGNATION IN AMERICAN 15H POLYBUTENE		
Tensile Strength, lb/inch width (kg/cm)		
	MD	26 (4.65)
	CMD	13.6 (2.43)
Elongation at Break, %		
	MD	3.5
	CMD	1.3
Tearing Strength, gm		
	MD	72
	CMD	101
Folding Endurance, double folds		
	MD	2000+
	CMD	2000+
100 Tan δ at 50 V/mil (1.97 kV/mm) and 60 Hz		
	$25^\circ C$	0.01
	$80^\circ C$	0.05
	$100^\circ C$	0.12
Dielectric Constant at 50 V/mil (1.97 kV/mm) and 60 Hz		
	$25^\circ C$	2.4
	$80^\circ C$	2.4
	$100^\circ C$	2.4
Dielectric Strength, at $25^\circ C$ and 60 Hz, V/mil (kVmm)		942(37.0)-1209(47.6)

Note: See Appendix 3 for references to applicable ASTM test methods for individual tests.

7.3 APPENDIX 3 - ASTM TEST PROCEDURES

In Table 7-3 are listed the ASTM procedures used in tests on specimens of insulating tapes and reported in Section 2 and Appendix 1 of this report. (Gurley stiffness, which is included in the data of Section 2 and Appendix 1, is not an ASTM procedure).

Table 7-3

ASTM PROCEDURES
FOR TESTS ON INSULATING TAPES

TEST NO.	ASTM NO.	TEST
1	D374	Thickness
2	D726-B	Air Resistance (Gurley)
3	D202	Apparent Density (Wet-Wet)
4	D202	Friction Angle
5	D828	Tensile
6	D828	Elongation
7	D689	Tear
8	D2176	Folding Endurance (M.I.T.)
9	D2413	Dissipation Factor (Tan δ)
10	D2413	Dielectric Constant
11	D149	Dielectric Strength

7.4 APPENDIX 4 - WEIBULL DISTRIBUTIONS OF 60 Hz DIELECTRIC STRENGTH TESTS ON OIL SAMPLES

In this appendix are given the Weibull distributions of 60 Hz dielectric strength data for various oils at 25°C and 100°C. The 99% probability value derived from each of these Weibull distributiions is the datum reported in Table 2-24 and Table 2-25 for 60 Hz dielectric strength at 25°C and 100°C, respectively. The tests were conducted at 0 psi (0 kg/cm^2) using 0.5 inch (13 mm) diameter steel spheres with 10 mil (0.254 mm) spacing. Each test was begun at 200 V/mil (7.87 kV/mm) and raised in steps of 12.5 V/mil (0.49 kV/mm)each 30 seconds.

