CABLE TECHNOLOGY LABORATORIES, INC.

DETERMINATION OF THRESHOLD AND MAXIMUM OPERATING ELECTRIC STRESSES FOR SELECTED HIGH VOLTAGE INSULATIONS

Investigation of Aged Polymeric Dielectric Cable

DOE CONTRACT DE-AC 02-80RA 50156

Final Report

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November 1995

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ABSTRACT

Based on the successful completion of the extensive research project DOE/ET/29303-1 February 1982 to develop a new method for the determination of threshold voltage in XLPE and EPR insulated cables, tests were initiated to establish the maximum safe operating voltage stresses of crosslinked polyethylene insulated cables that become wet when they operate in a moist environment. The present report covers the measurement of the threshold voltage, the a.c. breakdown voltage and the impulse breakdown voltage of XLPE cable after undergoing accelerated laboratory aging in water.

Model and 15 kV XLPE cables were manufactured in commercial equipment using state-of-the-art semiconducting shields and XLPE insulation. The threshold voltage, a.c. voltage breakdown and impulse voltage breakdown of the model cables were determined before aging, after aging one week and after aging 26 weeks. The model cable, following 26 weeks aging, was dried by passing dry gas through the conductor interstices which removed moisture from the cable. The threshold voltage, the a.c. voltage breakdown and the impulse voltage breakdown of the XLPE model cable after drying was measured.

The test results show a significant drop in threshold voltage, a.c. voltage breakdown and impulse voltage breakdown with respect to unaged cables, because of water entering the XLPE insulation during aging. In terms of a.c. voltage stress the threshold voltage fell from 1,020 to 70 V/mil for the model XLPE cable and from 630 to 42 V/mil for the 15 kV XLPE cable. There were significant decreases in the a.c. and impulse voltage breakdown values as well.

The test results show that subsequent drying after aging of the model XLPE cable raised its threshold voltage stress from 70 V/mil to 597 V/mil. Similar increases after drying also occurred in a.c. and impulse voltage breakdown values.

Distribution cable rated up to 35 kV operate at stresses of 32 to 58 V/mil, depending on the rated voltage of the cable. Therefore the results of this project indicate that 15 kV XLPE cable of the type manufactured in 1985 is not safe to operate in some wet environments because the threshold voltage will, in time, fall below the operating voltage level. When this occurs the insulation is likely to be damaged by scission of its molecular chains. Drying the cable insulation by passing dry gas through the conductor interstices, prior to reaching the breakdown level, will eliminate scission and extend cable life indefinitely. Cable life can alternately be extended by impregnating the XLPE insulation with a silicone fluid, as described elsewhere in the literature.

DETERMINATION OF THRESHOLD AND MAXIMUM OPERATING ELECTRIC STRESSES FOR SELECTED HIGH VOLTAGE INSULATIONS

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1.0 INTRODUCTION

This report presents the results of a study of the effect of moisture on the threshold voltage stress of crosslinked polyethylene (XLPE) insulated cable. The investigation, based on the concept of determining threshold voltage by dual polarity measurement technique, is the final part of a study of selected electrical insulations used in high voltage power systems (1). Study of XLPE insulated cable not exposed to moisture was the subject of Task 1 of the project (2). Oil-filled paper insulated cable was studied in Task 2, liquid filled polypropylene insulated capacitors in Task 3 and epoxy insulation in Task 4 (3, 4, 5). This final Task is concerned with XLPE insulated cable when exposed to moisture.

Task 1 assumed that neither chemical (environmental) nor mechanical deterioration of the XLPE cable insulation occurs during service life. This assumption is valid for cable made using a dry manufacturing process and fully protected from the environment during service. Most underground cable distribution systems utilize cable buried directly in the ground or installed in duct. In either case the cable is exposed to the effect of the environment. Relatively few systems utilize extruded cable protected from the entry of water, as by an extruded lead sheath. Even then, the cable joints sometimes are not covered by metallic sheath thereby allowing moisture to enter the cable.

When water enters dry insulation the micro-cracks and voids may fill with moisture and create conducting projections in the insulation. The voltage stress at the tips of these projections is enhanced. The higher stresses existing under these conditions cause local discharges or ionization at local areas. The electric charge generated is very small and cannot be detected by available partial discharge detectors. The voltage stress at which discharges are initiated has been designated as the threshold voltage stress. The energy however may be sufficient to cause scission of the molecular chains of the polymeric insulation and in this way promote formation and growth of electrochemical (water) trees. The voltage stress at the tips of the water tree branches increases with an increase of tree length. When the tree becomes sufficiently long, the stress at the tip of the branches reaches values high enough for intense discharges which lead to electrical trees and sometimes breakdown of the insulation. In most cases the threshold voltage stress is higher than the operating voltage, especially when the insulation is dry.

The purpose of the work of this final Task is to determine the effect of moisture permeating into the insulation during cable aging in wet environment and its effect on cable threshold voltage, a.c. voltage breakdown and impulse voltage breakdown. The work was performed as described in Amendment No. 7 to DOE Contract DE-AC02-80RA 50156.

2.0 DESCRIPTION OF TEST CABLES

The bulk of the tests were performed on model cable having a No. 2 AWG (7/w) concentric stranded copper conductor, 0.024 inch extruded semiconducting crosslinked polyethylene conductor shield, 0.050 inch HFDB 4201 extruded crosslinked polyethylene (XLPE) insulation, and 0.030 inch extruded semiconducting insulation shield. The materials for the insulation and shields were made by Union Carbide Corp. Three No. 22 AWG bare copper wires were applied helically over the insulation shield and polyester tape protection applied overall. The cable was made by Hendrix Wire & Cable Corp. The insulation and shields were cured in steam. The dimensions and other details of the model cable are given in Table 1.

TABLE 1

DESCRIPTION OF TEST CABLES

Model Cable

Voltage Rating:	None
Manufacturer:	Hendrix Wire & Cable Corp.
Date of Manufacture:	1985
Conductor:	No. 2 AWG (7/w) uncoated copper
Condr. Shield:	Semiconducting XLPE, HFDA 0580 by Union Carbide, 0.024 inch thick
Insulation:	Unfilled XLPE, HFDE 4201 by Union Carbide, 0.050 inch thick, nominal
Ins. Shield:	Semiconducting XLPE, DHDA 7704 by Union Carbide, 0.037 inch thick
Metallic Shield:	3 X No. 22 AWG uncoated copper wires
Protective Covering:	One layer 0.002 inch thick polyester tape, 1/8 lap

15 kV Cable

Voltage Rating:	15,000 Volts
Manufacturer:	Hendrix Wire & Cable Corp.
Date of Manufacture:	1985
Conductor:	No. 2 AWG (7/w) uncoated copper
Condr. Shield:	Semiconducting XLPE, HFDA 0580 by Union Carbide, 0.033 inch thick
Insulation:	Unfilled XLPE, HFDE 4201 by Union Carbide, 0.0175 inch thick, nominal
Ins. Shield:	Semiconducting XLPE, DHDA 7704 by Union Carbide, 0.043 inch thick
Metallic Shield:	3 X No. 22 AWG uncoated copper wires
Protective Covering:	One layer 0.002 inch thick polyester tape, 1/8 lap

For the purpose of verifying the model cable test results on full size cable, tests were performed on cable having a No. 2 AWG (7/w) concentric stranded copper conductor, extruded semiconducting XLPE conductor shield, 0.175 inch HFDB 4201 insulation, extruded semiconducting insulation shield. The cable was made in accordance with AEIC Specification CS5-82 by Hendrix Wire & Cable Corp. As with the model cable, 3 No. 22 AWG copper wires and a polyester tape were applied overall. Also, the insulation and shields were cured in steam. The dimensional details of the full size 15 kV cable are also given in Table 1.

3.0 TEMPERATURE CONDITIONING OF TEST CABLES

Cables with extruded XLPE insulation are known to change their dielectric strength over a time shortly after their manufacture. Freshly made cable contains residues of the crosslinking reaction in the form of acetophenone and other byproducts. The presence of these by-products in the insulation usually decreases the cable breakdown voltage. Under normal conditions at least part of the by-products will diffuse out from the insulation over a relatively short time of the service life of the cable. The diffusion out of the cable of these by-products results in changes in the dielectric strength of the cable.

To minimize the change of the cable breakdown voltage strength during the period of testing, due to the slow diffusion of the by-products, a special procedure was adopted. Fresh cable, as obtained from the manufacturer, was conditioned for a period of at least five days at a temperature of 90°C. This temperature was found to be both safe and effective for the diffusion out of the insulation of the by-products of the crosslinking reaction. Tests performed in an oven demonstrated that increasing the conditioning temperature to over 100°C may lead, on occasion, to the formation of cracks in the cable insulation structure. This effect is most probably due to the rapid expansion of the gases still present in the insulation mass.

In the present case, the temperature conditioning of the cable to remove the crosslinking by-products was carried out as follows: The cable, contained on a reel, was cut into sample lengths. The cable sections were then placed inside long steel tubes, 4 inches in diameter, which were heated by passing electrical current through them. A signal from a thermocouple attached to the tube center was fed to an electronic temperature controller which activated a relay at the current transformer. The cable sections remained in the tubes for a period of 5 to 7 days at the 90°C temperature. These samples were used subsequently for different breakdown tests.

4.0 TESTING OF XLPE INSULATED CABLE BEFORE AGING

4.1 Threshold Voltage Test

During work completed previously at Cable Technology Laboratories under the sponsorship of the Department of Energy (DOE, Contract ET-78-C-01-3062) it had been postulated that each type of polymeric insulation has a threshold voltage. An insulation stressed by a voltage below its threshold value is not subjected to electrical aging because there is no discharge in the insulation which could produce electrons (or other charges) having enough energy (10 electron volt or more) for degradation of the polymer. The threshold voltage discharge which originates in microvoids present in the insulation, is of such a low magnitude that it cannot be measured by presently available partial discharge detectors.

A new method for the determination of threshold voltage of polymeric insulated cables was devised at CTL. This method overcomes the problem of insufficient sensitivity of the conventional partial discharge detectors. The method allows to establish the true value of the partial discharge inception voltage (the threshold voltage) regardless of the magnitude of the apparent charge generated in the void.

This method is based on the determination of breakdown voltages using dual polarity pulses.

A circuit diagram for determination of the threshold voltage by means of a dual pulse method is shown in Fig. 1. This circuit allows for sequential application of two pulses with independently adjustable amplitudes. During this study the first pulse consisted of a d.c. voltage and the second pulse was an opposite polarity impulse voltage. A typical voltage transient generated by the circuit of Fig. 1 is shown in Fig. 2.

The test procedure consists of measuring the impulse breakdown voltage (by the second pulse) while the sample is pre-stressed with a d.c. voltage (applied as the first pulse). The test is repeated at various levels of d.c. voltage pre-stressing. At each of these levels the impulse voltage is increased until it results in a breakdown of the sample. The impulse breakdown voltage remains constant when the amplitude of the d.c. voltage is increased from zero to a value equal to the threshold voltage. This is because during application of the impulse the d.c. voltage across the sample discharges without leaving any evidence that such a voltage was applied to the insulation before the impulse application. When the level of the d.c. voltage exceeds the threshold voltage a space charge is generated and this space

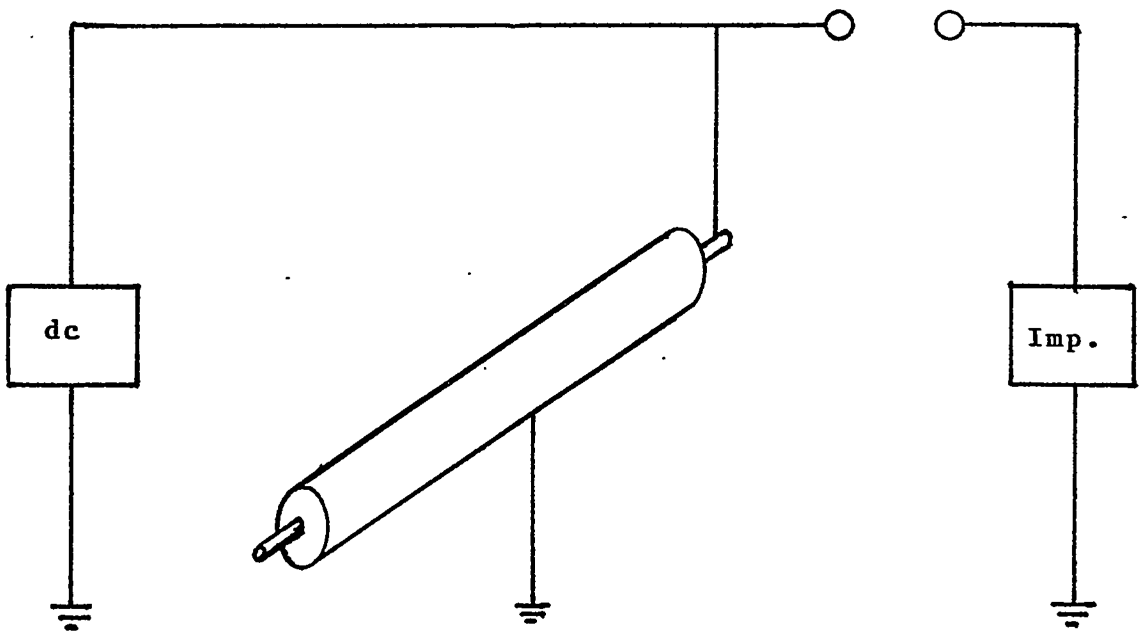


Fig. 1 - Circuit diagram used for application of dual pulse to cable sample for determination of threshold voltage.

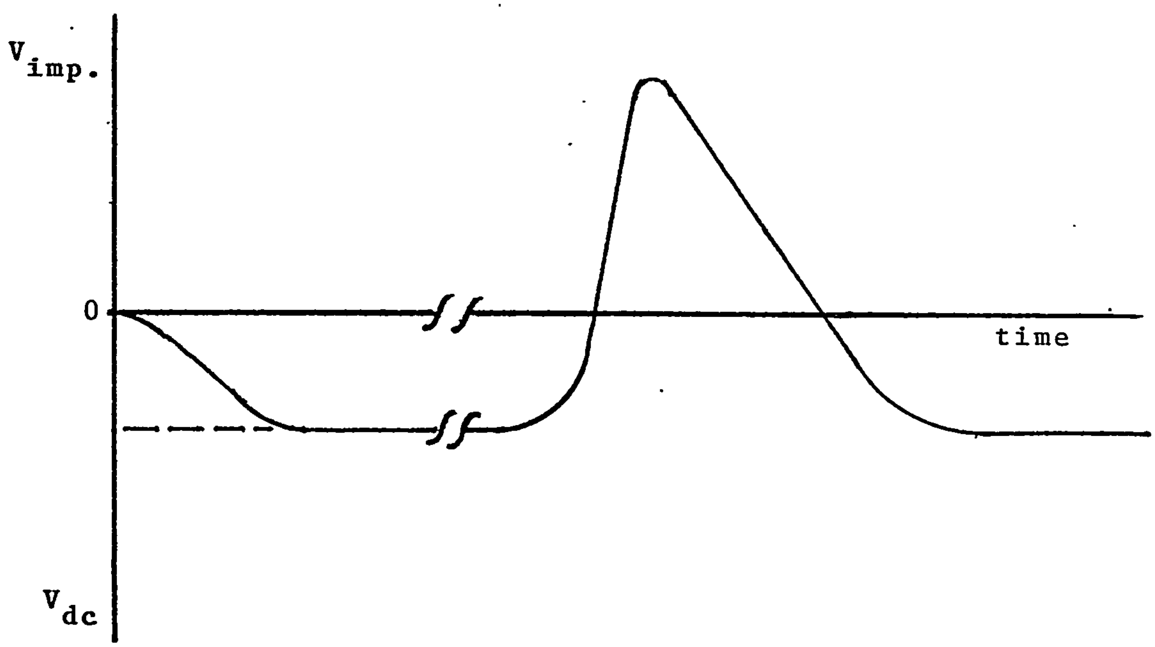


Fig. 2 - Typical voltage transient generated by the circuit of Fig. 1.

charge causes a decrease of the impulse breakdown voltage (V_{impb}). Consequently, the peak-to-peak value of the breakdown voltage (V_{dc} + V_{impb}) increases with an increase of d.c. voltage from zero to the value of the d.c. threshold voltage. Above the threshold voltage the peak-to-peak value increases at a slower rate or remains constant because the impulse breakdown voltage decreases.

In general, for homogeneous and non-homogeneous insulations, an increase in d.c. voltage above the threshold voltage causes a decrease in the impulse breakdown voltage, although the peak-to-peak value of the voltage may remain constant or may increase with an increase of d.c. voltage.

Fig. 3 indicates a typical plot of impulse breakdown voltages versus level of d.c. pre-stress voltages. In this plot,

$$V_{impb} = V_{p\text{-}p} - V_{dc} \qquad (1)$$

the discontinuity in the impulse breakdown voltage curve (location of sharp bend) indicates the so called d.c. threshold voltage V_{dcth}. This d.c. threshold voltage readily can be converted into an a.c. threshold voltage using the following relationship:

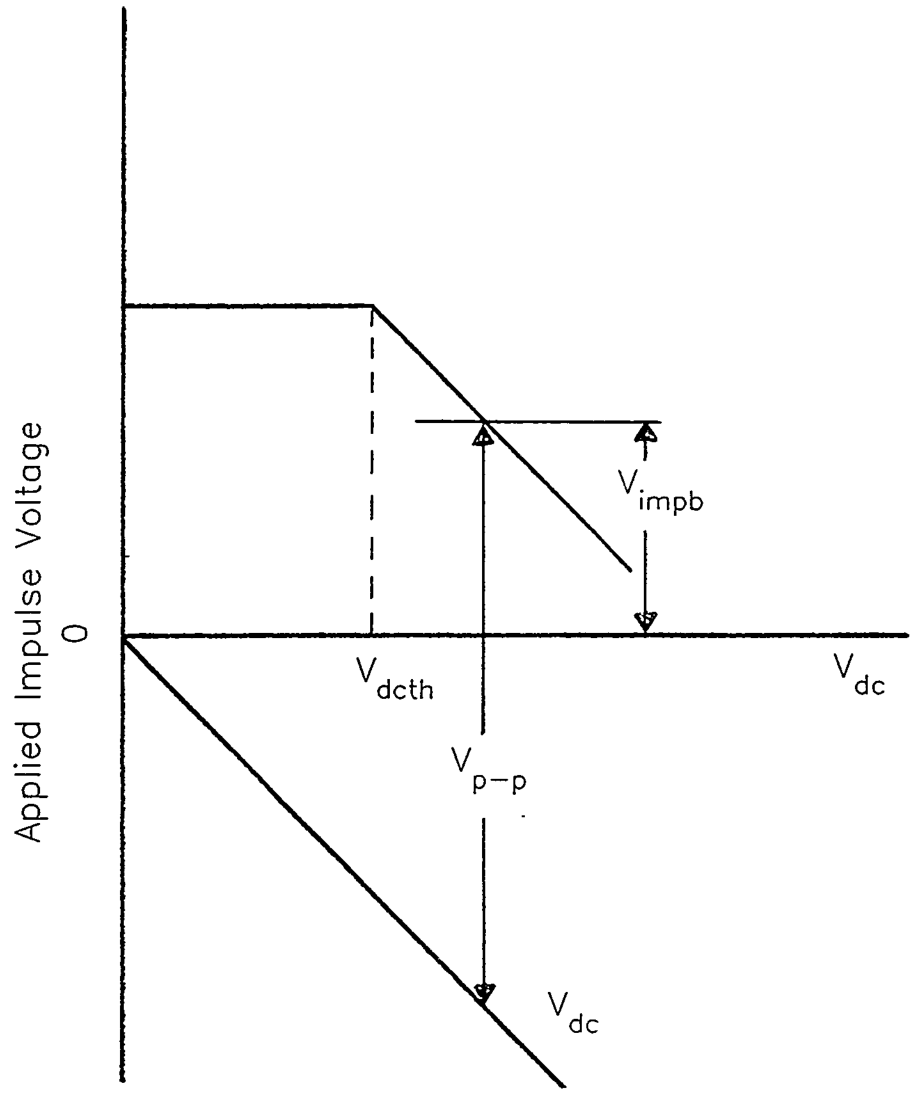


Fig. 3 — Typical plot of impulse breakdown voltage vs. applied levels of dc voltage .

V_{dcth} — dc threshold voltage

V_{impb} — impulse breakdown voltage

V_{dc} — dc prestress voltage

V_{p-p} — peak-to-peak impulse voltage applied to the sample

$$V_{acth} = \frac{V_{dcth}}{2\sqrt{2}} \qquad (2)$$

This conversion is based on the fact that it is customary to indicate the a.c. threshold voltage (similarly to the inception voltage) as an r.m.s. value. Hence, the peak-to-peak value of the d.c. voltage V_{dcth} should be divided by $2\sqrt{2}$.

Determination of the impulse breakdown voltage of polymeric insulated cables, such as XLPE and EPR, at each of various levels of d.c. voltage pre-stressing should be conducted on 5 or preferably more cable samples (for each data point) in order to take into account the scatter of the breakdown voltages. Based on these measurements the 63% probability of the impulse breakdown voltage values are determined from Weibull graphs and plotted versus d.c. voltage as illustrated in Fig. 3. Under this condition the value of the threshold voltage corresponds also to a 63% probability.