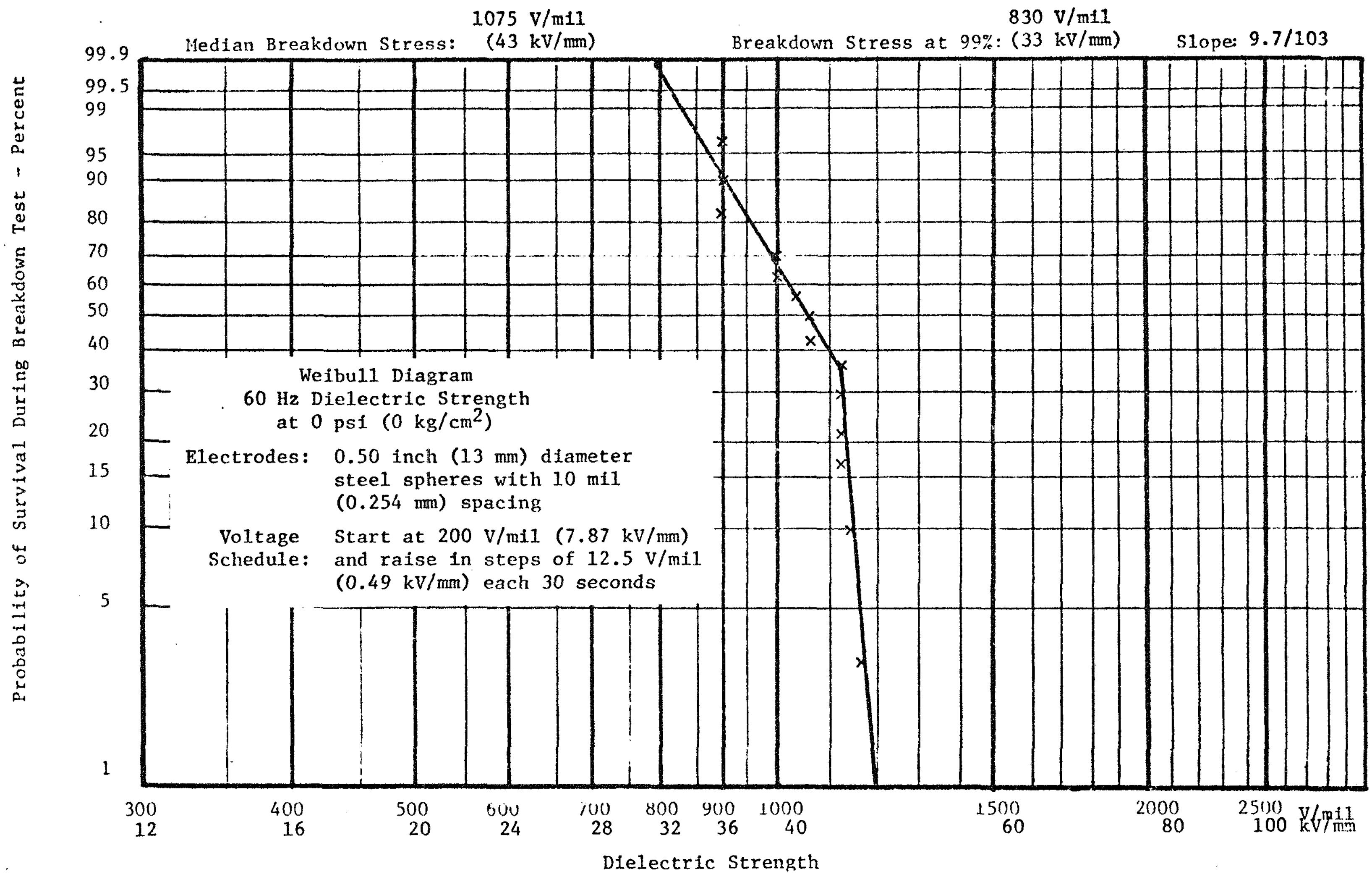


Figure 7-1. Weibull Probability vs. Dielectric Strength for Cosden 015 EG, As-Received, at 25°C

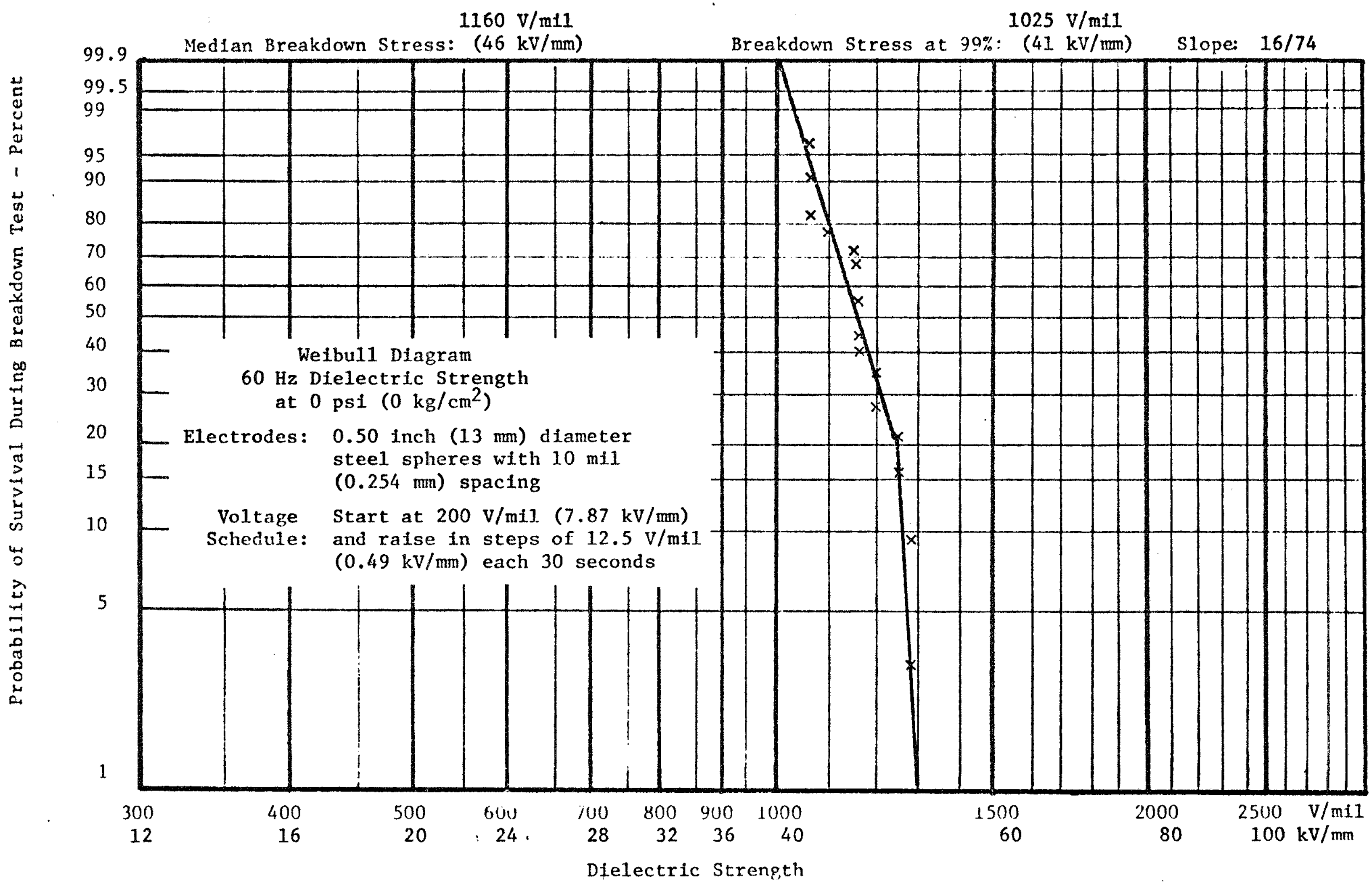


Figure 7-2. Weibull Probability vs. Dielectric Strength for Cosden 015 EG, Degassed and Dried, at 25°C

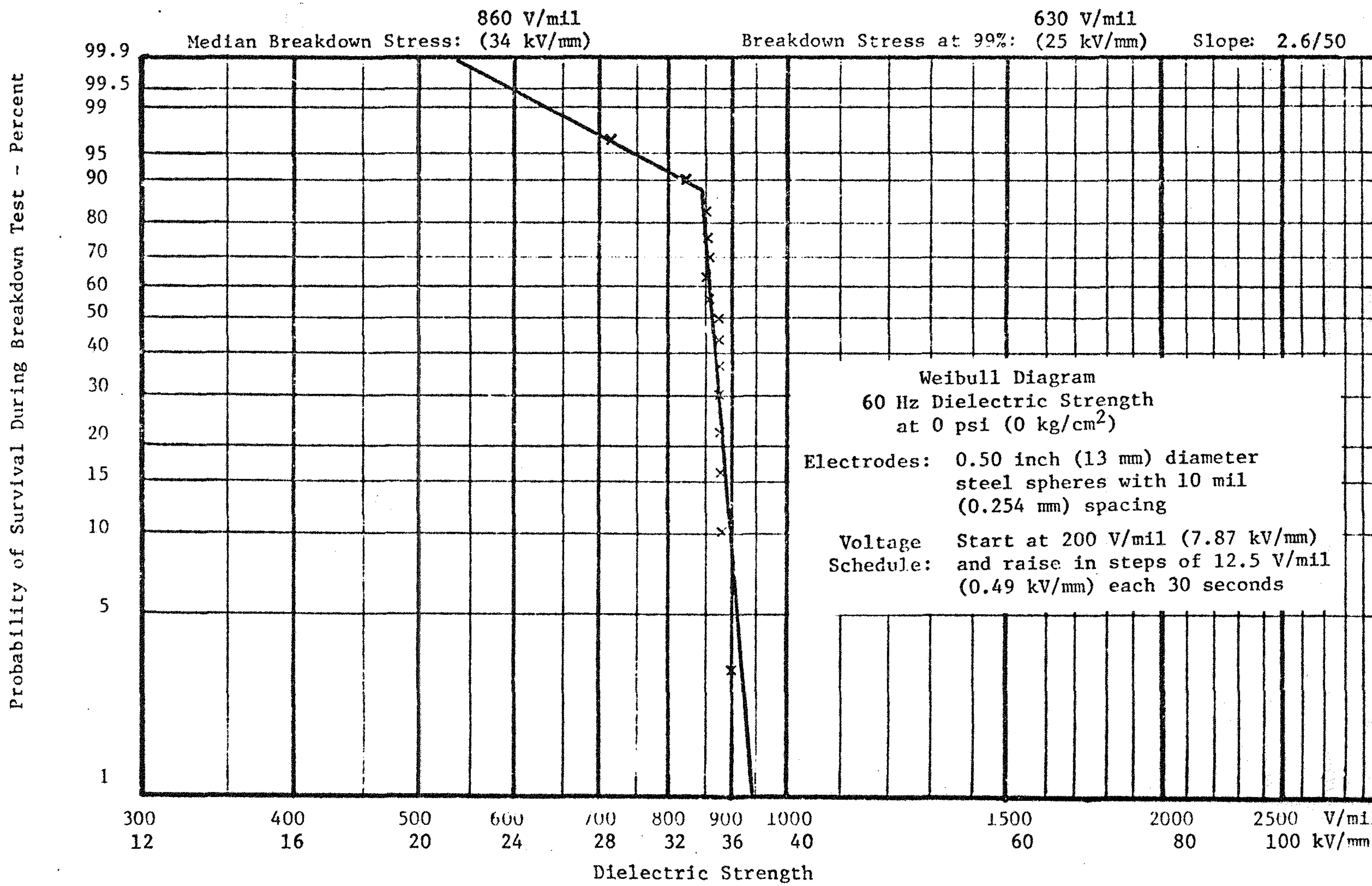


Figure 7-3. Weibull Probability vs. Dielectric Strength for Dow Corning DC200-50 Commercial Grade, As-Received, at 25°C