To establish the threshold voltage stress level of the cable, bipolar (or dual polarity) voltage breakdown tests were conducted. Table 2 gives the planned tests on the model and 15 kV cables.

TABLE 2

THRESHOLD VOLTAGE TESTS SCHEDULED AND LEVELS OF D.C. PRE-STRESSING

(At aging times and d.c. pre-stress voltages indicated by "X")

Cable Designation	Model				15 kV	
Aging Temperature - °C	23				23	
Electrical Aging in Water - Weeks	0	1	26	26*	0	26
D.C. Pre-stressing Voltage						
0	x	x	x	x	x	x
-10 kV			x	x		
-25 kV				x		
-30 kV			x			
-40 kV	x					x
-50 kV		x	x	x		
-60 kV	x					x
-70 kV			x			
-75 kV		x				
-80 kV						x
-100 kV	x	x		x	x	x
-140 kV	x					
-150 kV						x
-160 kV	x			x		
-200 kV	x				x	

*Followed by 13 weeks of drying

During actual tests the cable conductor was connected to a d.c. voltage source of negative polarity while an opposite polarity standard impulse (1.5/40μs) was applied to the cable insulation shield. The transient of voltage between the conductor and the insulation shield is shown in Fig. 2. Tests with different d.c. pre-stressing levels were carried out for the cable. The procedure outlined above was applied to the analysis of the data obtained with the tested cable.

4.2 Measurement of Threshold Voltage Stress on XLPE Model Cable Before Aging

The Weibull probability distributions of impulse breakdown without d.c. pre-stressing and of impulse breakdown voltage stress for different levels of d.c. pre-stressing on the model cable before aging are given in Figs. 4 to 10. The dependence of impulse breakdown stress on the d.c. pre-stressing is shown in Fig. 11 in the form of intersecting lines. The individual points on the curve are obtained by implementing equation (1). The abscissa of the intersection of the lines is equal to the d.c. threshold voltage stress. Fig. 11 indicates that the threshold voltage (V_{dcth}) of the model cable is 2900 V/mil.

Fig. 4

Unaged Model Cable
Impulse Breakdown Test Results

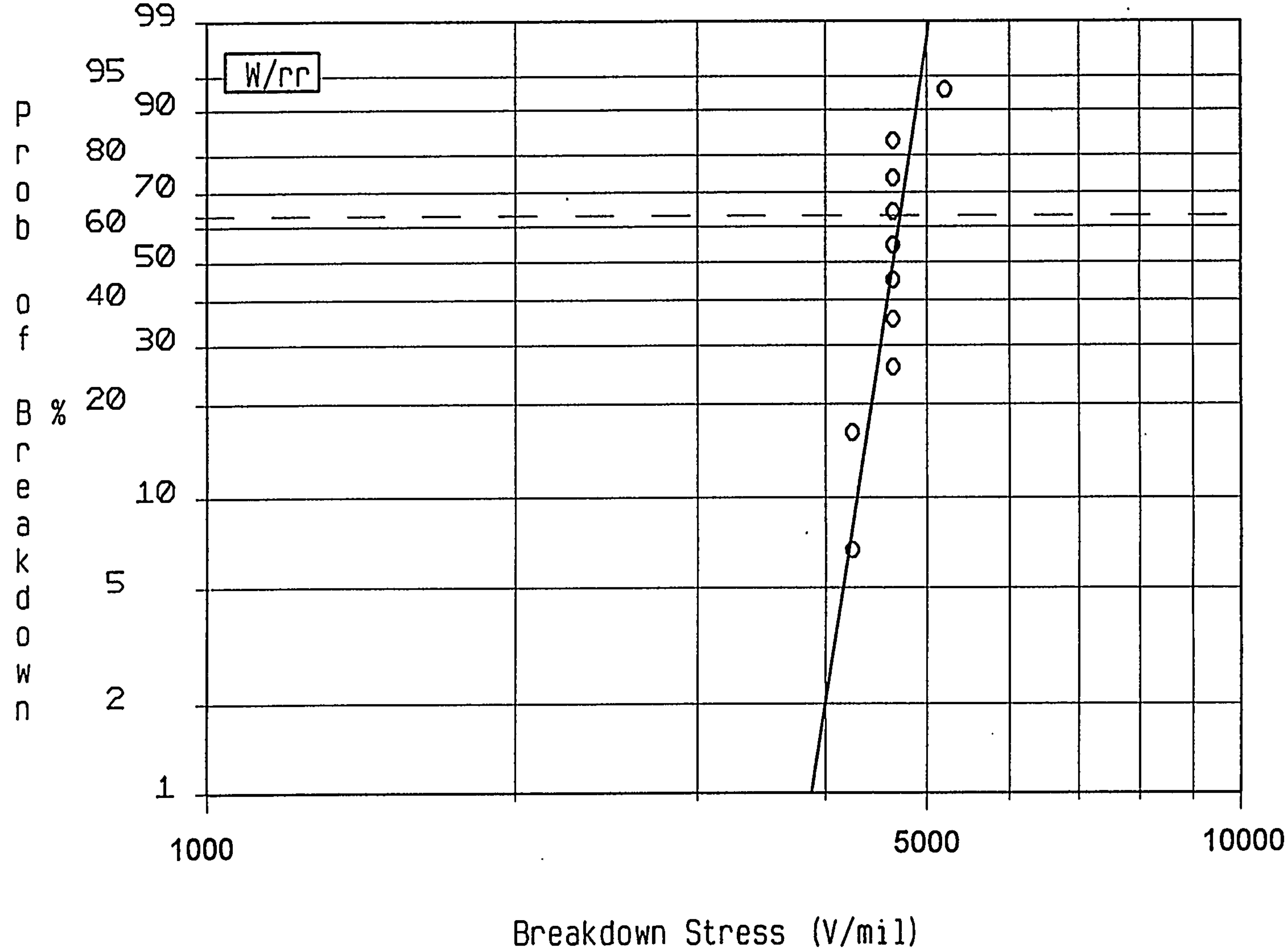


Fig. 5

Unaged Model Cable
Impulse Breakdown Test Results (-40 kV d.c.)

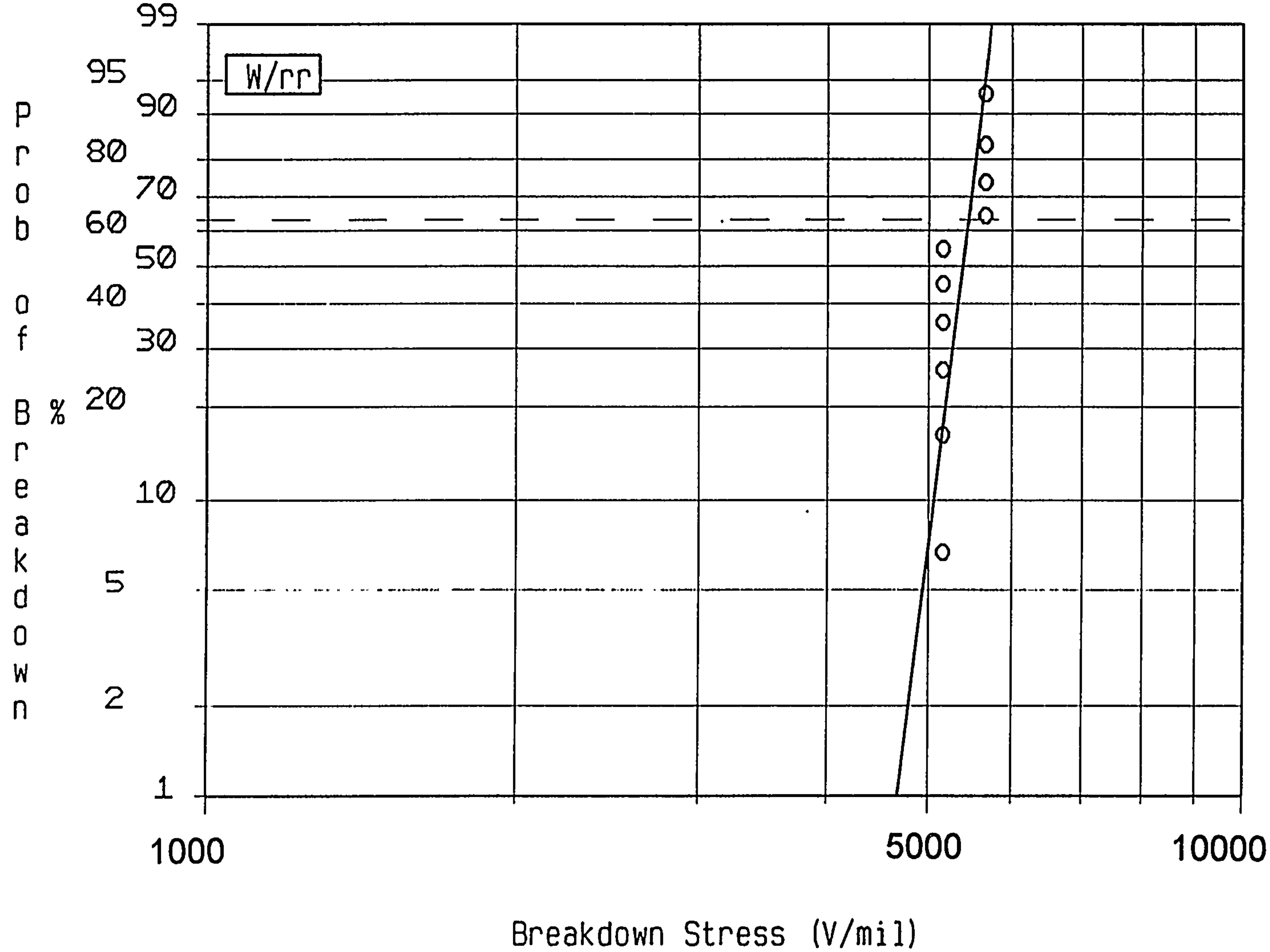


Fig. 6

Unaged Model Cable
Impulse Breakdown Test Results (-60 kV d.c.)

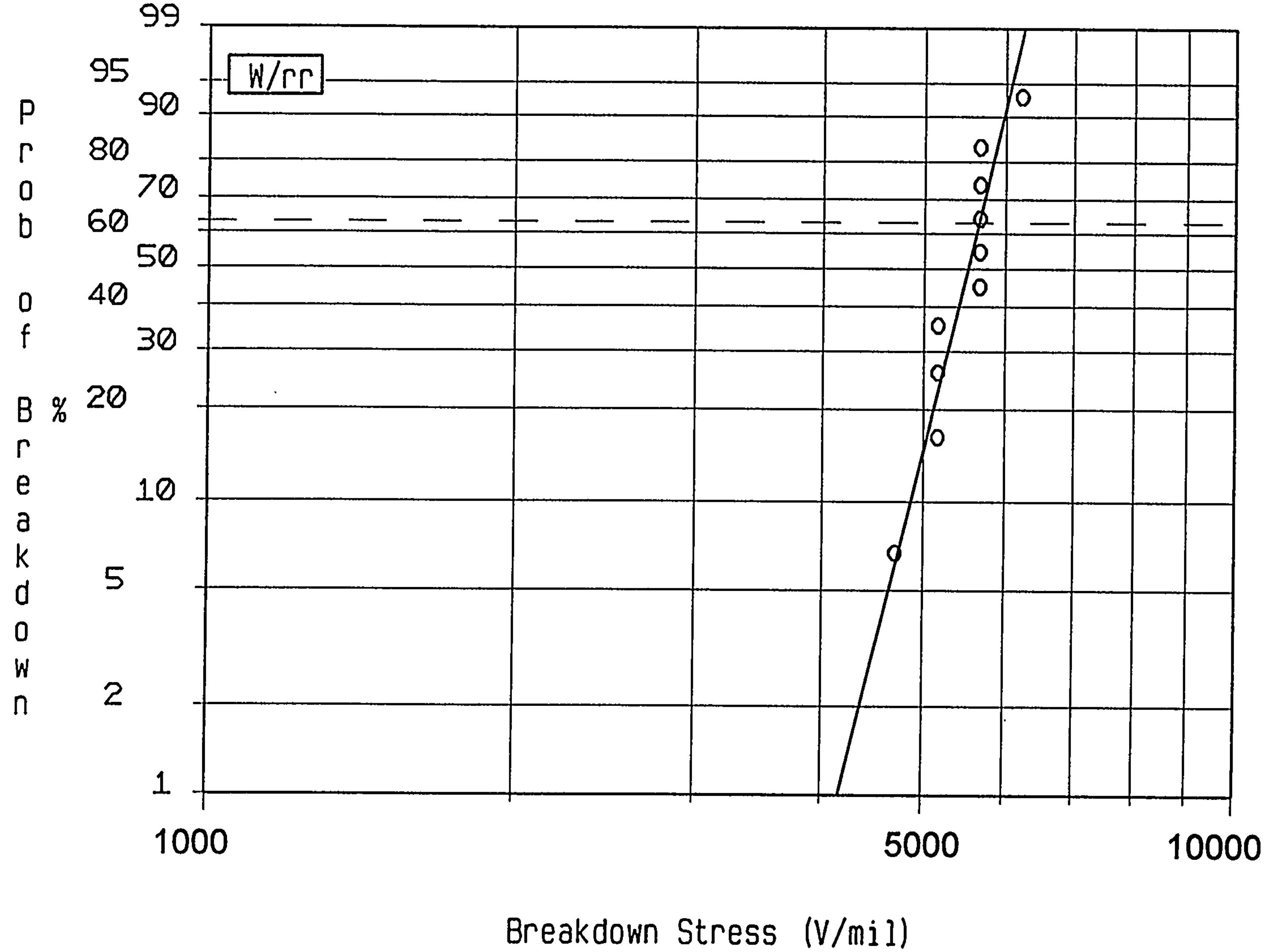


Fig. 7

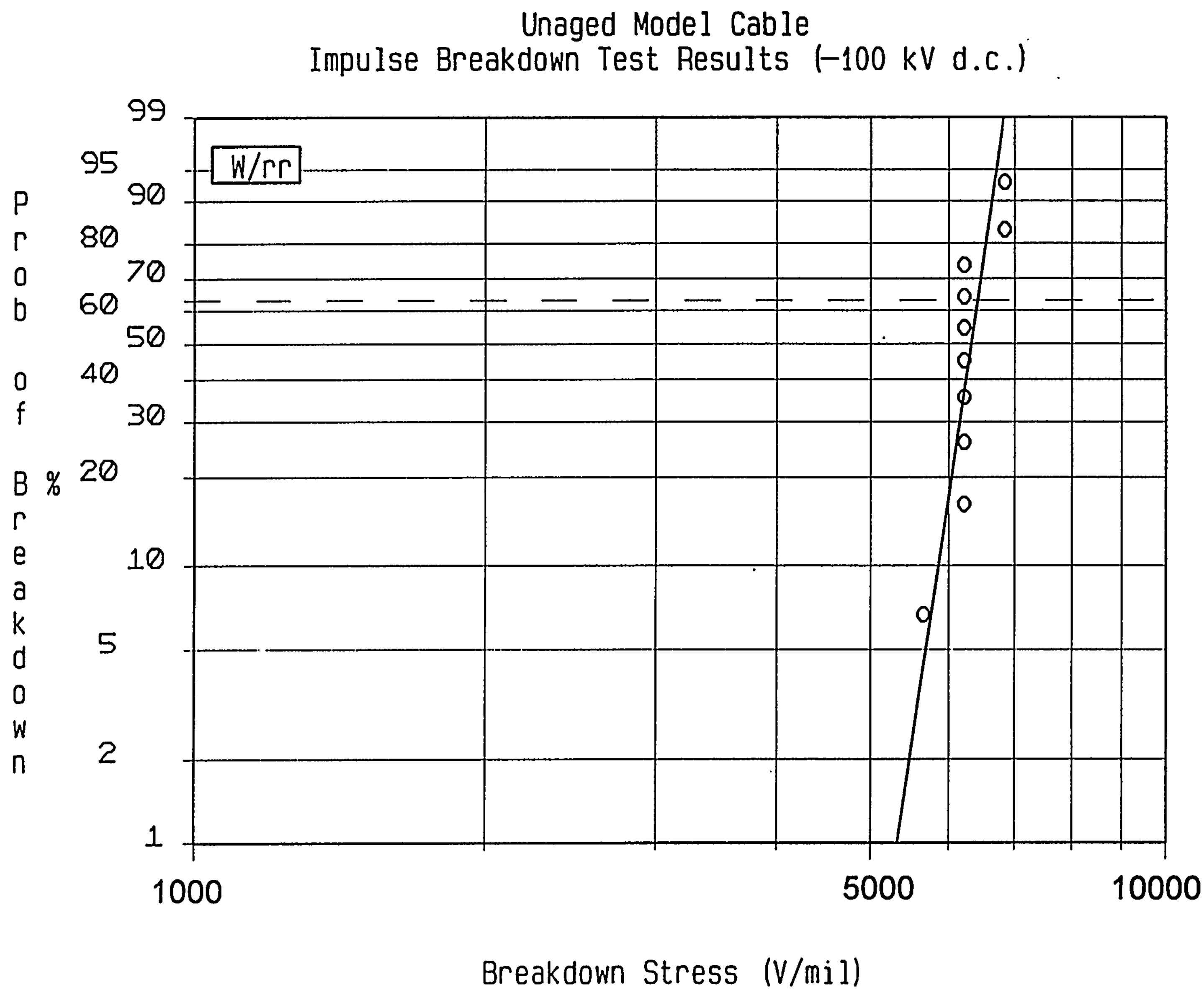

Unaged Model Cable
Impulse Breakdown Test Results (–100 kV d.c.)
W/rr
99
95
90
80
70
60
50
40
30
20
10
5
2
1
Prob of Breakdown %
1000
5000
10000
Breakdown Stress (V/mil)

Fig. 8

Unaged Model Cable
Impulse Breakdown Test Results (−140 kV d.c.)

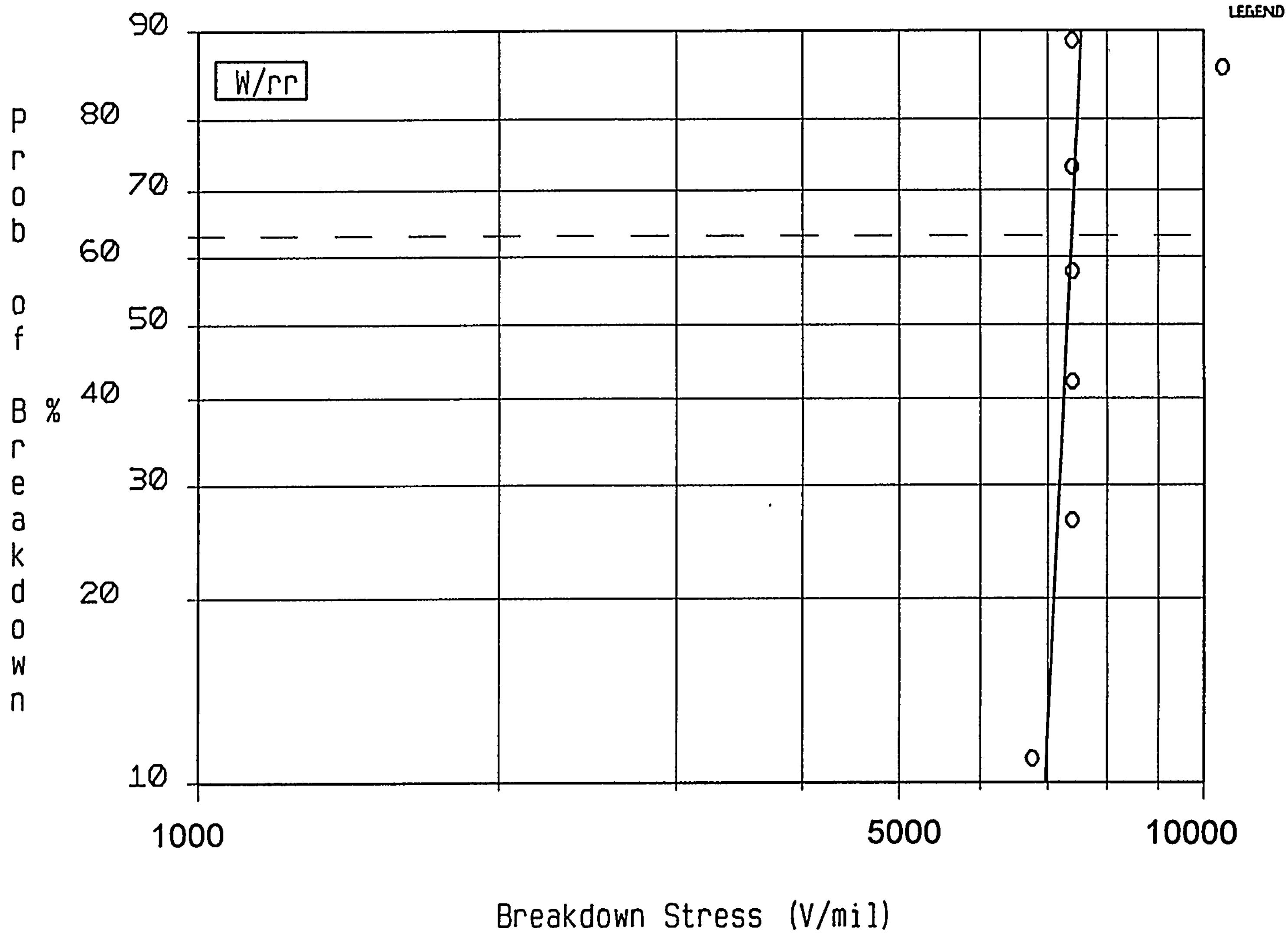


Fig. 9

Unaged Model Cable
Impulse Breakdown Test Results (-160 kV d.c.)