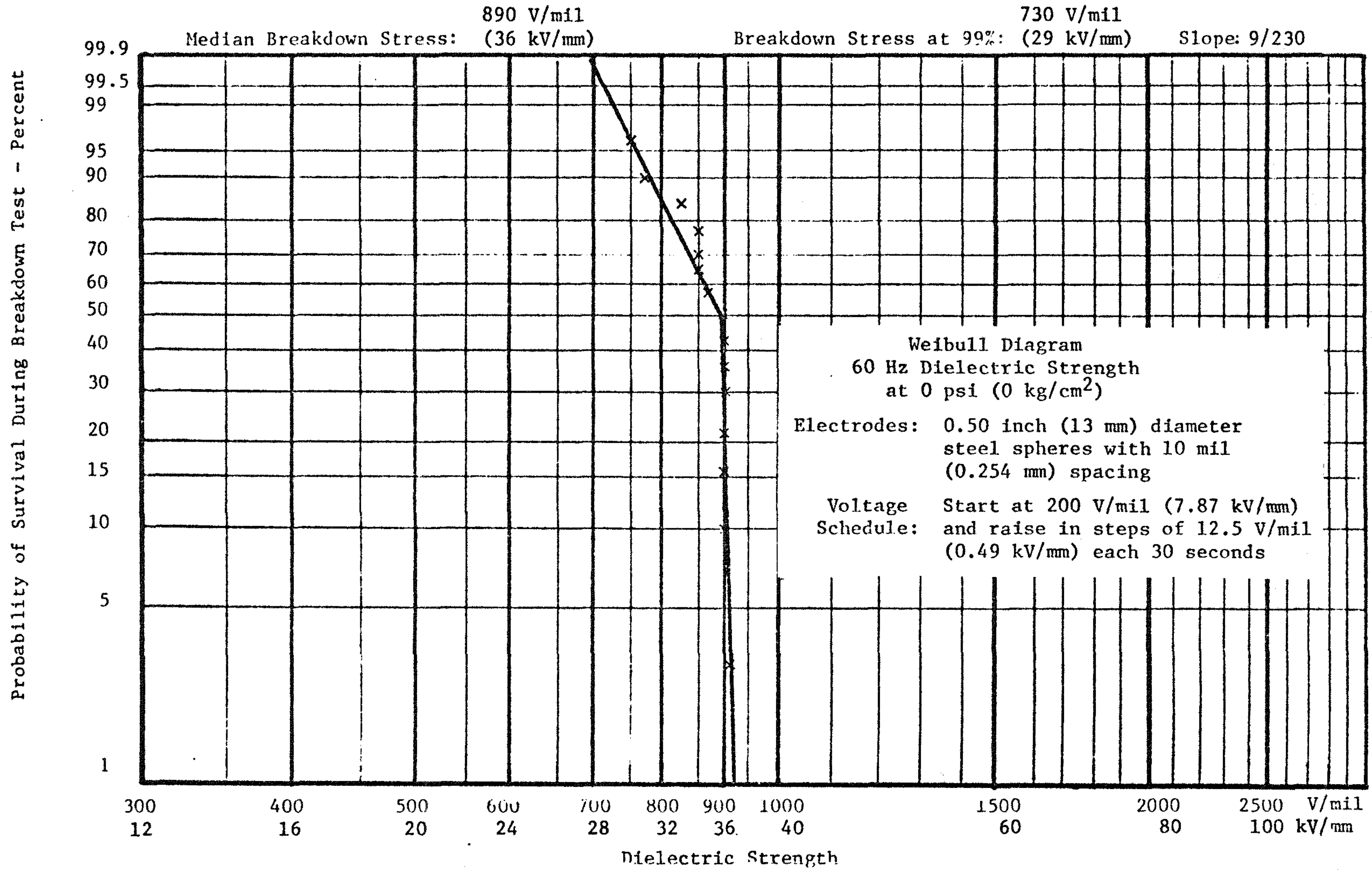


Figure 7-4. Weibull Probability vs. Dielectric Strength for Dow Corning DC200-50 Commercial Grade, Degassed and Dried, at 25°C

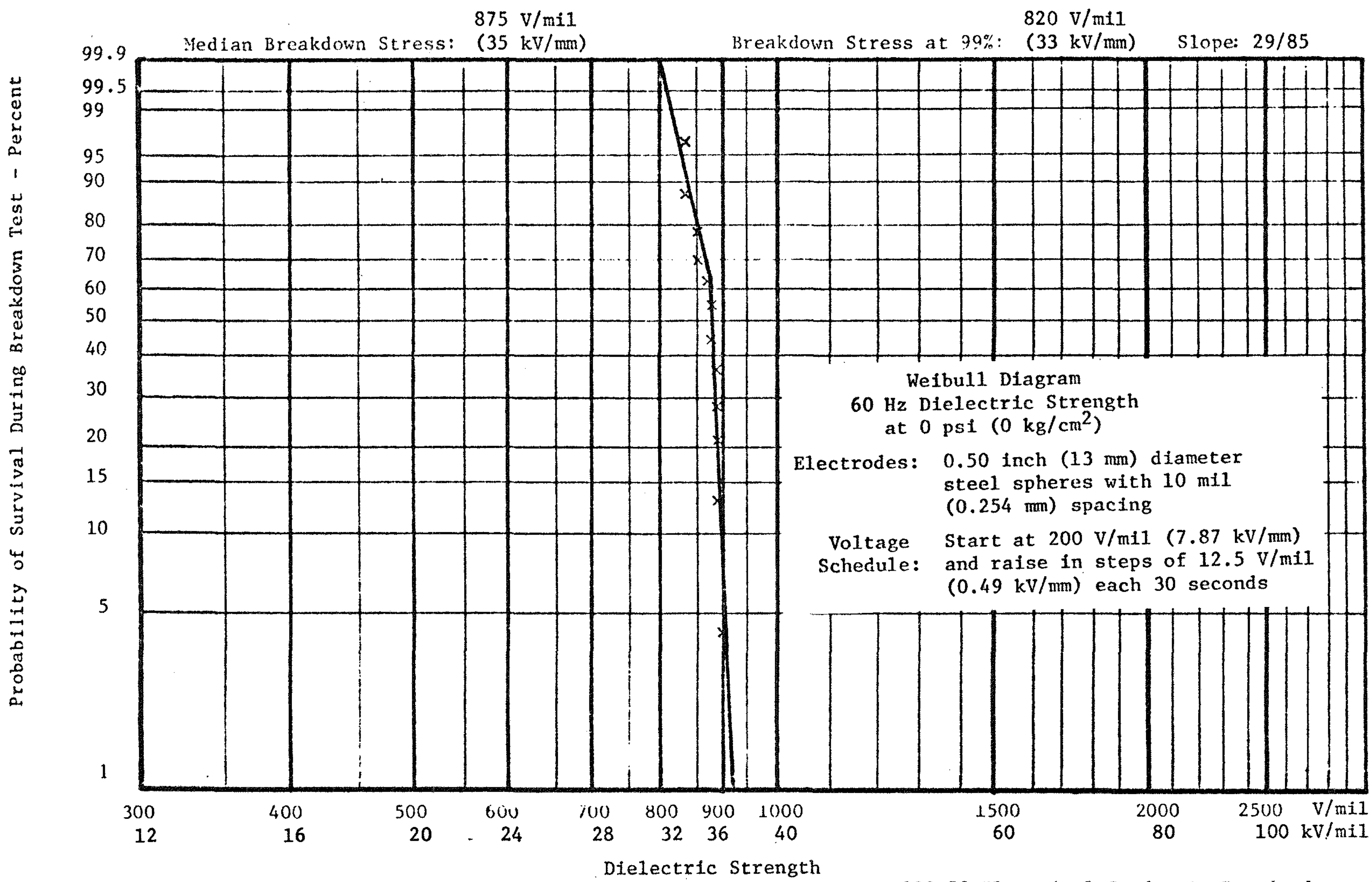


Figure 7-5. Weibull Probability vs. Dielectric Strength for Dow Corning DC200-50 Electrical Grade, As-Received, at 25°C

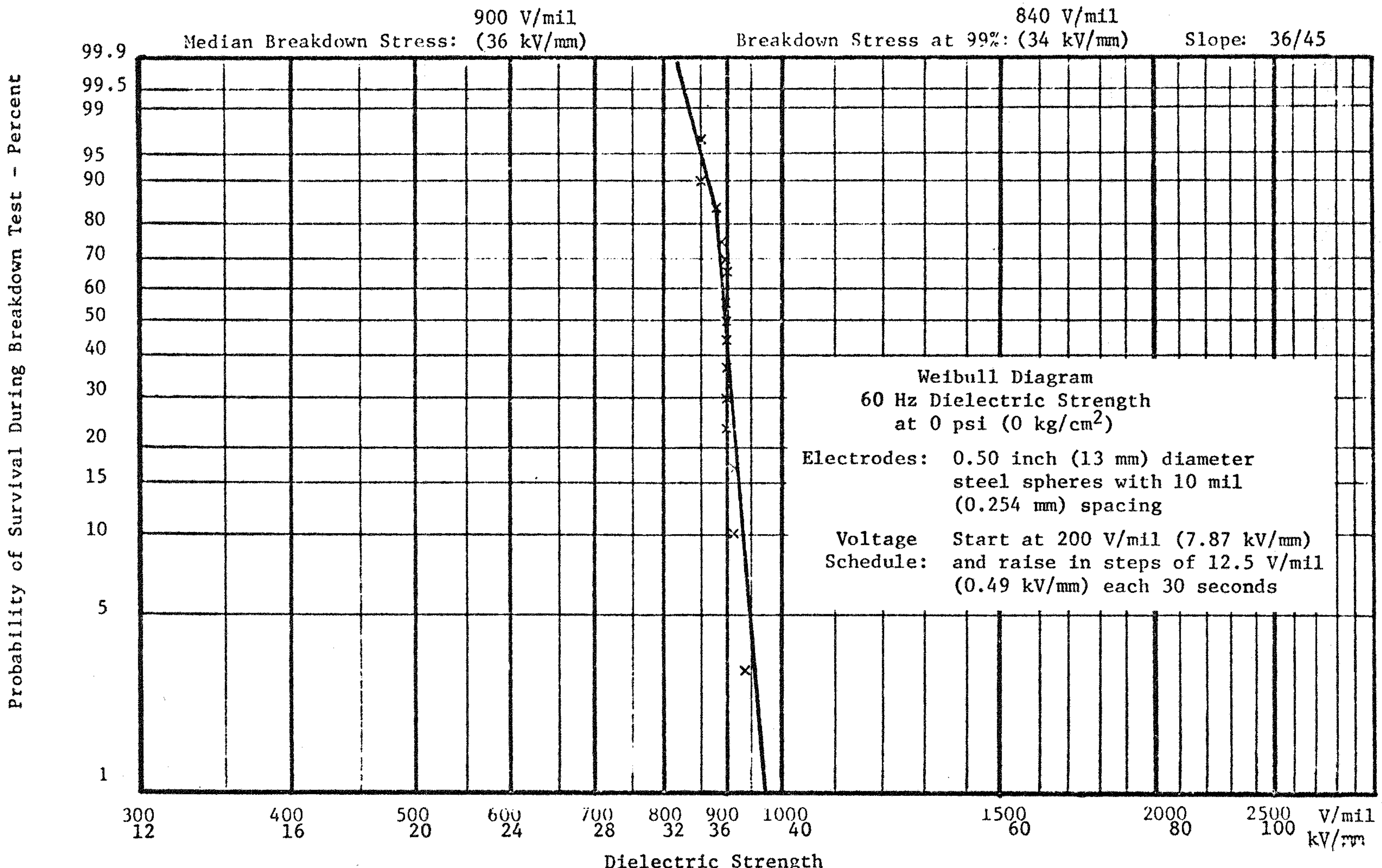


Figure 7-6. Weibull Probability vs. Dielectric Strength for Dow Corning DC200-50 Electrical Grade, Degassed and Dried, at 25°C