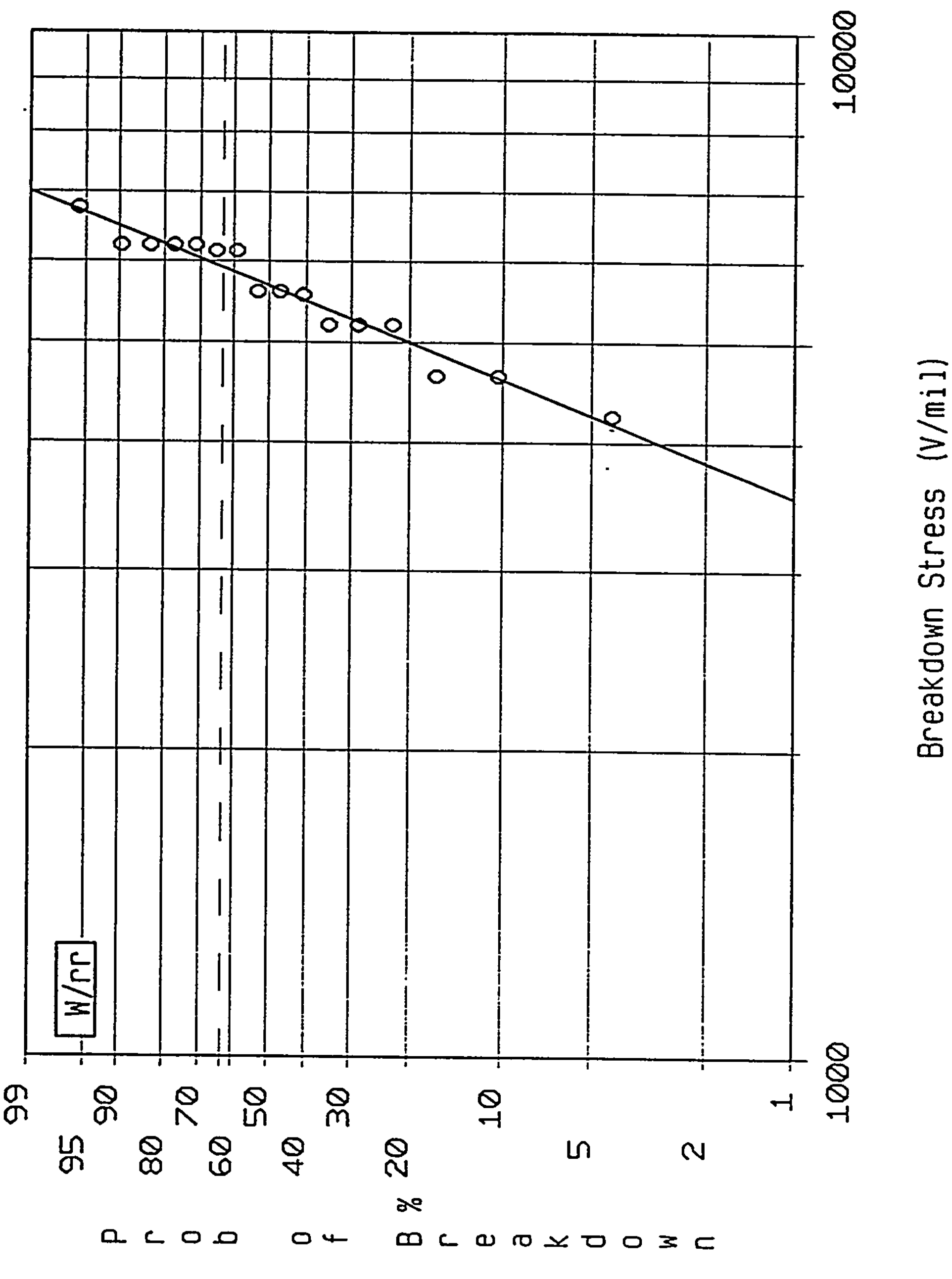
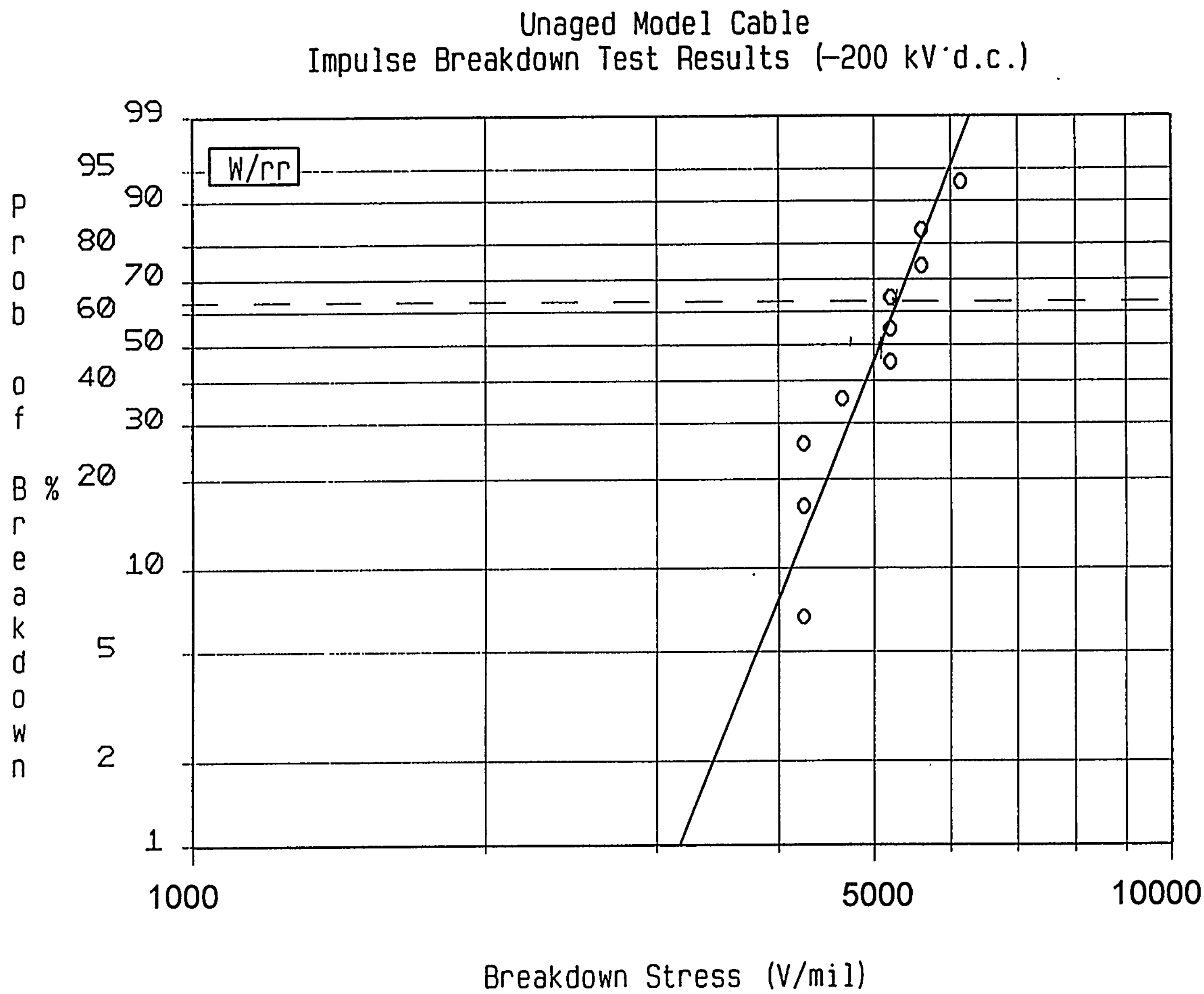


Fig. 10


Unaged Model Cable
Impulse Breakdown Test Results (-200 kV·d.c.)
W/rr
Prob of Breakdown %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
1000
5000
10000
Breakdown Stress (V/mil)

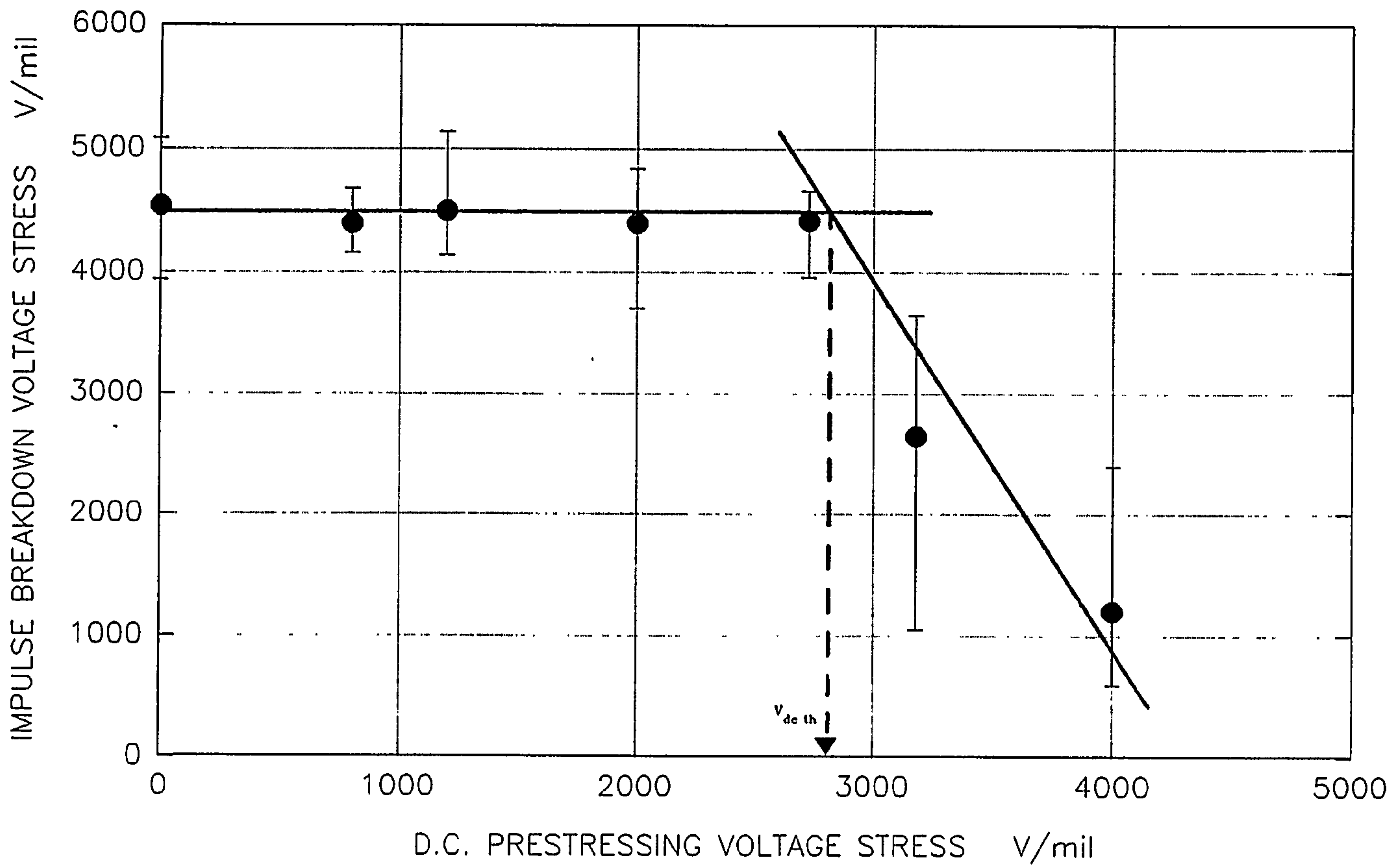


Fig. 11 Determination of Threshold Voltage Stress of XLPE Model Cable Before Aging .

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4.3 Measurement of A.C. Voltage Breakdown of XLPE Model Cable Before Aging

The a.c. breakdown tests were conducted at ambient temperature. The length of the samples tested was 10 feet. The step voltage test procedure was used, increasing the voltage 10% each 1 minute. The initial voltage step was about 50% of the anticipated breakdown voltage. Ten samples were tested. The breakdown voltages were plotted on Weibull probability graph paper. The Weibull probability distribution of a.c. voltage breakdown stresses are given in Figure 12.

The scheduled a.c. and d.c. breakdown tests for unaged and aged cables are tabulated in Table 3.

4.4 Measurement of Threshold Voltage Stress of XLPE 15 kV Cable Before Aging

The procedure outlined in Section 4.2 to establish the threshold voltage stress for XLPE model cable, was also followed for XLPE 15 kV cable. Typical Weibull probability distributions of impulse and of impulse breakdown voltage

Fig. 12

Unaged Model Cable
A.C. Breakdown Test Results (1 Minute Steps)

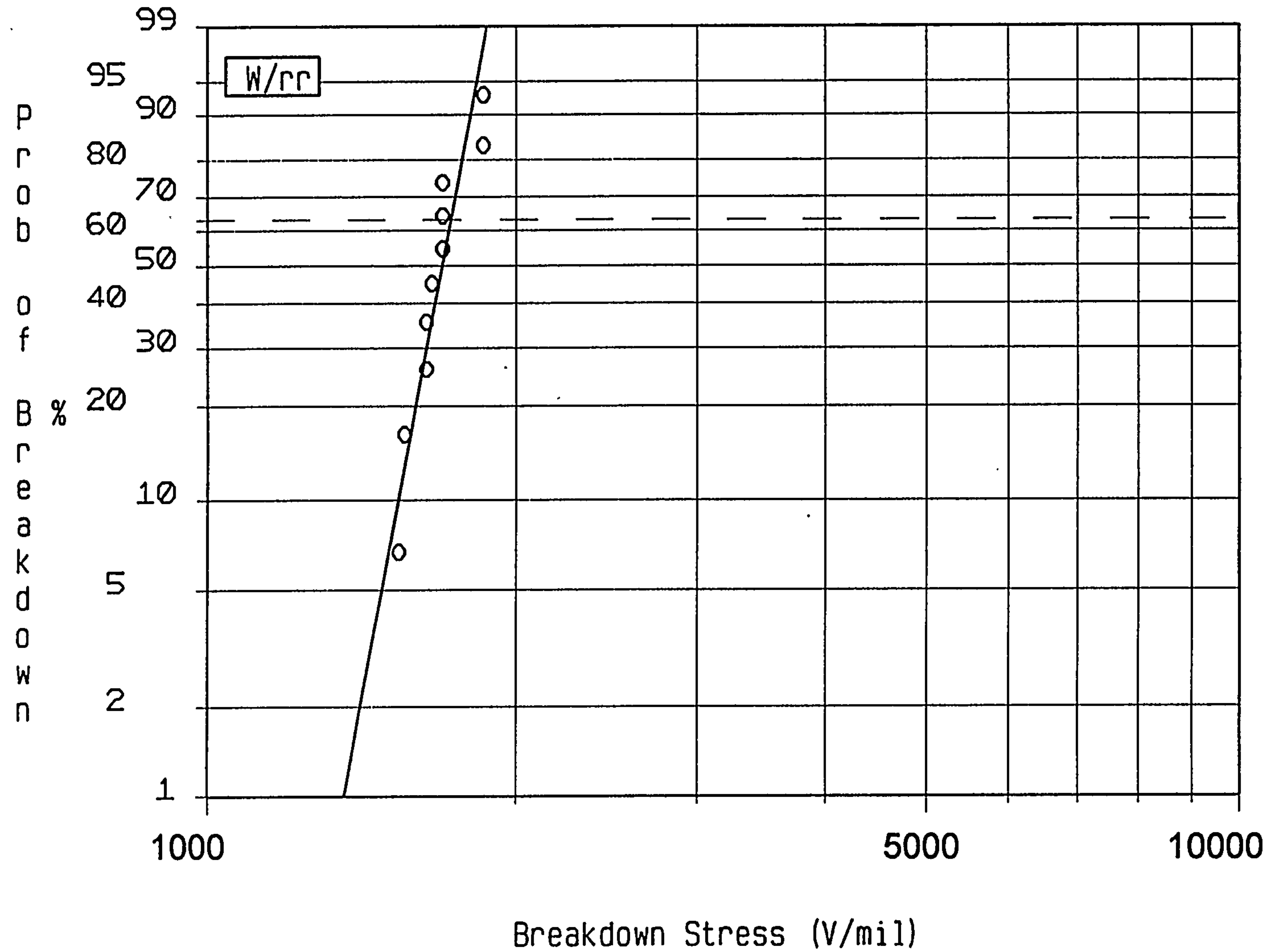


TABLE 3

SCHEDULE OF A.C. AND D.C. VOLTAGE BREAKDOWN TESTS*

Cable Designation	Model				15 kV	
Aging Temperature - °C	23				23	
Electrical Aging in Water - Weeks	0	1	26	26*	0	26
A.C. breakdown step time:						
1 min.	x	x	x	x	x	x
5 min.	--	x	x	x	x	--
60 min.	--	x	x	--	--	--
960 min.	--	x	x	--	--	--
D.C. breakdown step time:						
1 min.	--	x	x	x	--	--
*Followed by 13 weeks of drying						

stress for different levels of d.c. pre-stressing are given in Figs. 13, 14 and 15. The results are plotted in Fig. 16 which shows the threshold voltage of the XLPE cable before aging. The Weibull probability distribution for d.c. pre-stressing values of -300 and -350 kV, shown on Fig. 16, are not included because only 3 determinations were made at each of these d.c. pre-stress values due to limited availability of samples.

The estimated threshold voltage as indicated in Fig. 16 is 1800 V/mil.

Fig. 14

Unaged 15 kV Cable
Impulse Breakdown Test Results (-100 kV d.c.)