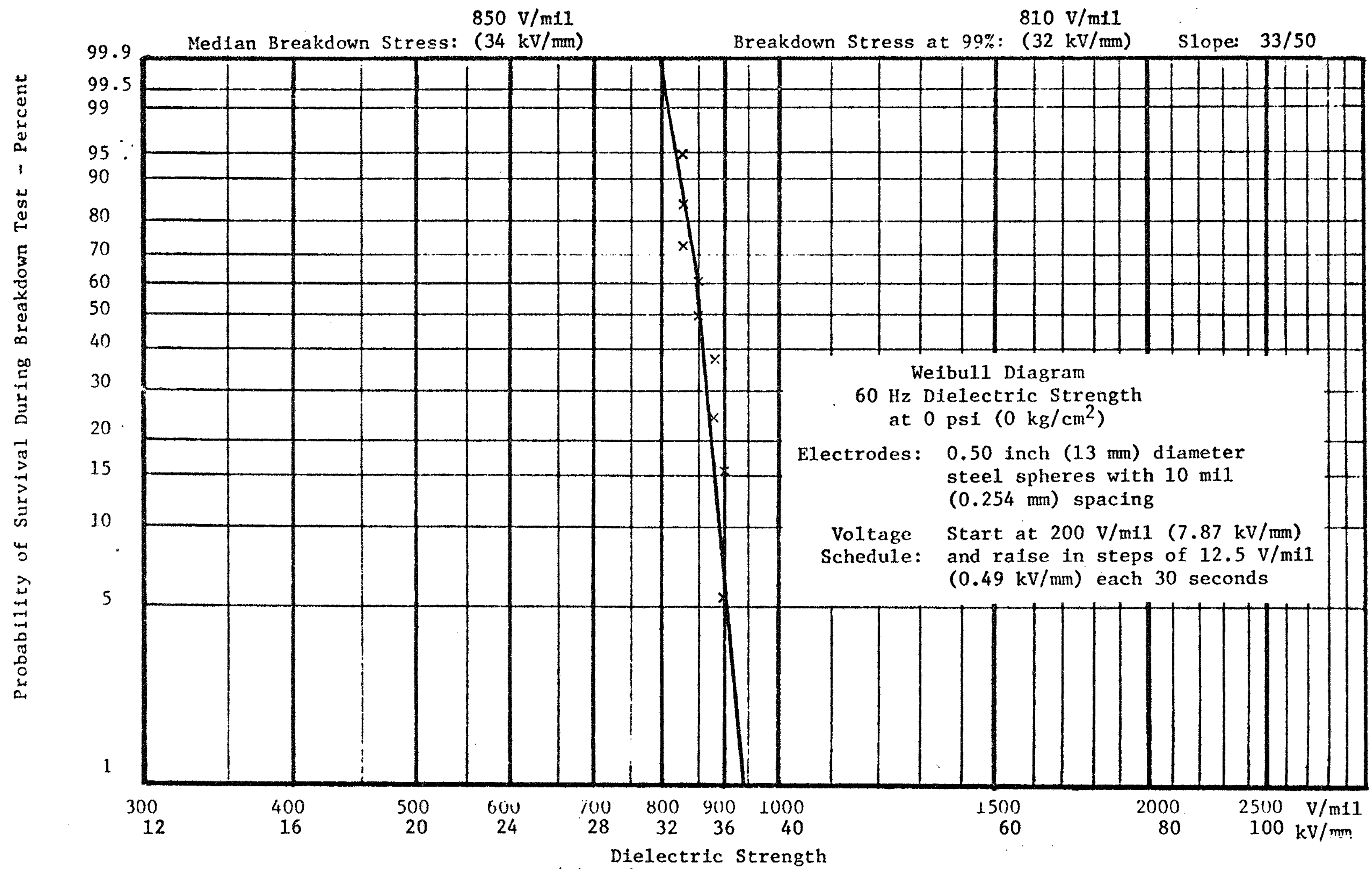


Figure 7-7. Weibull Probability vs. Dielectric Strength for Mixture of 97% Dow Corning DC200-50 Electrical Grade plus 3% Alkylate 21, Degassed and Dried, at 25°C

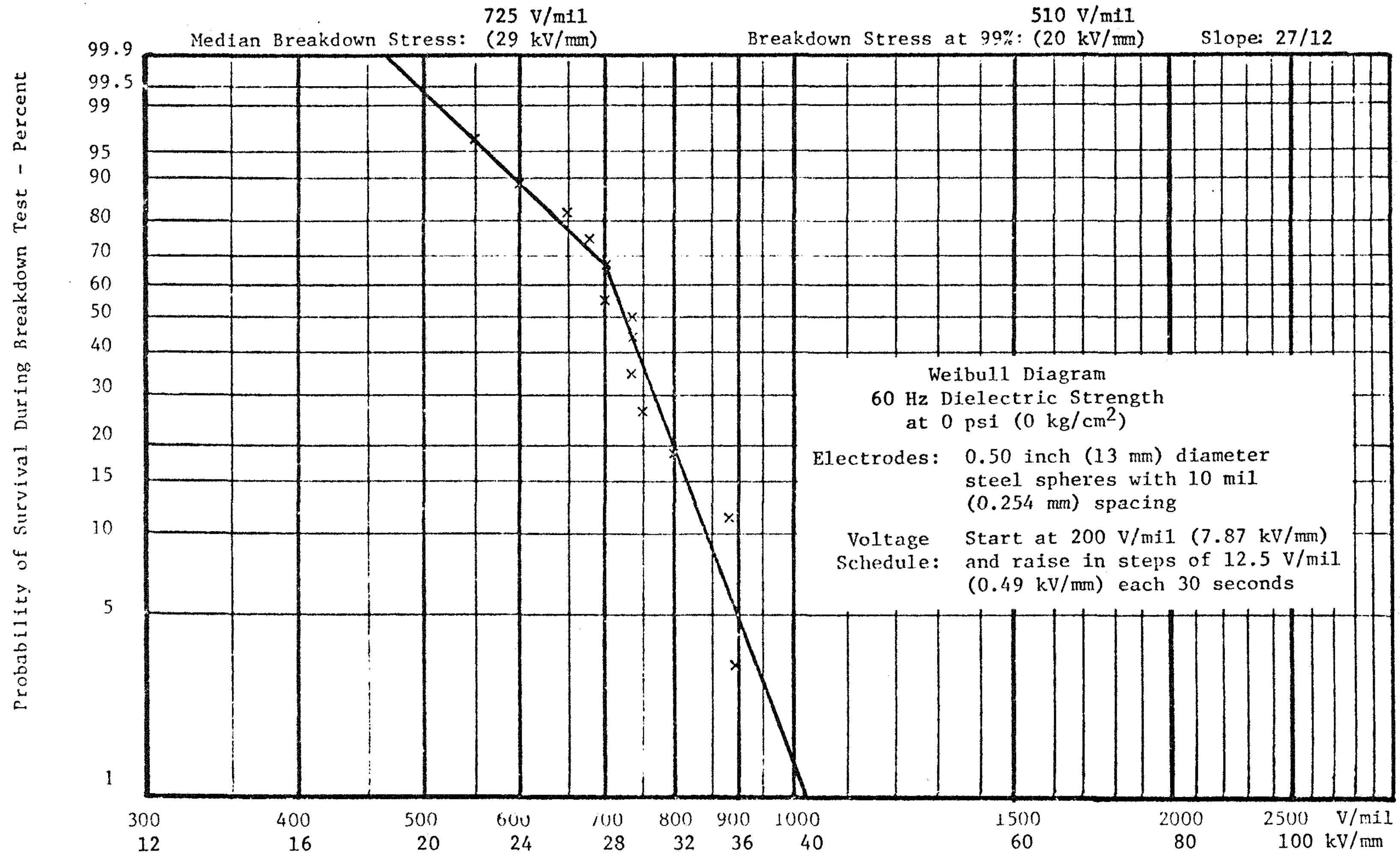


Figure 7-8. Weibull Probability vs. Dielectric Strength for Cosden 015 EG, Degassed and Dried, at 100°C