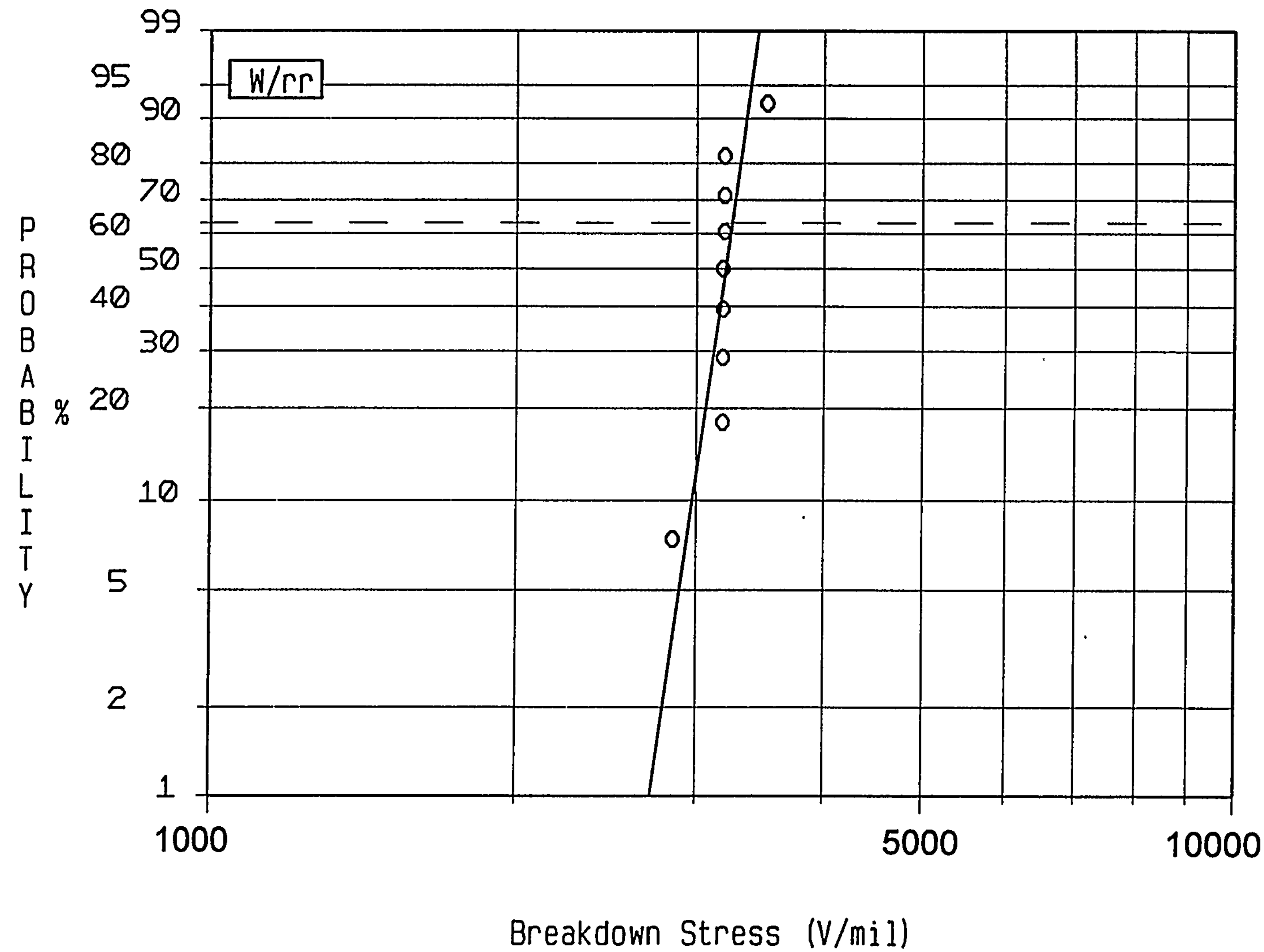
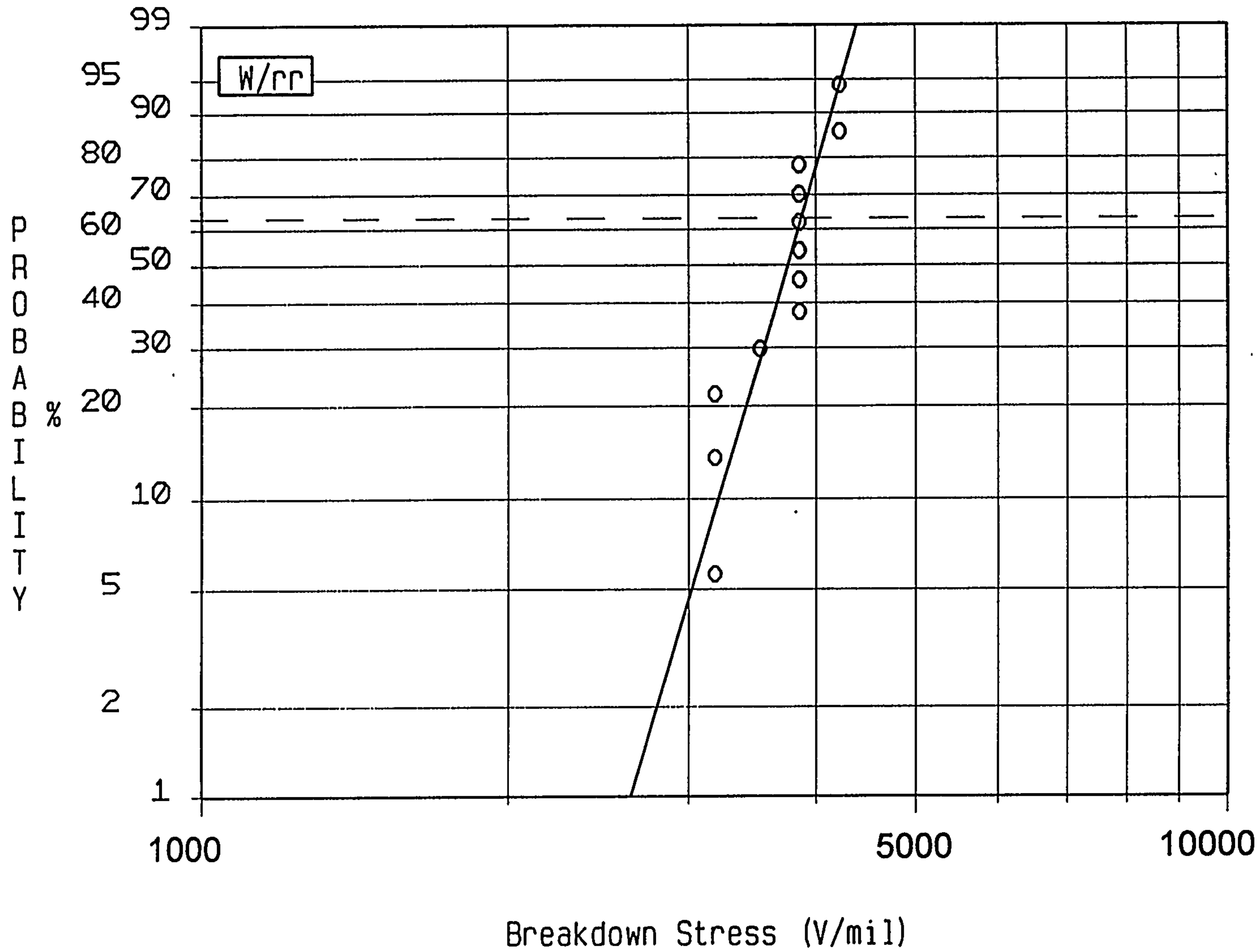


Fig. 15

Unaged 15 kV Cable
Impulse Breakdown Test Results (-200 kV d.c.)



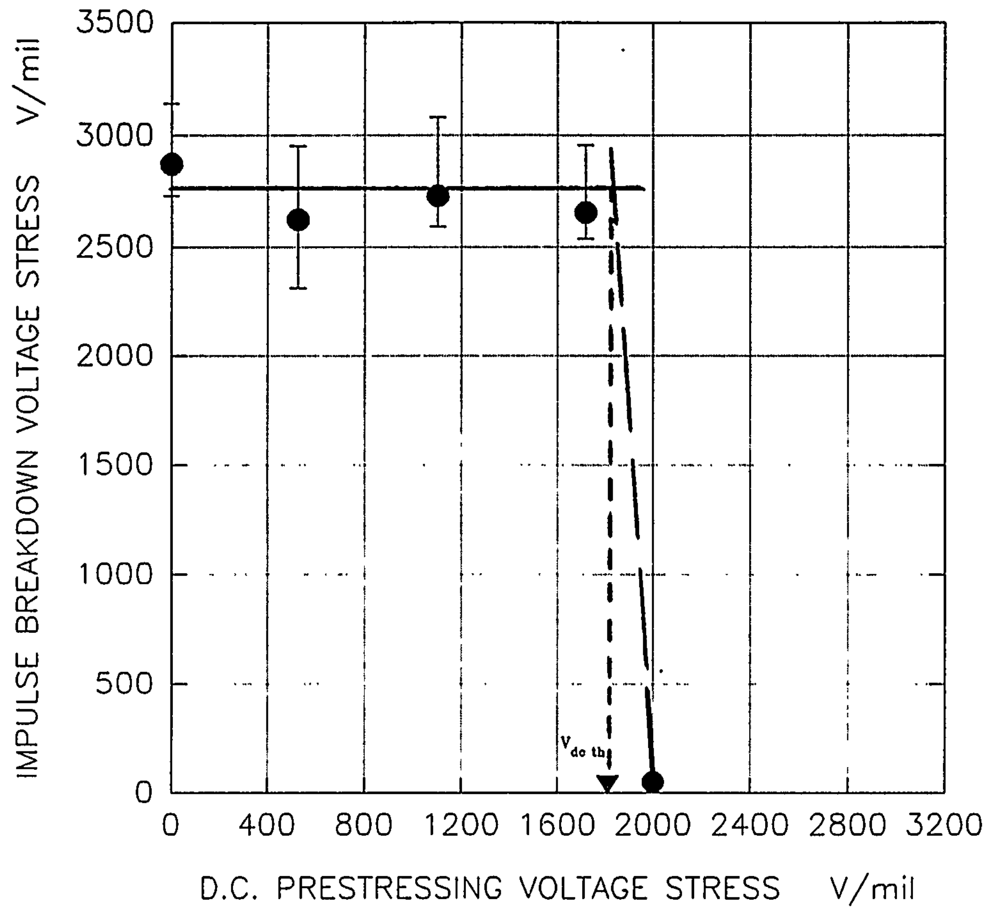


Fig. 16 Determination of Threshold Voltage Stress of XLPE 15 kV Cable Before Aging.

4.5 Measurement of A.C Voltage Breakdown of XLPE 15 kV Cable Before Aging

The 60 Hz breakdown tests were conducted at ambient temperature. The length of the tested samples was 10 feet. During the test procedure used, voltage was increased 10% at each step. The initial voltage step was about 50% of the anticipated breakdown voltage. The duration of each step was either 1 or 5 minutes. About 10 samples were broken at each of these voltage steps. The purpose of different step duration was to establish a voltage stress-time to breakdown relationship. The breakdown voltage was plotted on Weibull probability graph paper. The Weibull probability distributions of a.c. voltage breakdown stress are given in Fig. 17. Table 4 gives a summary of the a.c. voltage breakdown at the two times used for duration of the steps providing simultaneously an idea of the effect of step time duration on the breakdown strength.

5.0 AGING OF XLPE CABLES

The cables were made into coils and placed in large containers filled with tap water. Water also was injected between the strands of the conductor of each cable. The aging was accelerated by continually applying higher than

Fig. 17

Unaged 15 kV Cable
A.C. Breakdown Test Results

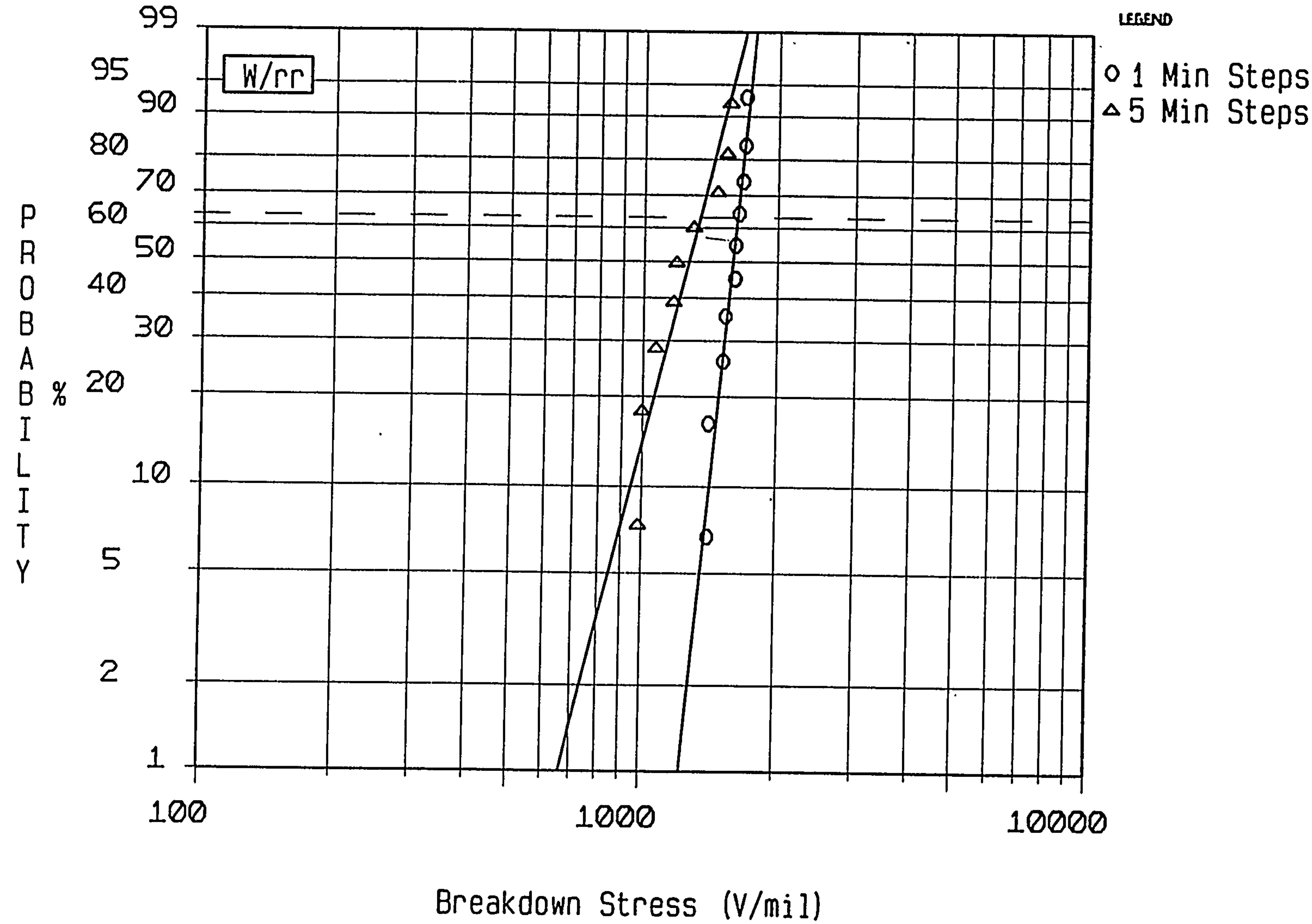


TABLE 4

A.C. BREAKDOWN OF UNAGED XLPE 15 KV CABLE

Voltage Step Time min	A.C. Breakdown Voltage kV	A.C. Breakdown Voltage Stress	
		V/mil	kV/mm
1	80.6	1610	66.1
5	66.4	1330	54.4

operating voltage stress. The model cable was aged at 60 Hz, 8.6 kV (between conductor and shield) and the 15 kV cable at 60 Hz, 26 kV corresponding to approximately 3 times rated voltage of 15 kV cable.

To determine the degree of degradation during aging, samples of the model and 15 kV cables were removed periodically from the aging containers and their dielectric strength measured. The intention was to characterize the model cable after the dielectric strength fell to about 70% and to 40% of the original values of a.c. breakdown strength. This was approximately realized by aging the model cable 1 week and 6 months. The intention was to age 15 kV cable until it fell to 40% of its original a.c. breakdown strength. This was approximately obtained by aging 6 months.

6.0 DRYING OF AGED MODEL XLPE CABLE

Model cable that was aged in water for 6 months was dried at ambient temperature by flowing dry nitrogen gas through the conductor interstices. Coils, 450 feet long, of model cable were set up for drying. The degree of drying was established by monitoring the water content of the conductor shield. The flow of nitrogen was virtually continuous for 13 weeks. During the latter portion of this period current was passed through the cable conductor to raise its temperature to about 90°C to enhance drying. The conductor shield after drying the model cable contained 0.18 percent moisture by weight. This value compares with 0.64 percent moisture content by weight before drying (after aging for 6 months).

7.0 TESTING OF AGED XLPE CABLES

As indicated in Table 2 the threshold voltage of aged model cable was determined at ambient temperature after aging 1 week, after aging 26 weeks; and after drying the cable 13 weeks following the 26 week aging period.

The threshold voltage of aged 15 kV cable was measured at ambient temperature after 26 weeks aging.

Table 3 provides a.c. and d.c. voltage breakdown tests conducted on model and 15 kV cables. These data were utilized to obtain the Weibull probability of breakdown voltage, which is helpful in establishing the degree of aging and establishing a voltage stress-time to breakdown relationship. It is also useful in establishing the relationship between threshold voltage and cable breakdown strength.

7.1 Measurement of Threshold Voltage Stress of Aged XLPE Model Cable

The test and analysis procedures to establish threshold voltage at ambient temperature were the same as described in Section 4.2. The Weibull probability distribution of impulse and of impulse breakdown voltage stress for different levels of d.c. pre-stressing are given in Figs. 18 through 21 for model cable aged one week and in Figs. 22 through 27 for cable aged 26 weeks.

The dependence of impulse breakdown stress on the d.c. pre-stressing is shown in Fig. 28 for the cables aged 1 and 26 weeks and is compared to the unaged XLPE model cable.

Fig. 18

Model Cable Aged 1 Week
Impulse Breakdown Test Results

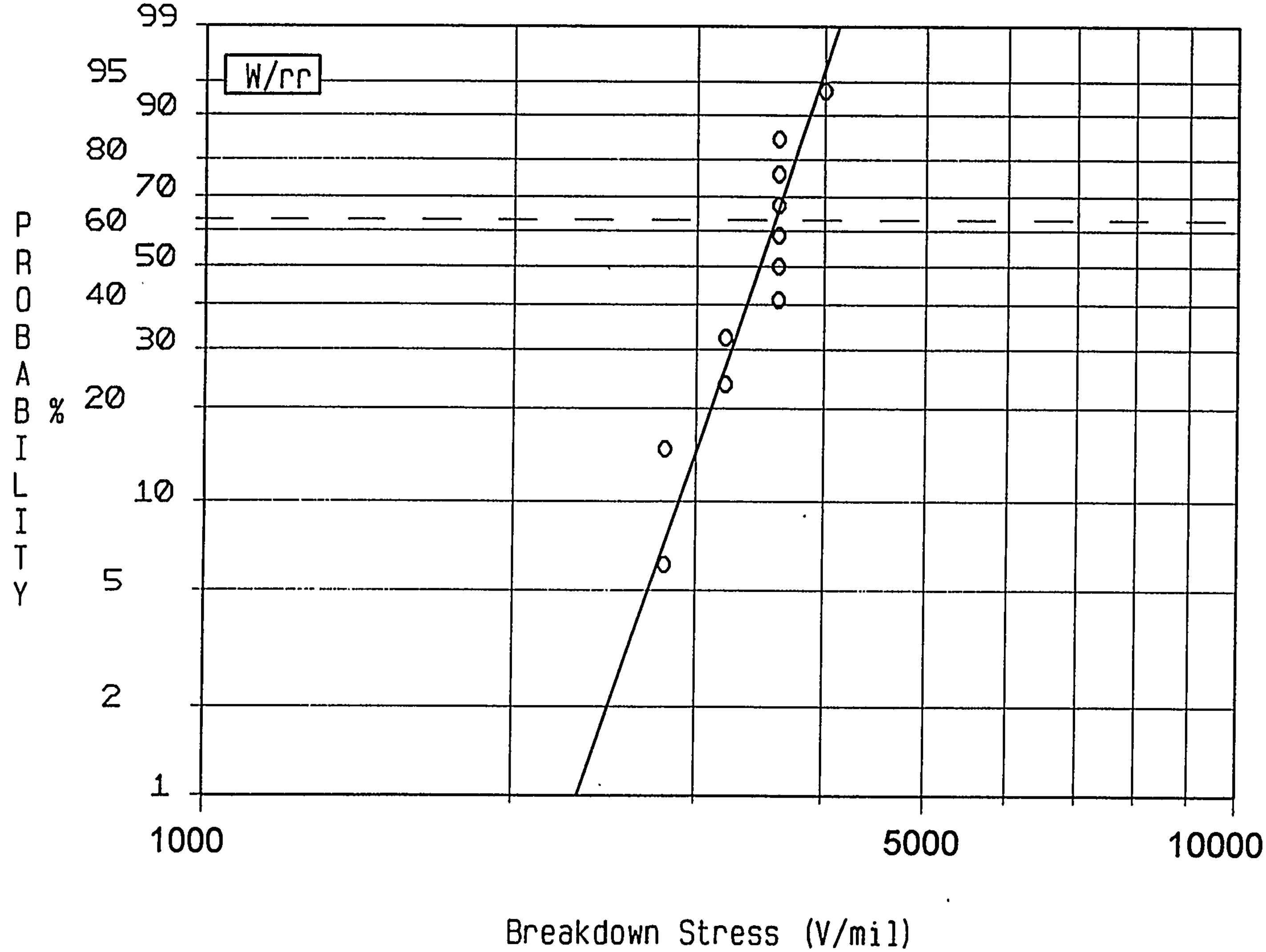


Fig. 19

Model Cable Aged 1 Week
Impulse Breakdown Test Results (-50 kV d.c.)

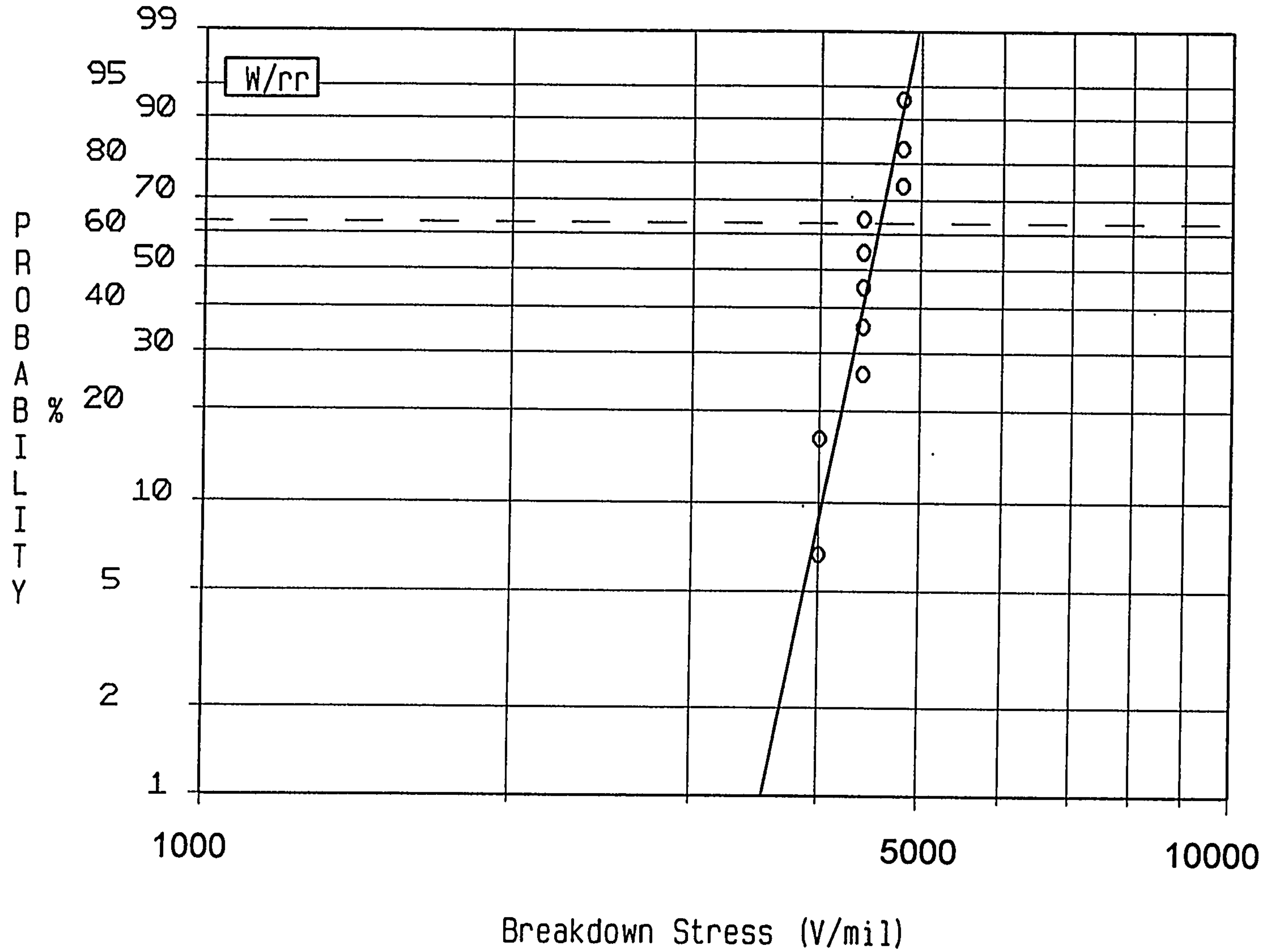


Fig. 20

Model Cable Aged 1 Week
Impulse Breakdown Test Results (-75 kV d.c.)