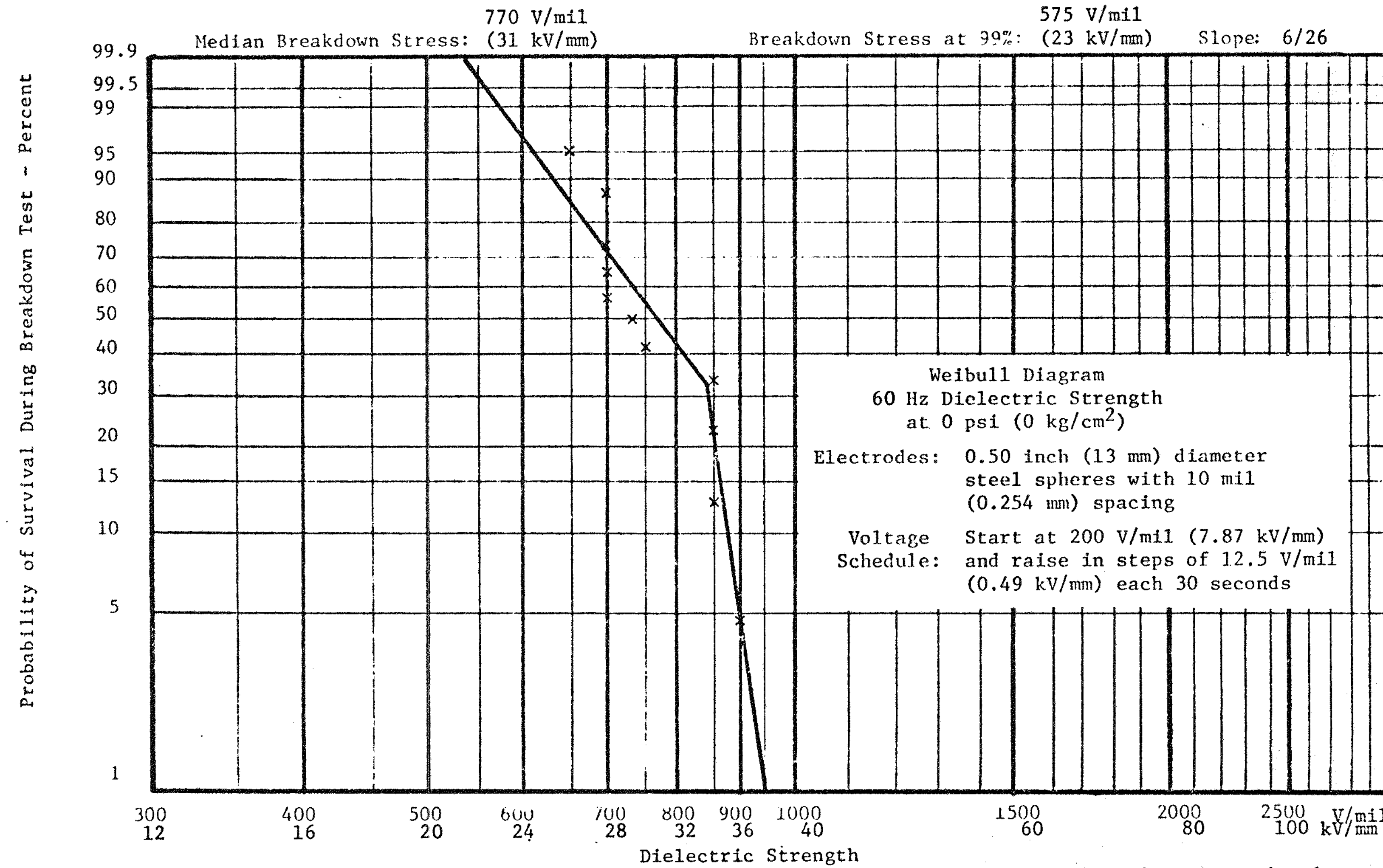
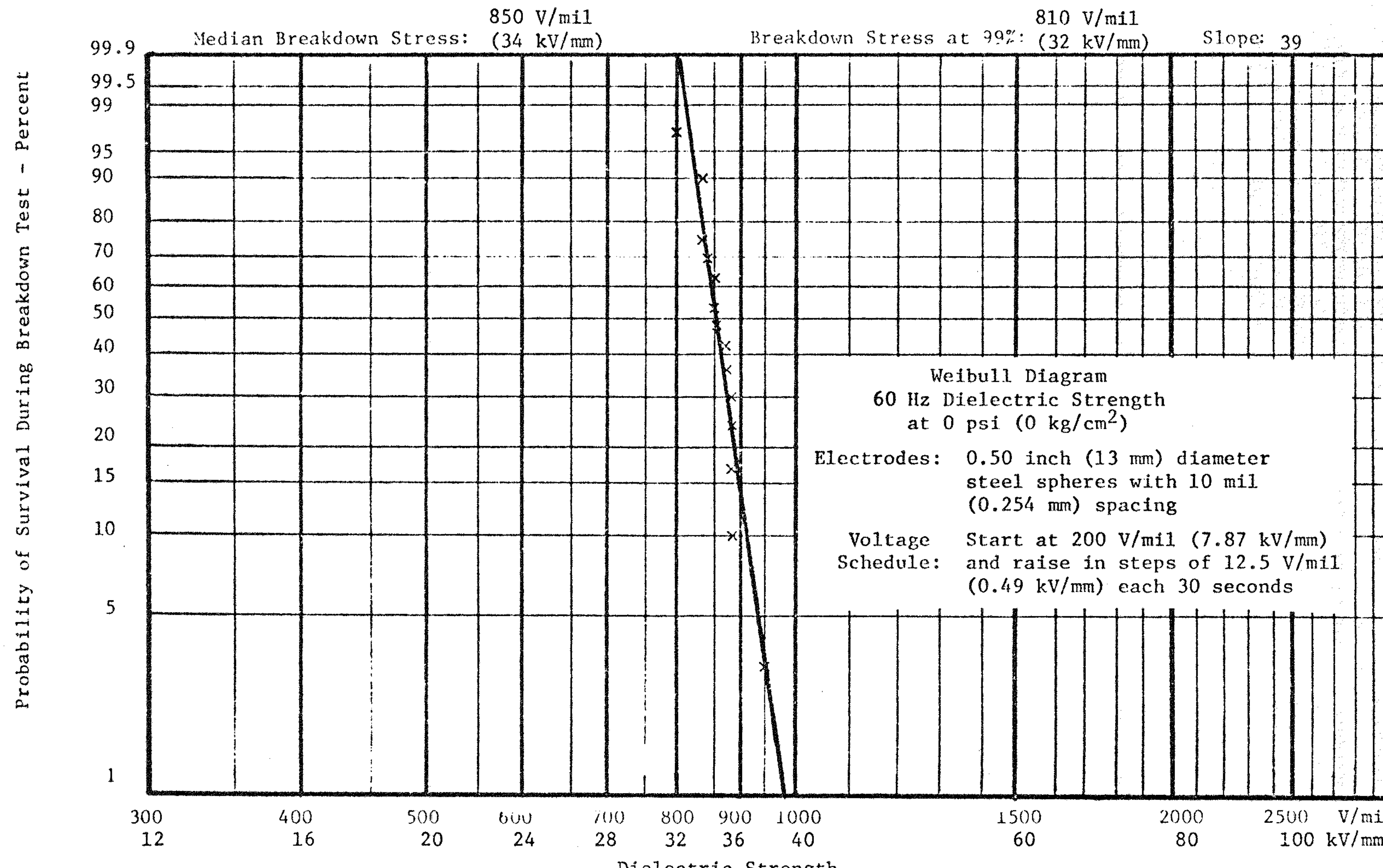


Figure 7-9. Weibull Probability vs. Dielectric Strength for Dow Corning DC200-50 Electrical Grade, Degassed and Dried, at 100°C



<u>Figure 7-10</u>. Weibull Probability vs. Dielectric Strength for Mixture of 97% Dow Corning DC200-50 Electrical Grade plus 3% Alkylate 21, Degassed and Dried, at 100°C