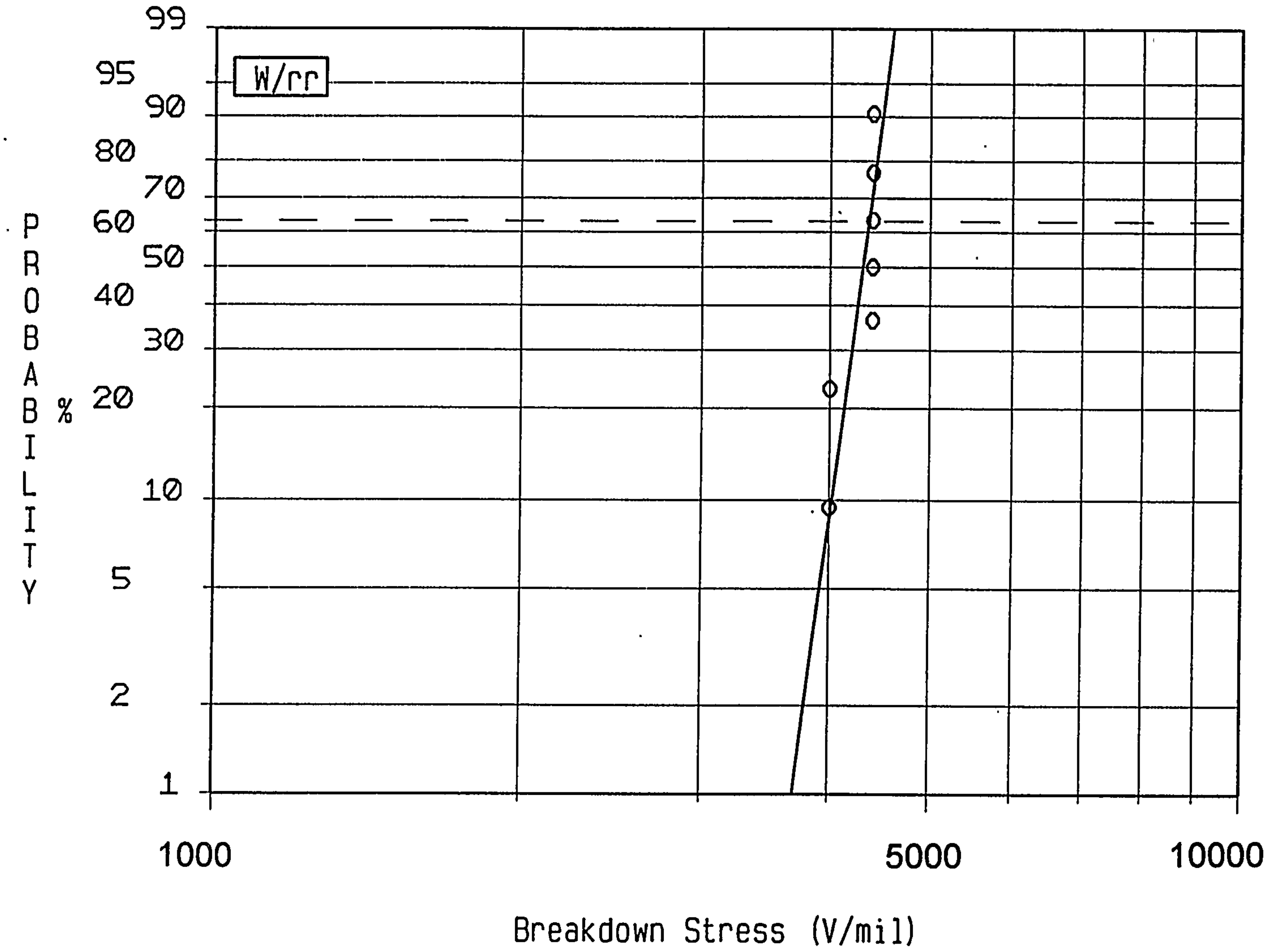


Fig. 21

Model Cable Aged 1 Week
Impulse Breakdown Test Results (-100 kV d.c.)

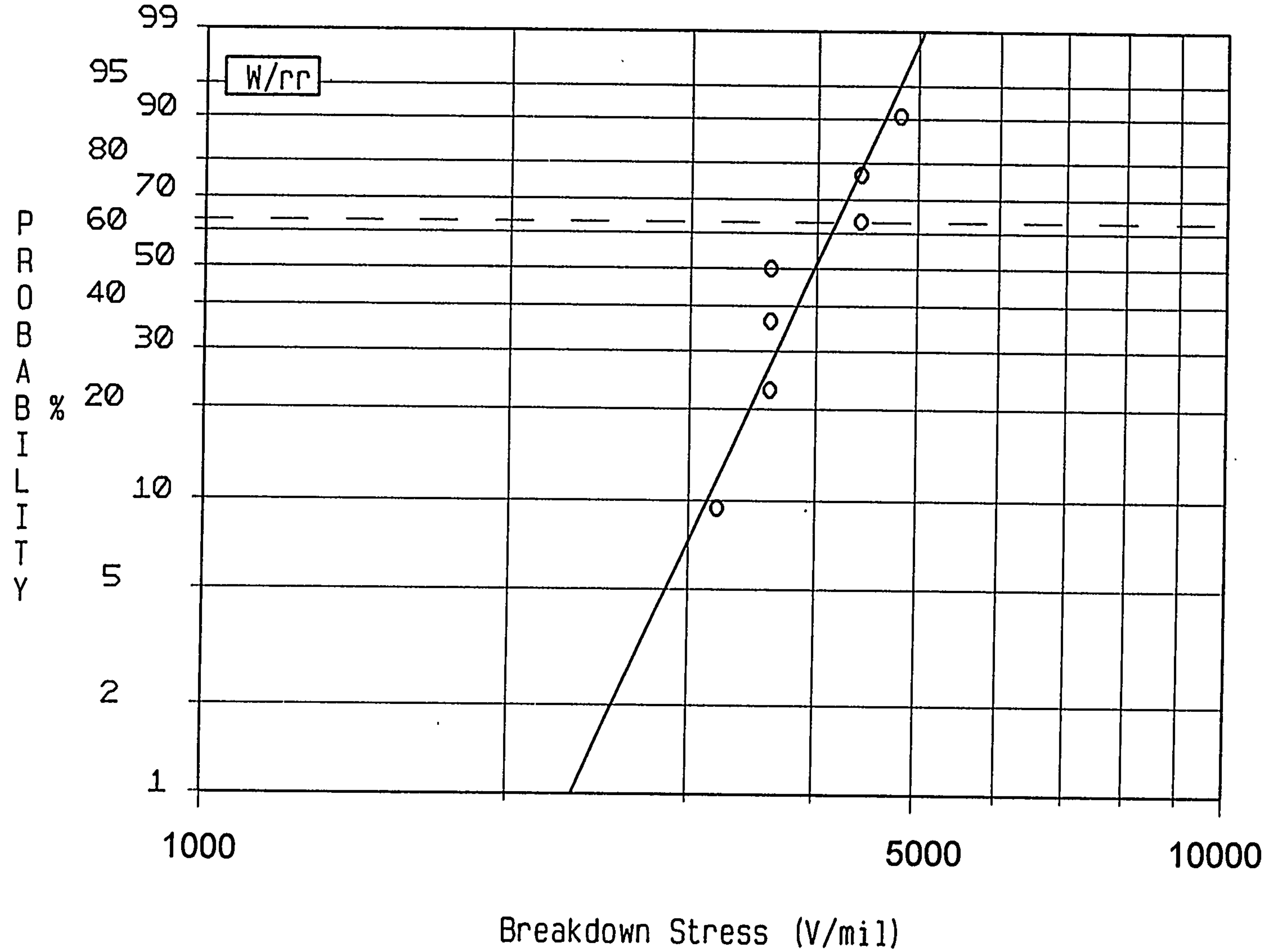


Fig. 22

Model Cable Aged 26 Weeks
Impulse Breakdown Test Results

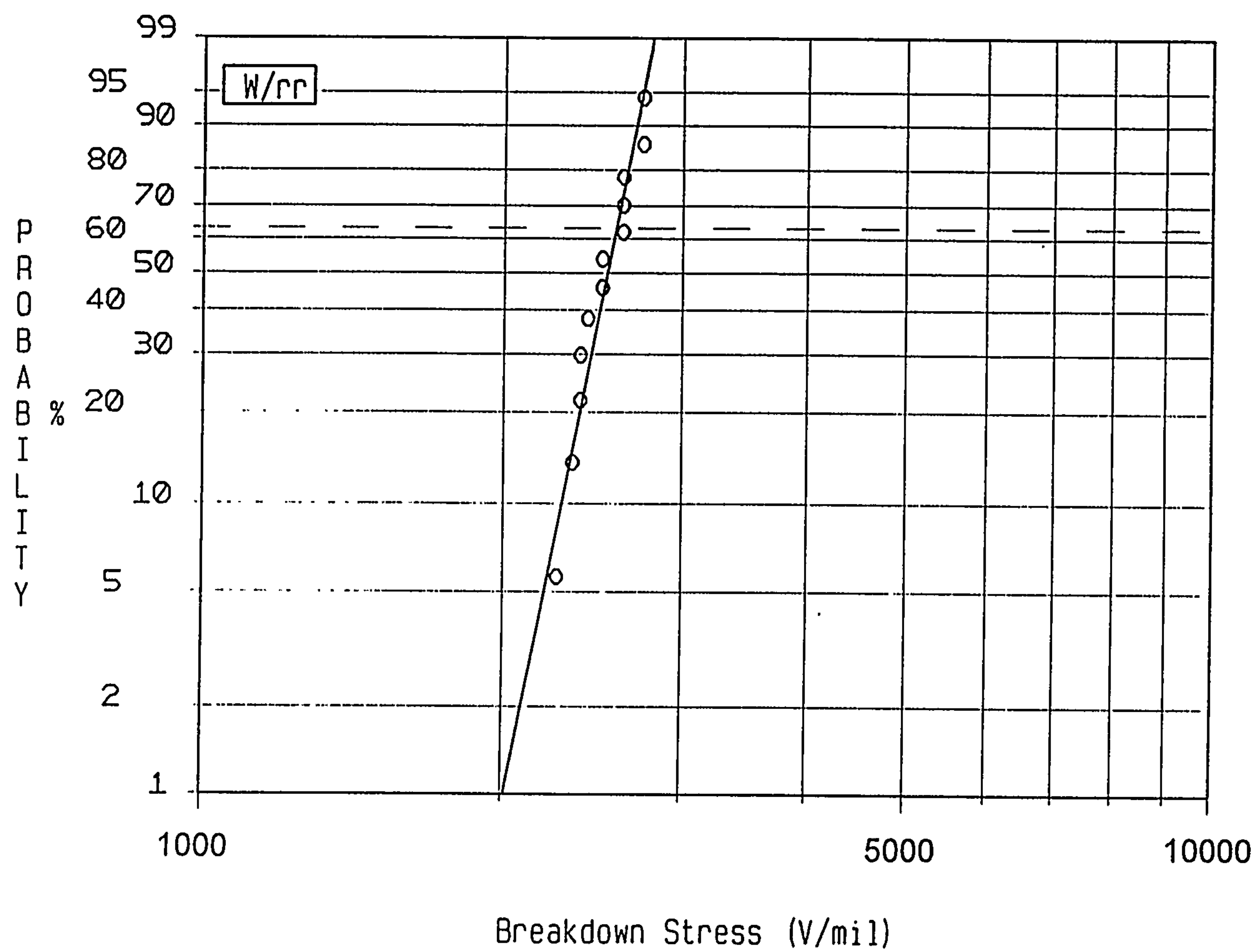
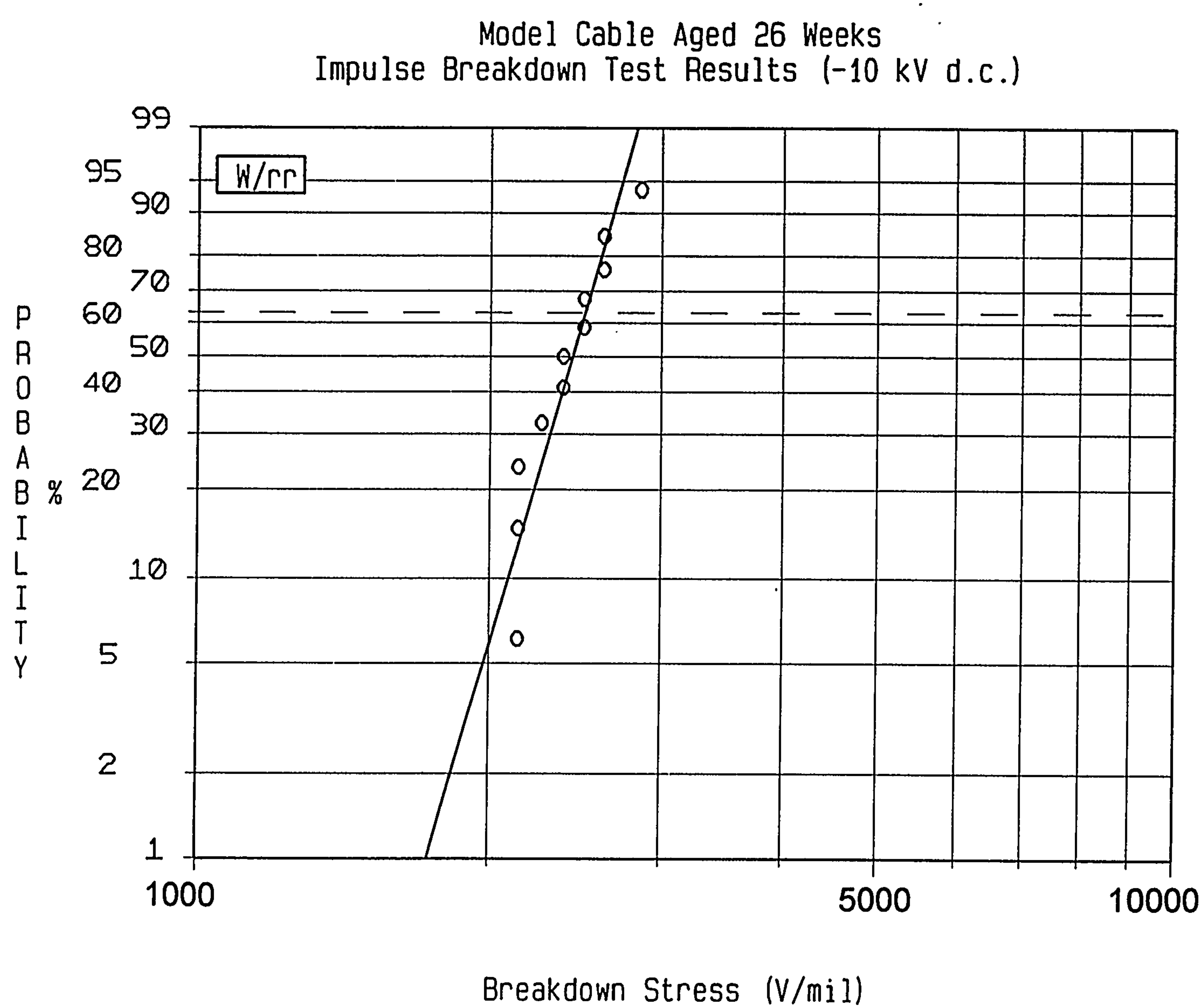


Fig. 23



Model Cable Aged 26 Weeks
Impulse Breakdown Test Results (-10 kV d.c.)
W/rr
99
95
90
80
70
60
50
40
30
20
10
5
2
1
PROBABILITY %
1000
5000
10000
Breakdown Stress (V/mil)

Fig. 24

Model Cable Aged 26 Weeks
Impulse Breakdown Test Results (-20 kV d.c.)

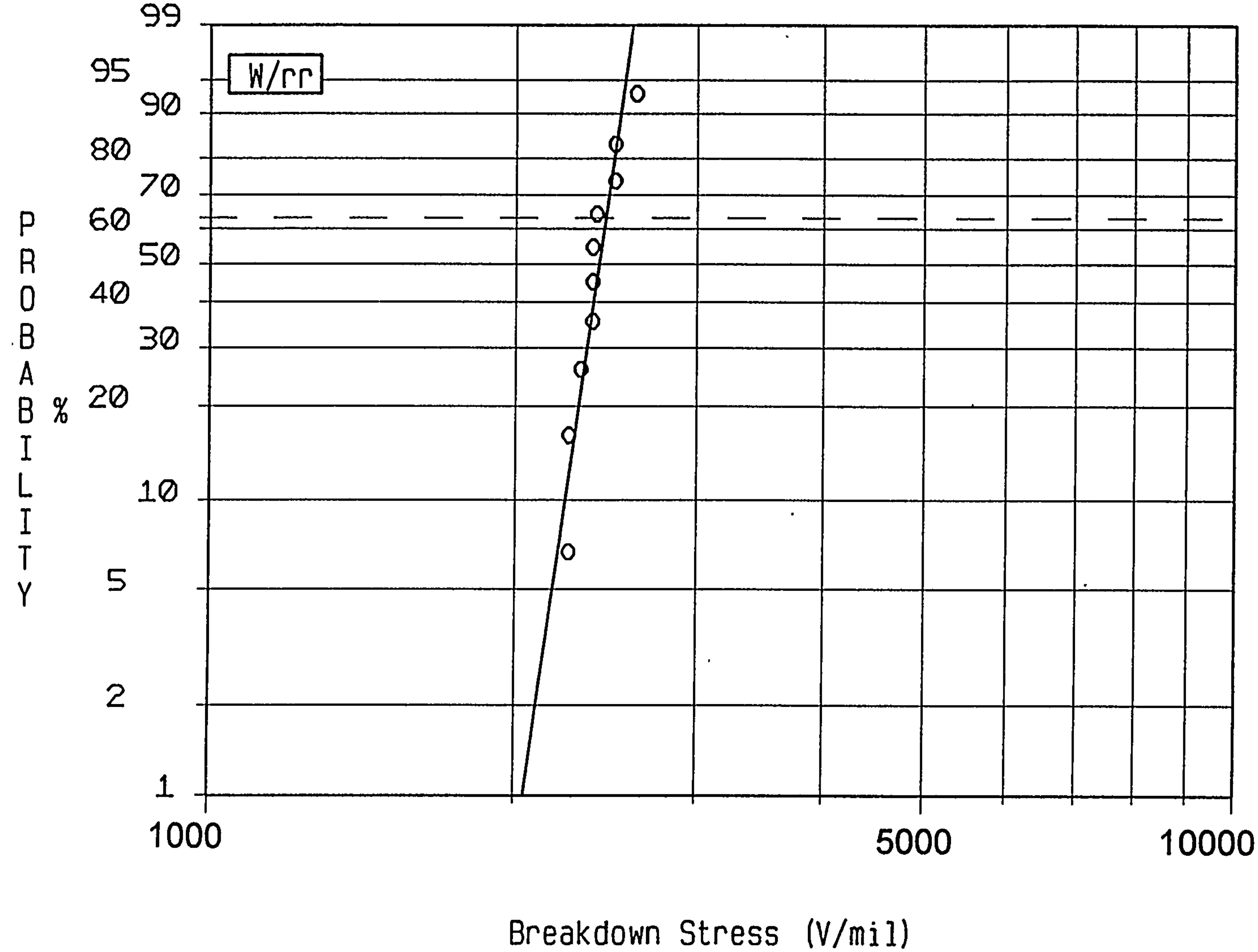


Fig. 25

Model Cable Aged 26 Weeks
Impulse Breakdown Test Results (-30 kV d.c.)

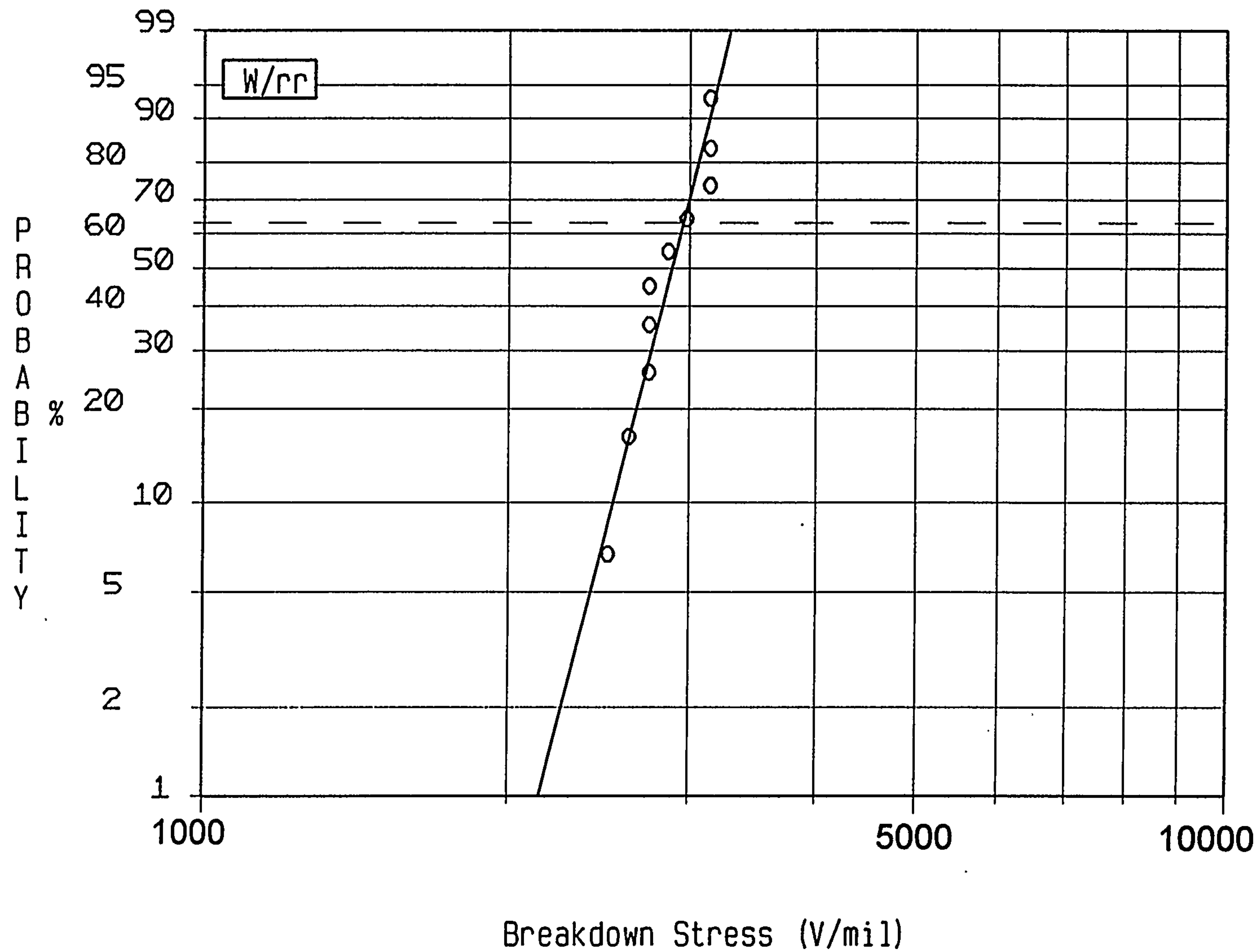


Fig. 26

Model Cable Aged 26 Weeks
Impulse Breakdown Test Results (-50 kV d.c.)

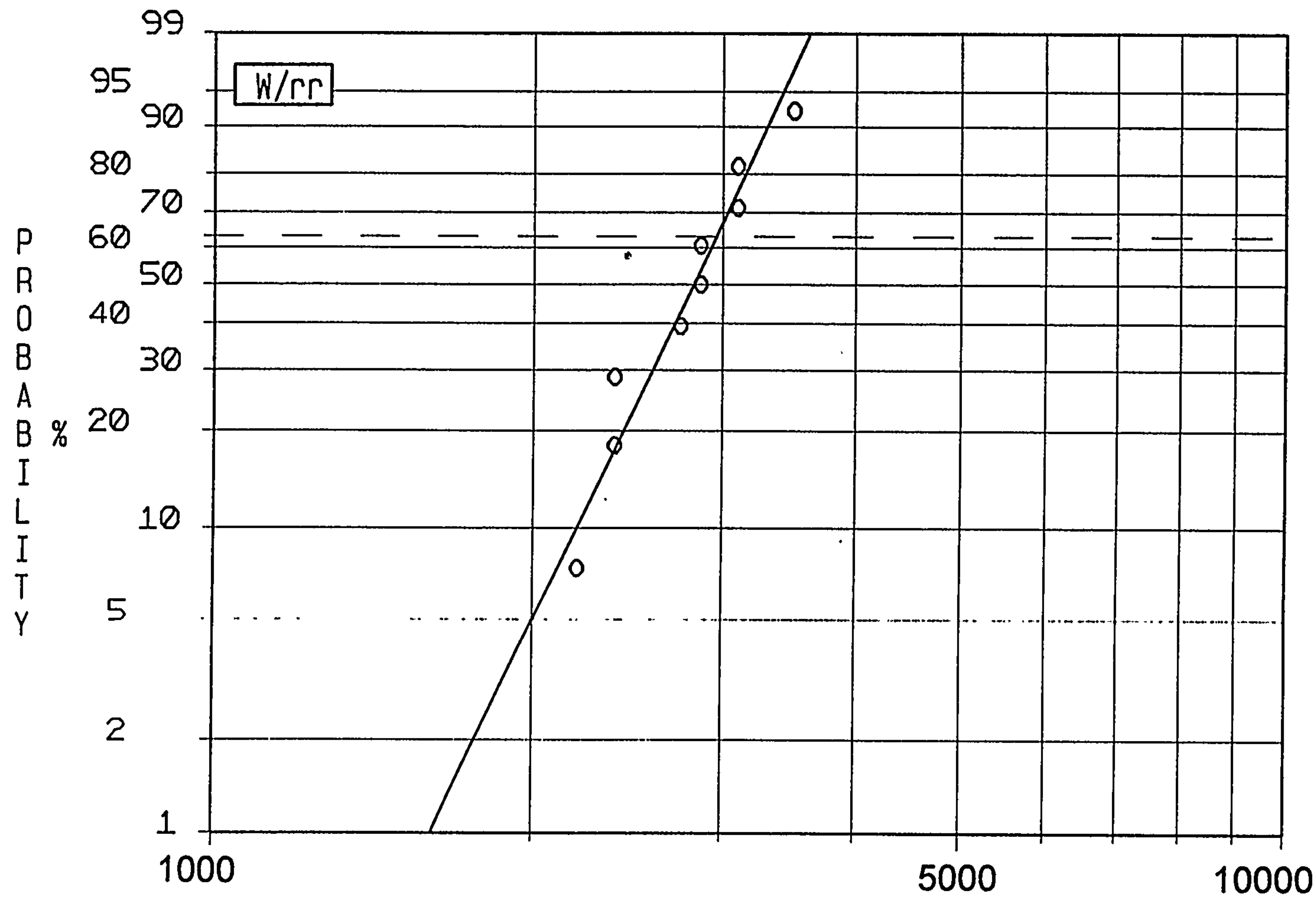
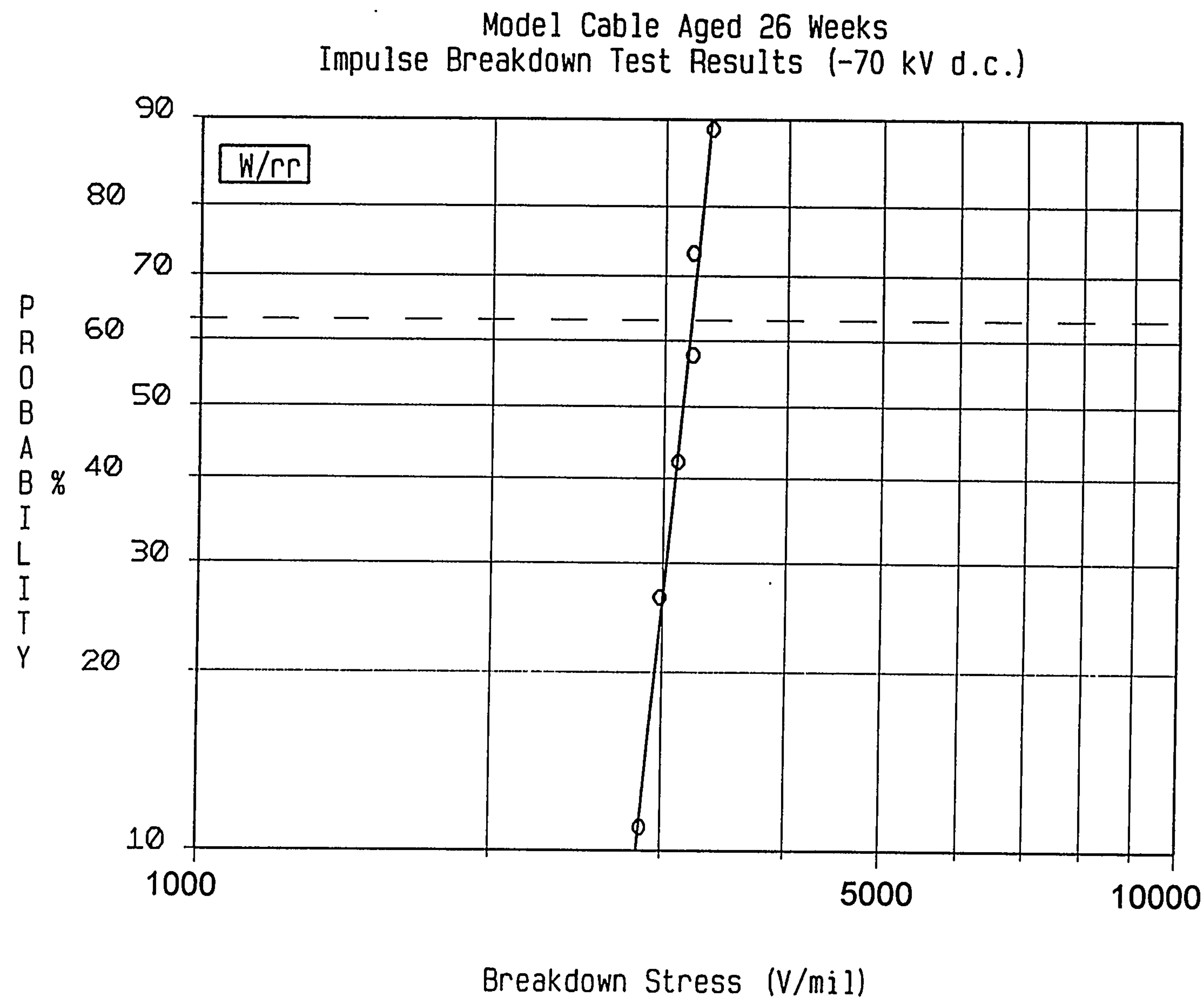


Fig. 27



Model Cable Aged 26 Weeks
Impulse Breakdown Test Results (-70 kV d.c.)
W/rr
PROBABILITY %
90
80
70
60
50
40
30
20
10
1000
5000
10000
Breakdown Stress (V/mil)

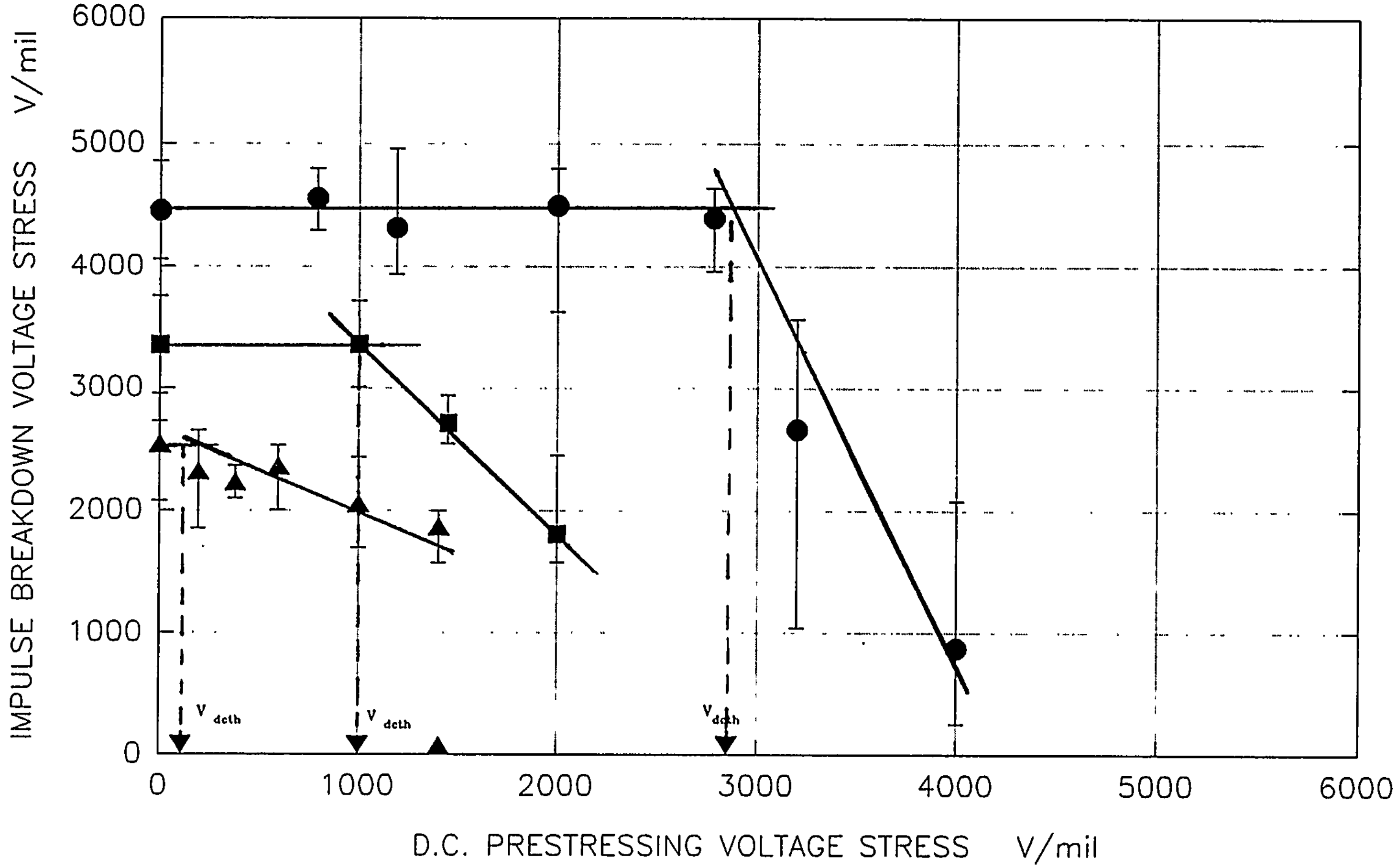


Fig. 28 Determination of Threshold Voltage Stress of XLPE Model Cable After Various Aging Periods.
1) Unaged ●
2) After Aging 1 week ■
3) After Aging 26 weeks ▲

DOE5

7.1.1 Measurement of Threshold Voltage Stress of Aged Then Dried XLPE Model Cable

A portion of the model cable that was aged for 26 weeks was dried for a period of 13 weeks by passing dry nitrogen gas through the conductor interstices. At the end of drying the moisture content of the conductor shield was 0.18% by weight. The drying with nitrogen was supplemented by heating the cable to about 90°C by passing current in the conductor.

The tests and analysis procedures to establish threshold voltage at ambient temperature were the same as described in Section 4.2. The Weibull probability distribution voltage stress for different levels of pre-stressing are presented in Figs. 29-33.

The threshold voltage dependence of impulse breakdown stress on the d.c. pre-stressing is shown in Fig. 34 for the XLPE model cable after 6 months of aging followed by 13 weeks of drying.

Fig. 29

Model Cable Aged 26 Weeks & Dried
Impulse Breakdown Test Results

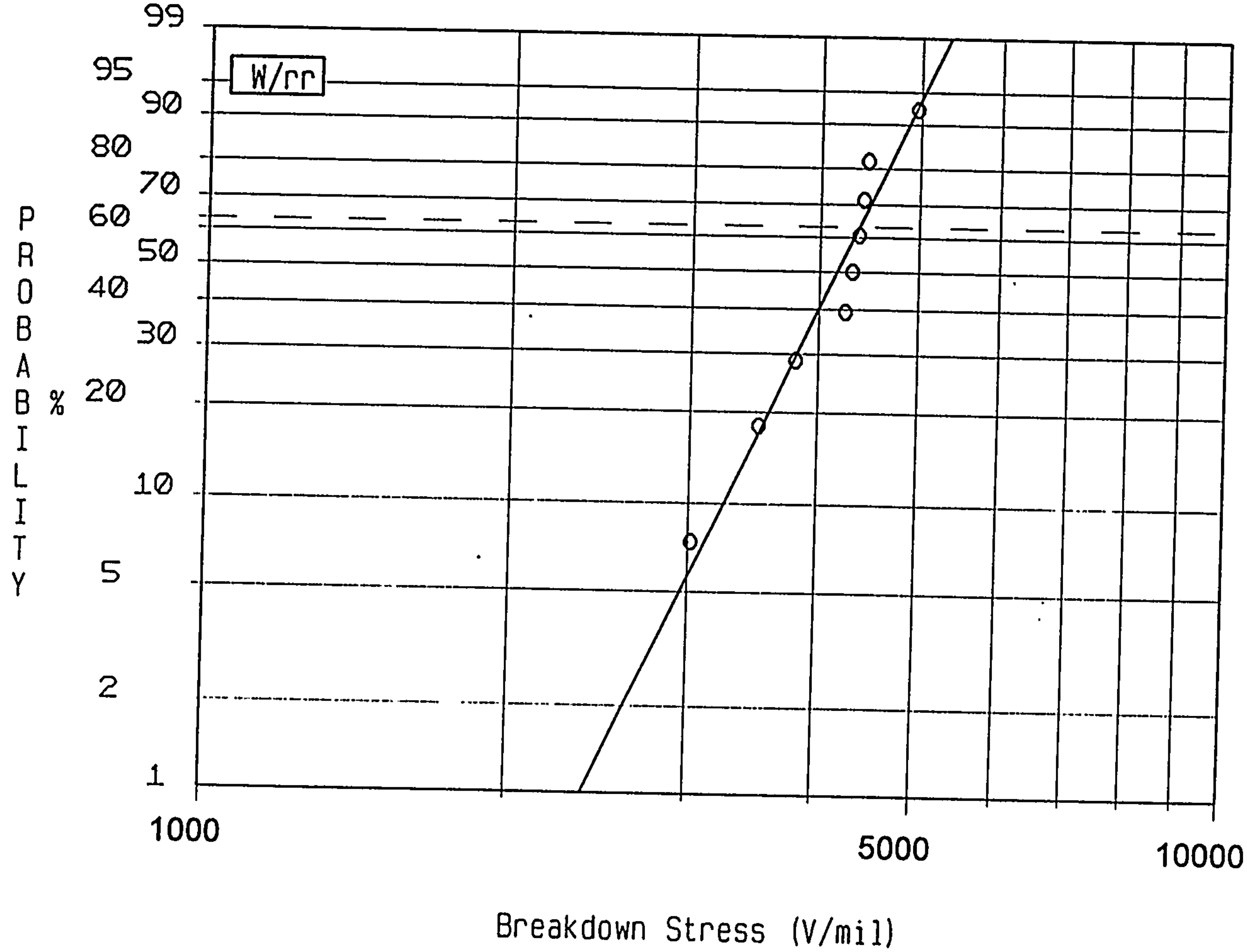


Fig. 30

Model Cable Aged 26 Weeks & Dried
Impulse Breakdown Test Results (-25 kV d.c.)

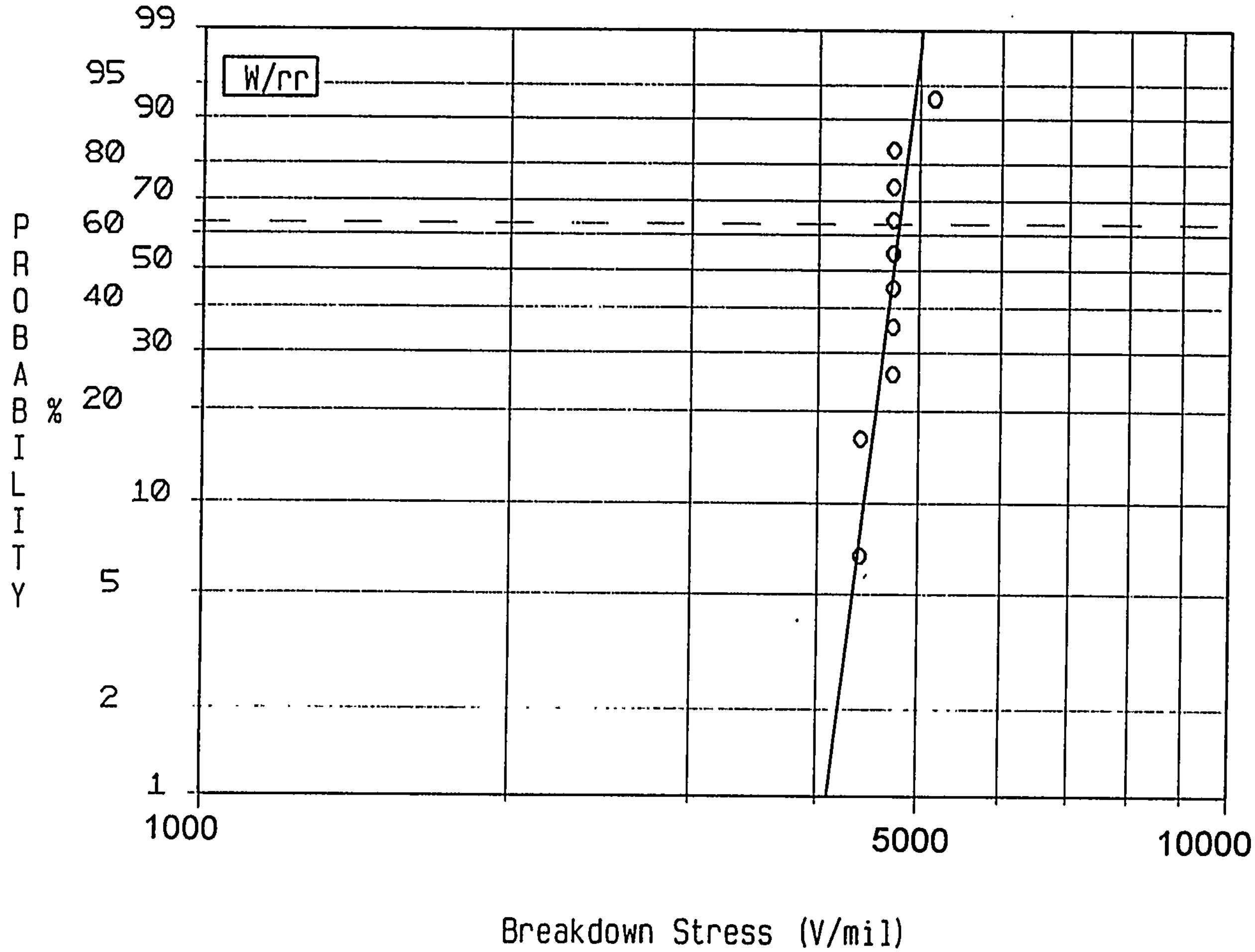


Fig. 31

Model Cable Aged 26 Weeks & Dried
Impulse Breakdown Test Results (-50 kV d.c.)

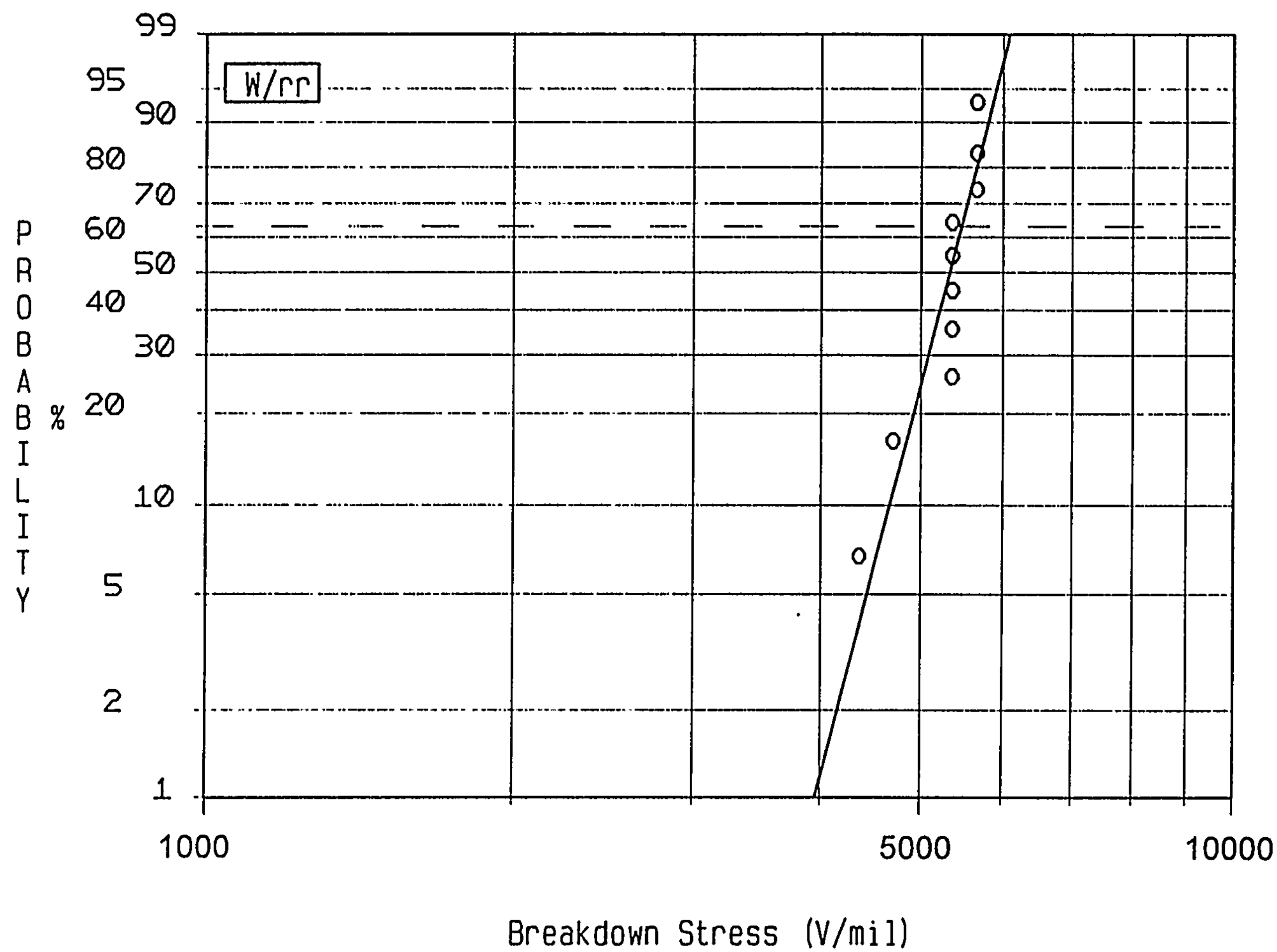


Fig. 32

Model Cable Aged 26 Weeks & Dried
Impulse Breakdown Test Results (-100 kV d.c.)

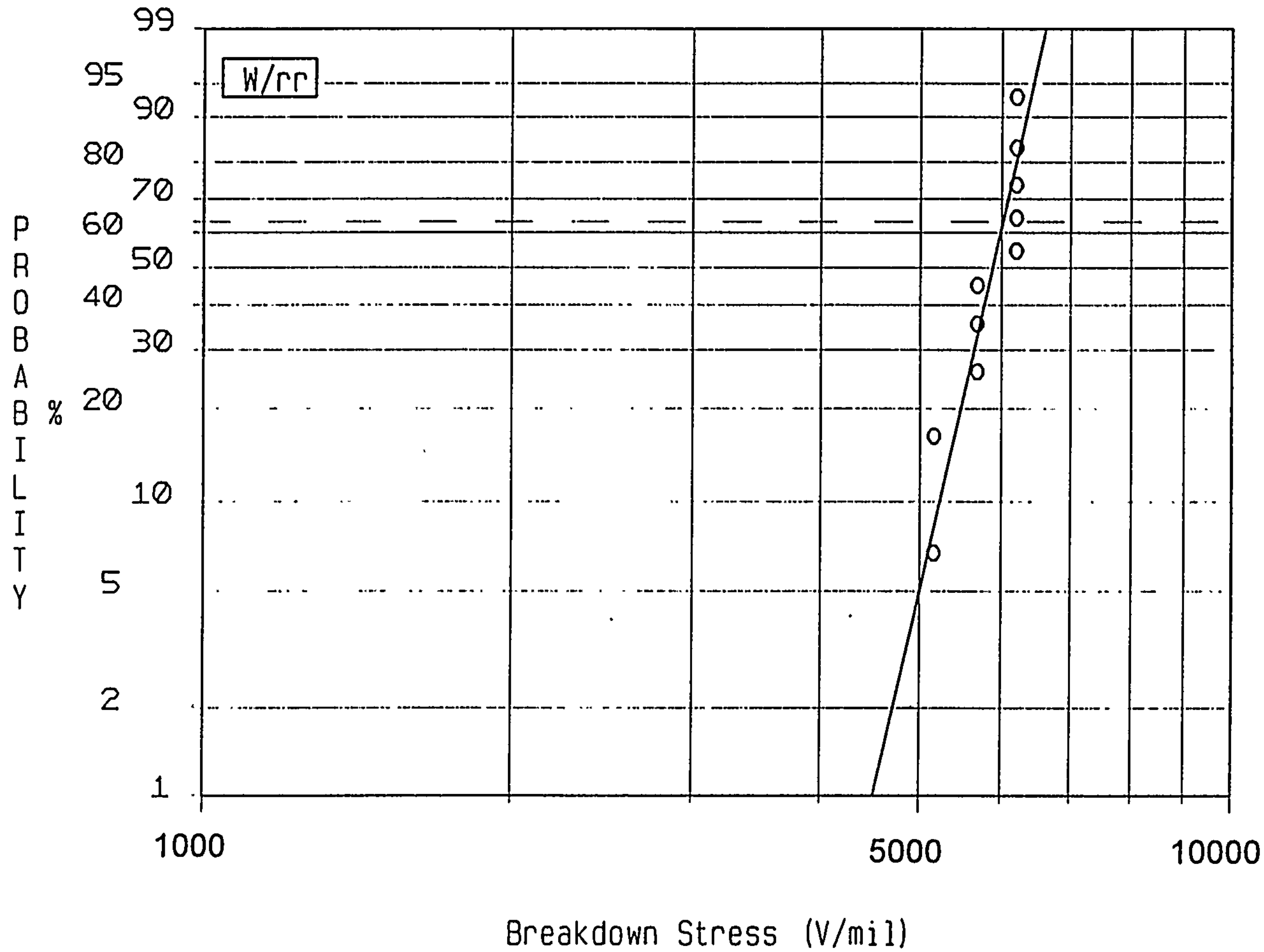
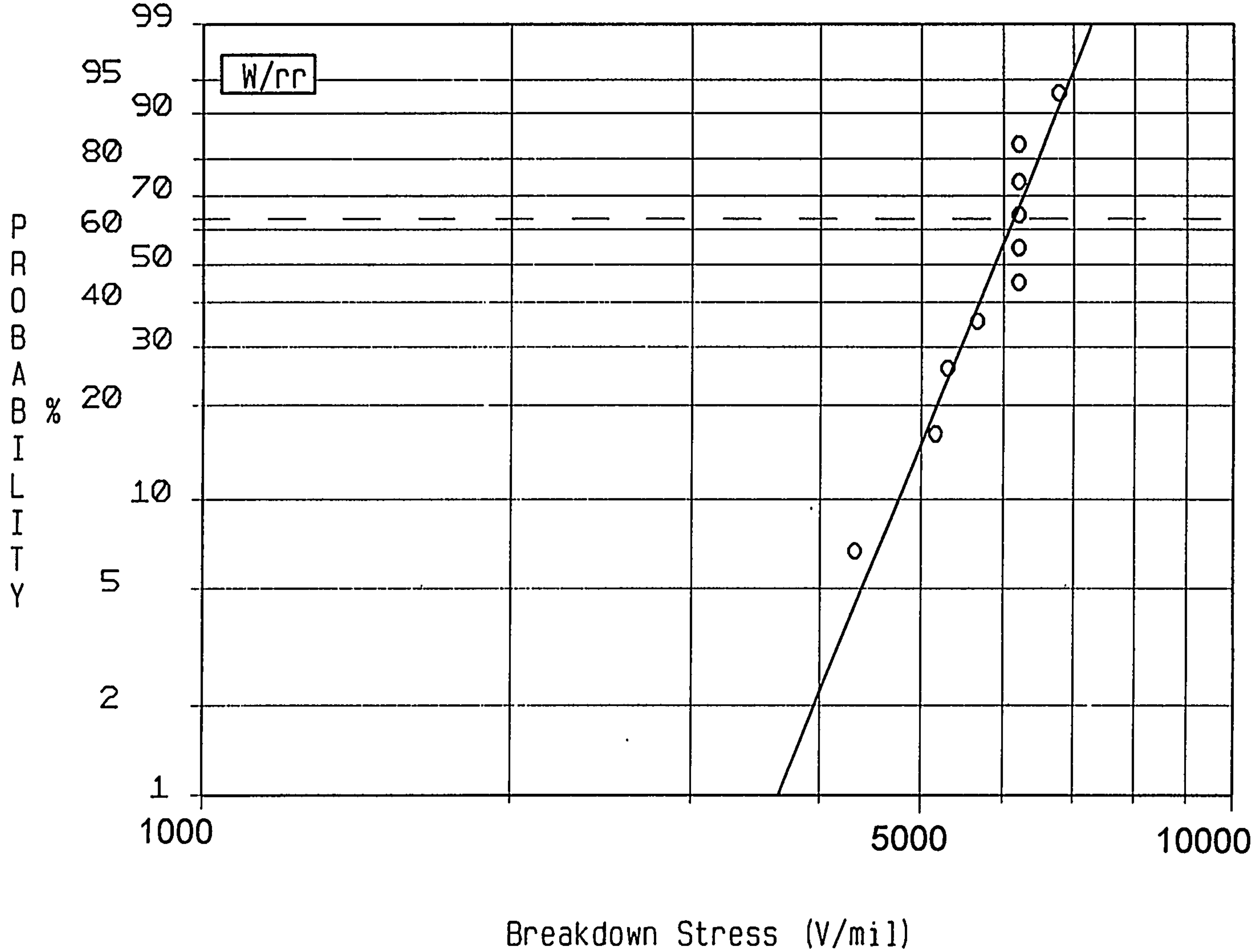


Fig. 33

Model Cable Aged 26 Weeks & Dried
Impulse Breakdown Test Results (-160 kV d.c.)



7.2 Measurement of A.C. Voltage Breakdown of Aged XLPE Model Cable

The a.c. breakdown tests were conducted at ambient temperature. The length of the samples tested was 10 feet. The step voltage procedure was used and the voltage was increased 10% at each step. Step duration varied from 1 to 960 minutes. The initial voltage was about 50% of the anticipated breakdown. The breakdown voltage was plotted on Weibull probability graph paper. The Weibull probability distributions of a.c. voltage breakdown stress are given in Figs. 35 to 38 for cable aged 1 week and in Figs. 39 to 42 for cable aged 26 weeks. The data is presented in summarized form as part of Table 7 and is used to establish the voltage stress-time to breakdown relationship (Fig. 56) for this cable.

7.2.1 Measurement of A.C. Voltage Breakdown of Aged XLPE Model Cable After Drying

A portion of the XLPE model cable that was aged for 26 weeks and then dried for 13 weeks in accordance with the procedure explained in Section 7.1.1 was subjected to a.c. voltage breakdown and the data plotted and analyzed as explained in Section 4.5.

Fig. 35

Model Cable Aged 1 Week
A.C. Breakdown Test Results (1 Minute Steps)

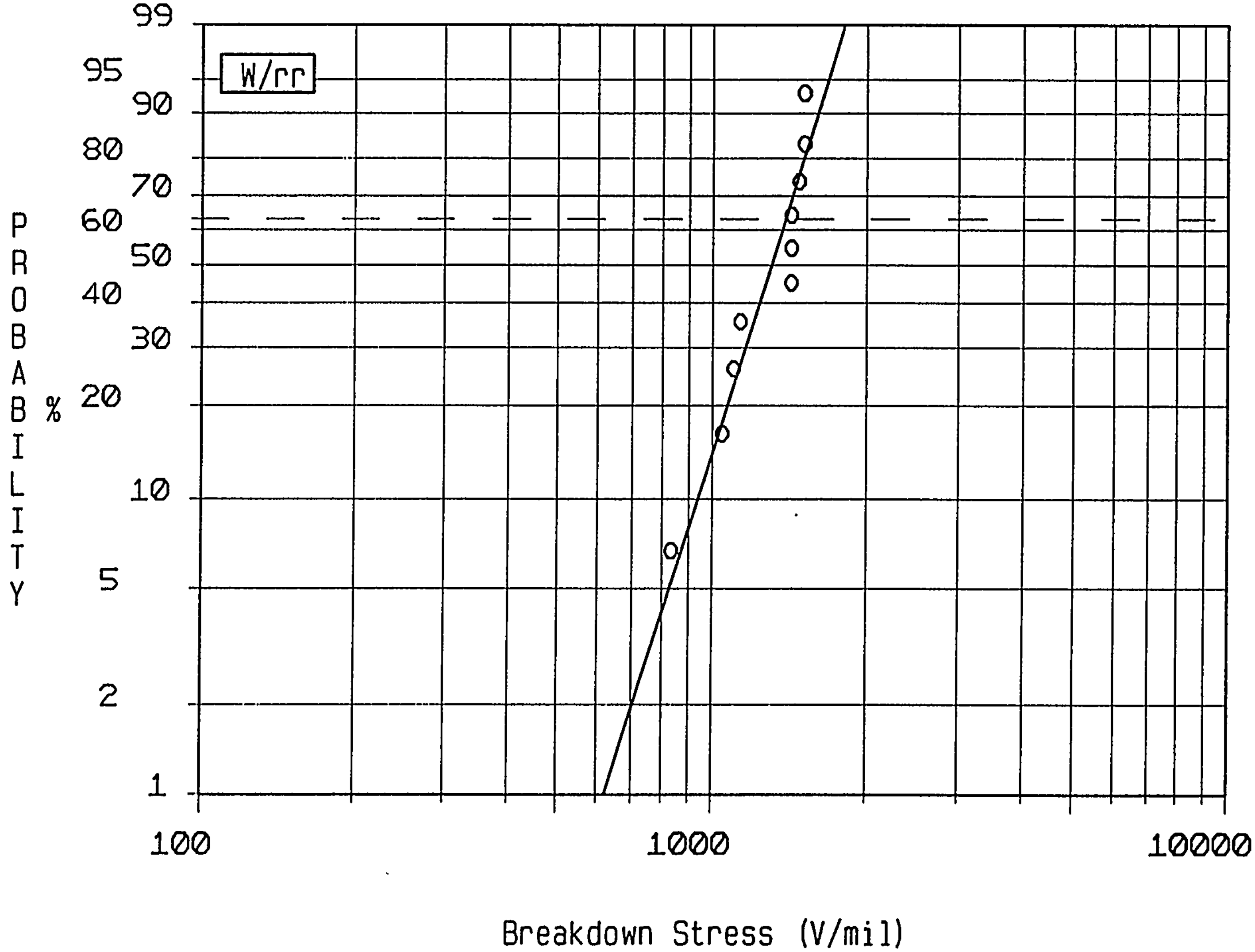


Fig. 36

Model Cable Aged 1 Week
A.C. Breakdown Test Results (5 Minute Steps)

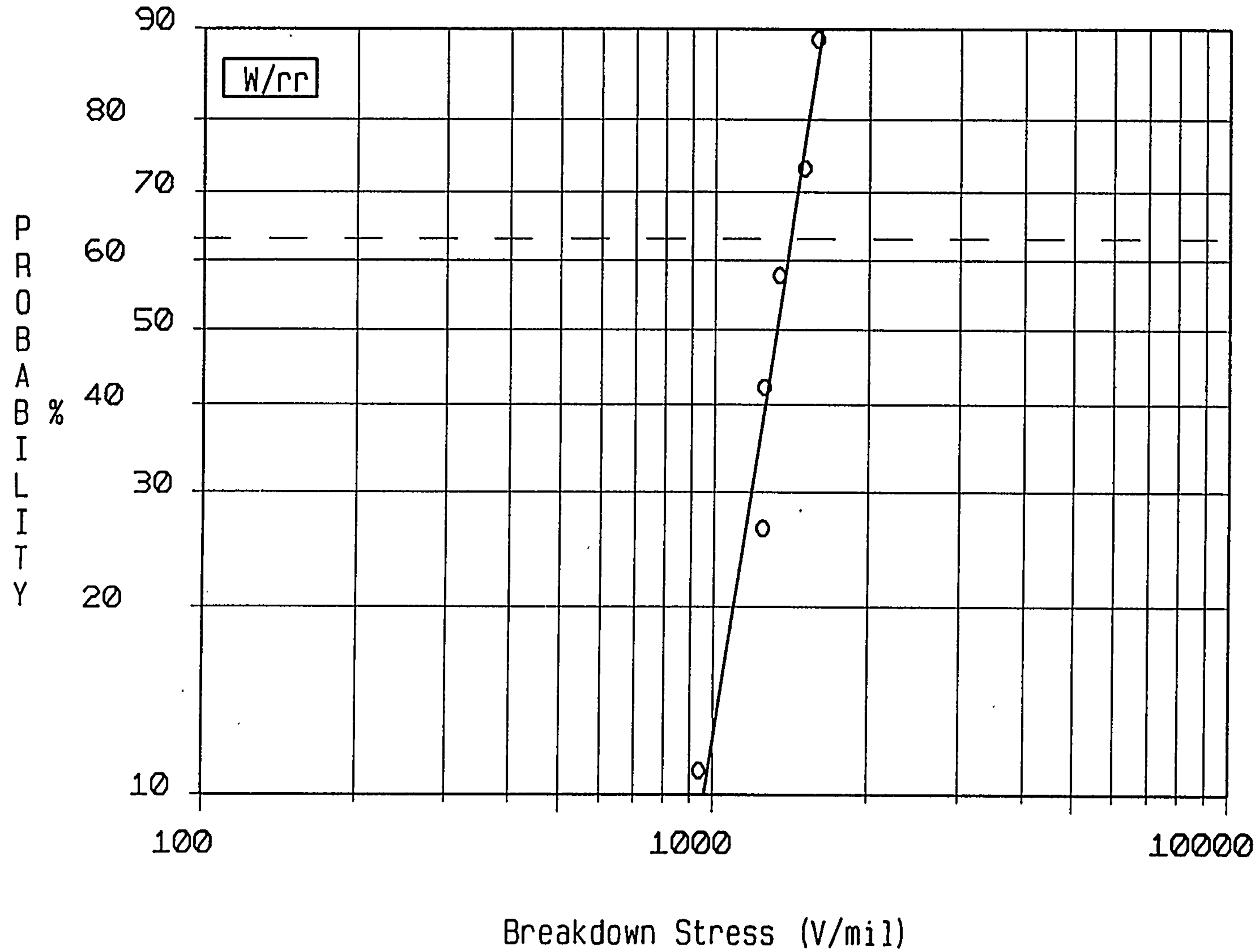


Fig. 37

Model Cable Aged 1 Week
A.C. Breakdown Test Results (1 Hour Steps)

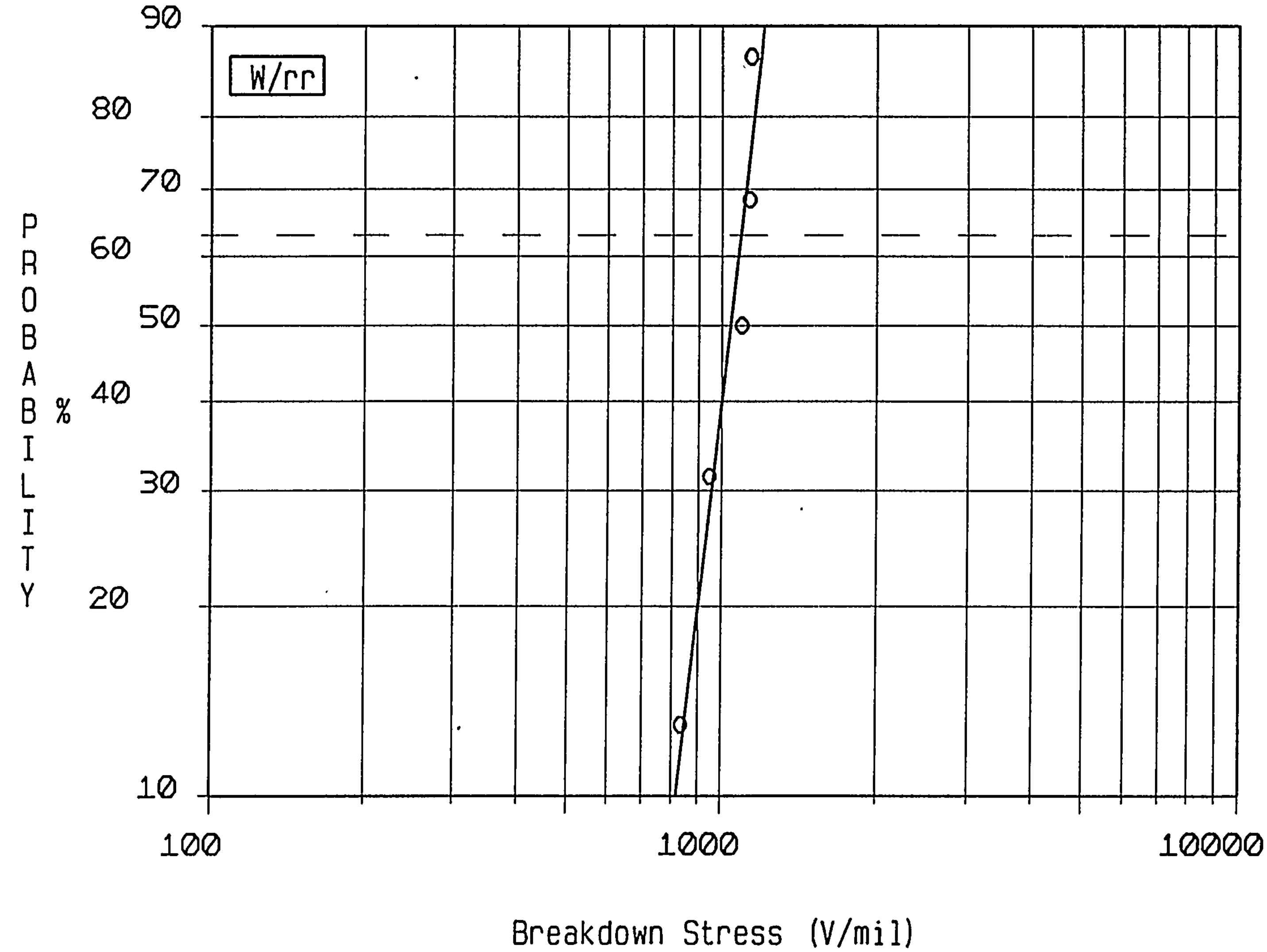


Fig.38

Model Cable Aged 1 Week
A.C. Breakdown Test Results (16 Hour Steps)

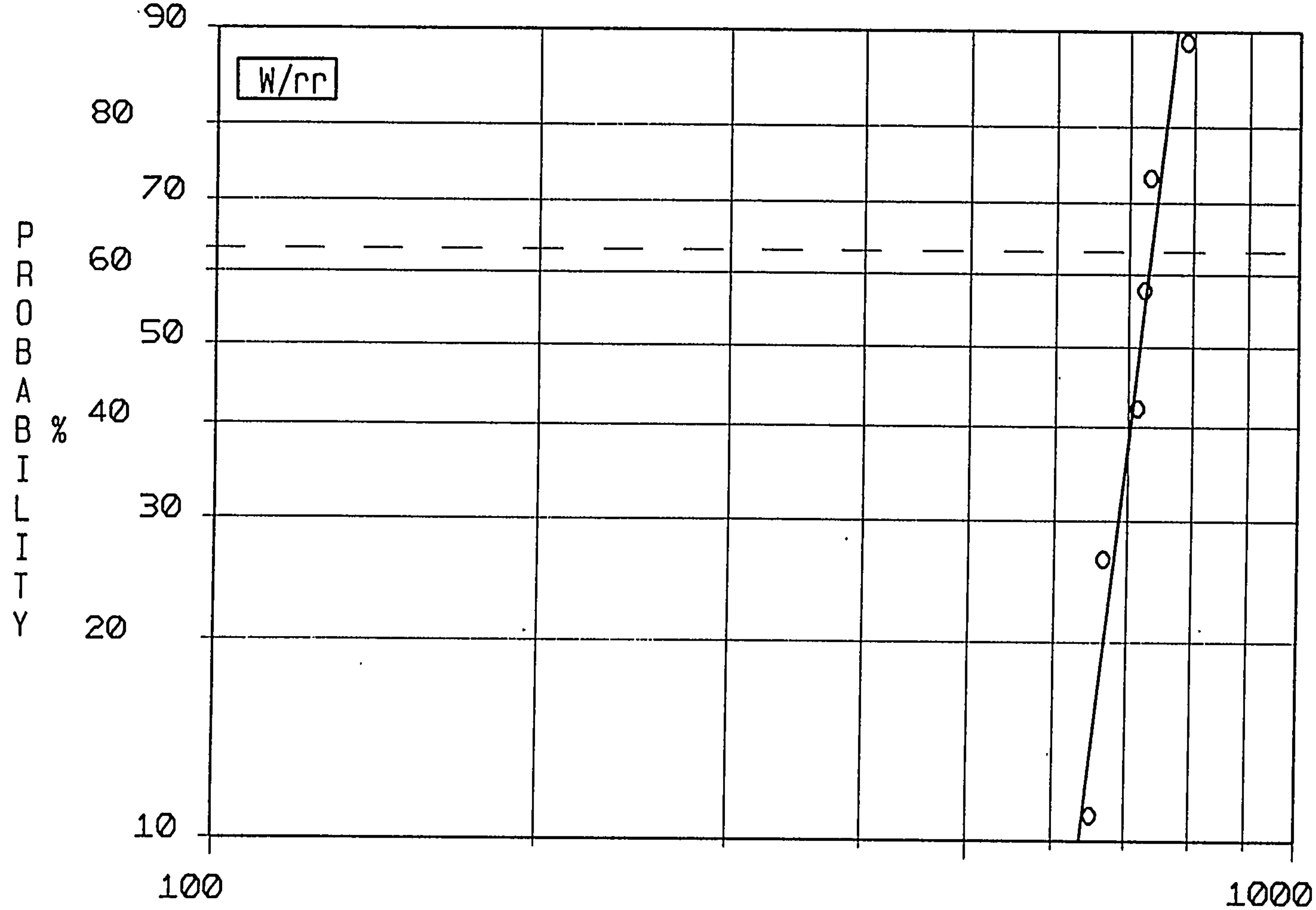


Fig. 39

Model Cable Aged 26 Weeks
A.C. Breakdown Test Results (1 Minute Steps)

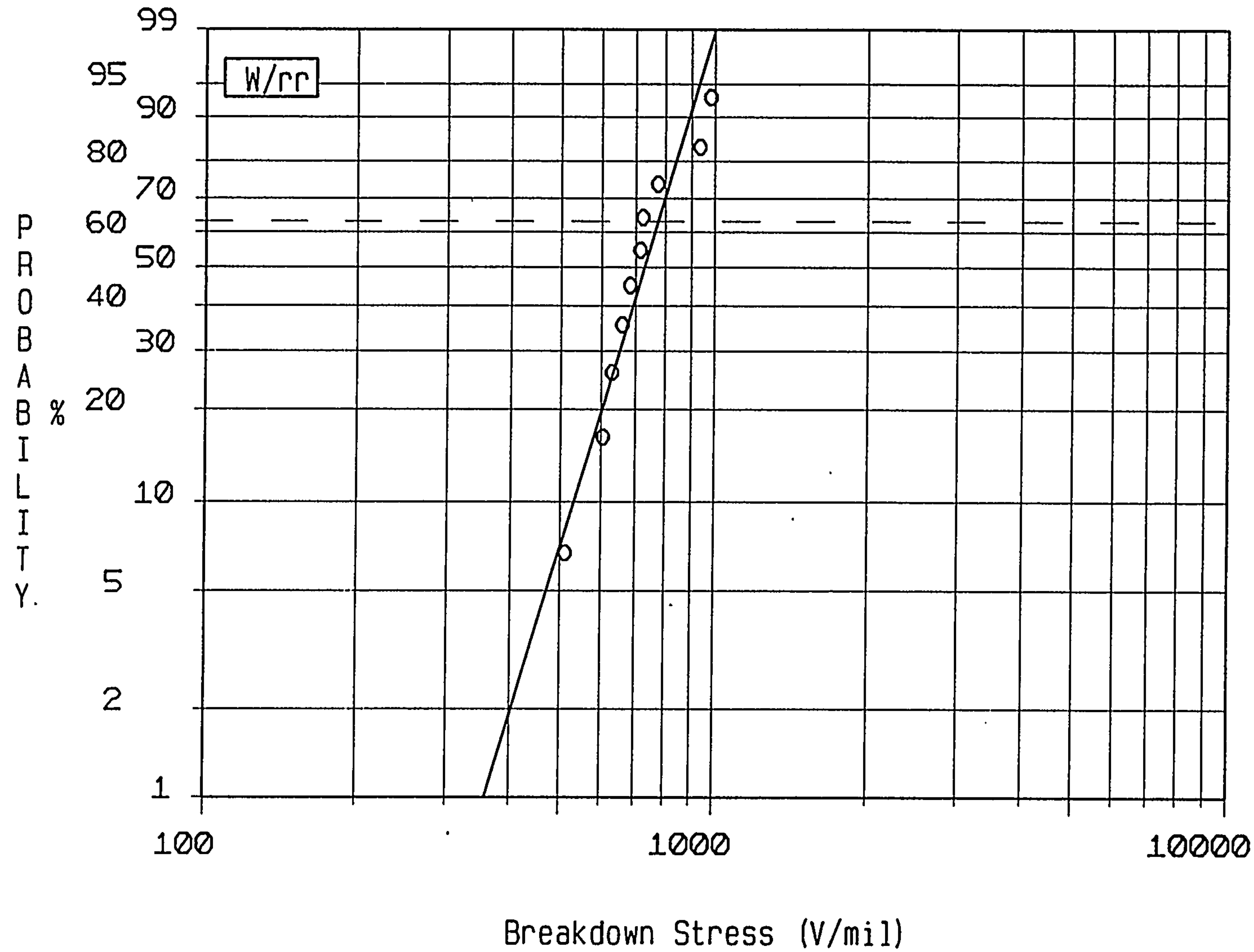


Fig. 40

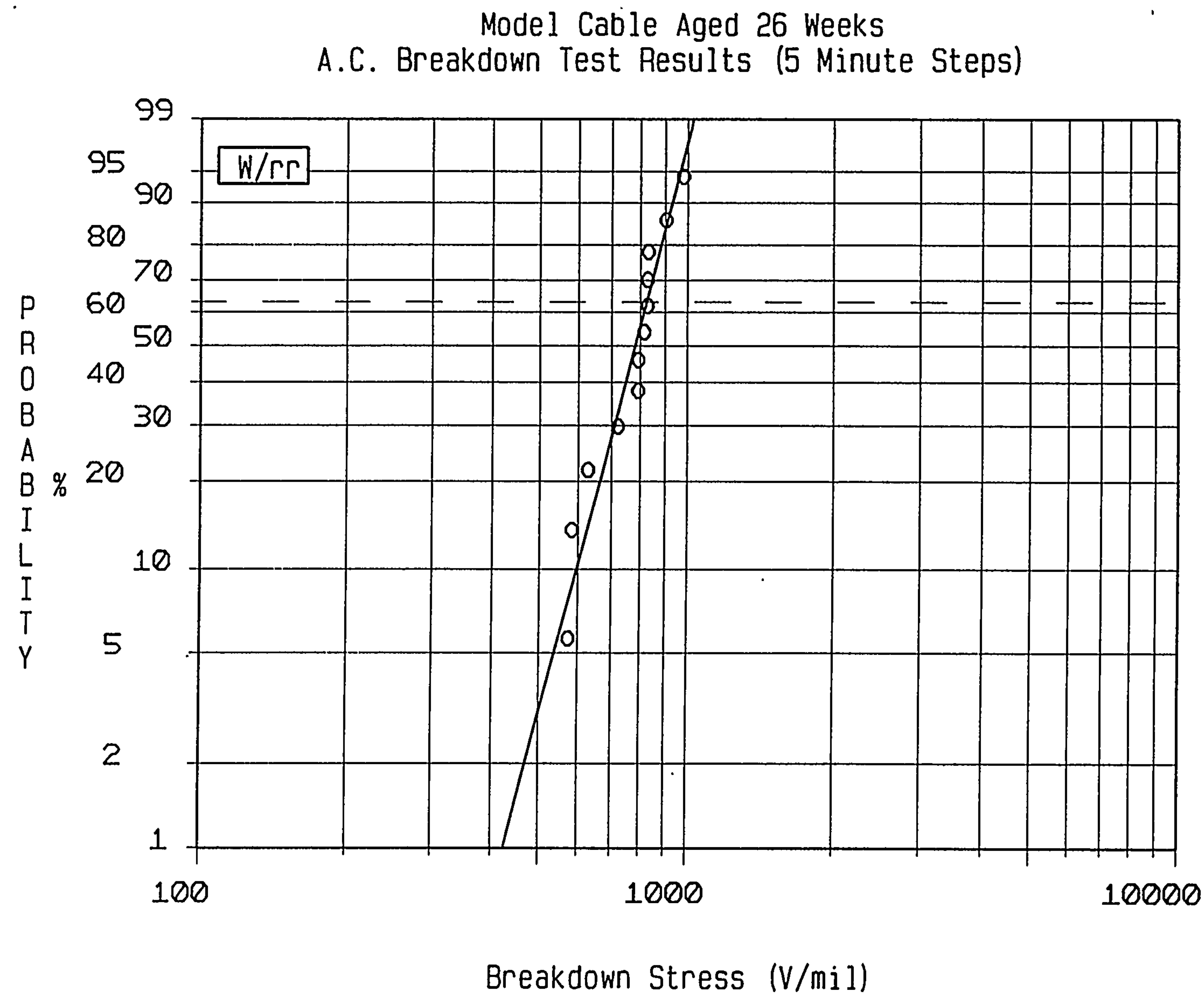

Model Cable Aged 26 Weeks
A.C. Breakdown Test Results (5 Minute Steps)
W/rr
PROBABILITY %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
10000
Breakdown Stress (V/mil)

Fig. 41

Model Cable Aged 26 Weeks
A.C. Breakdown Test Results (1 Hour Steps)

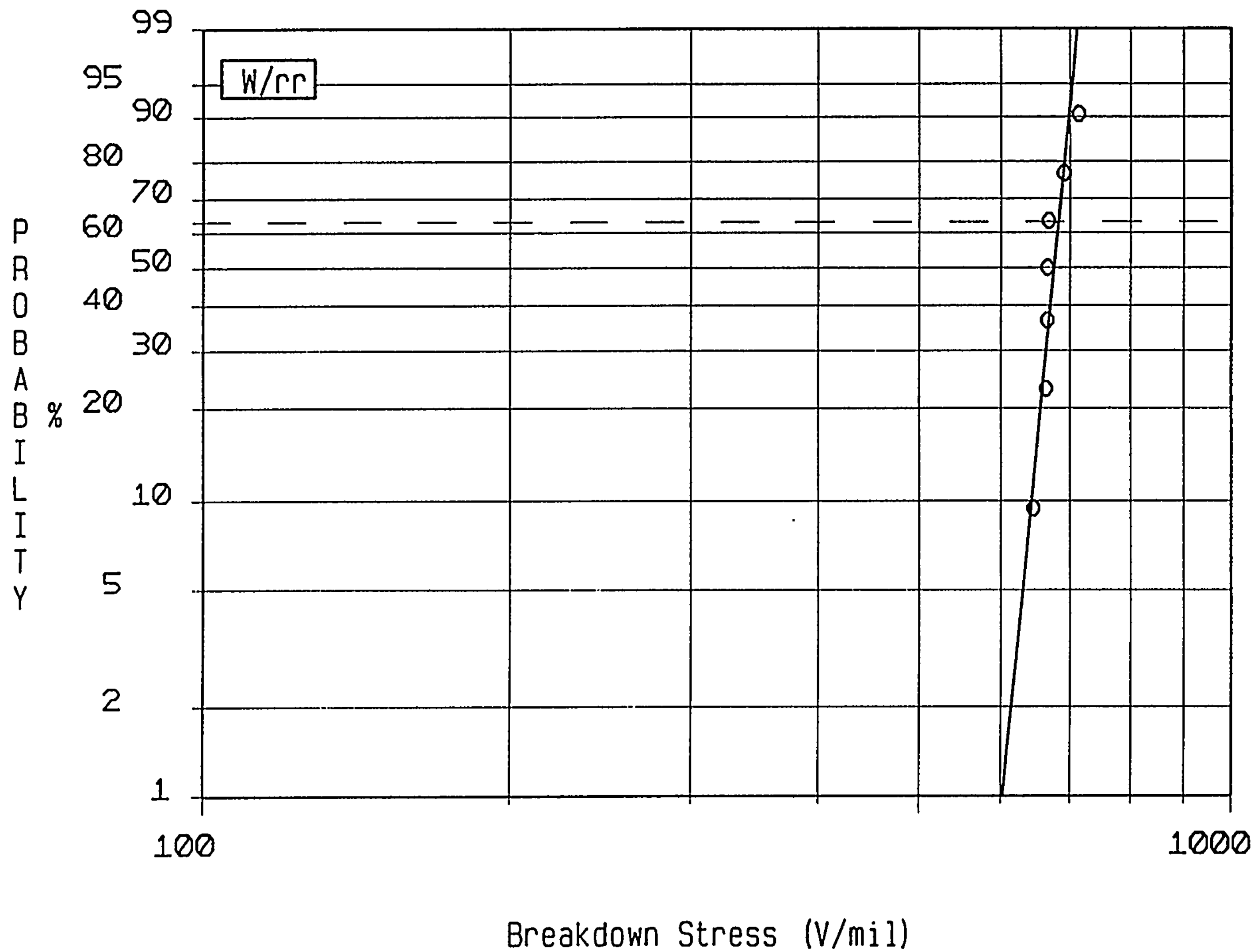
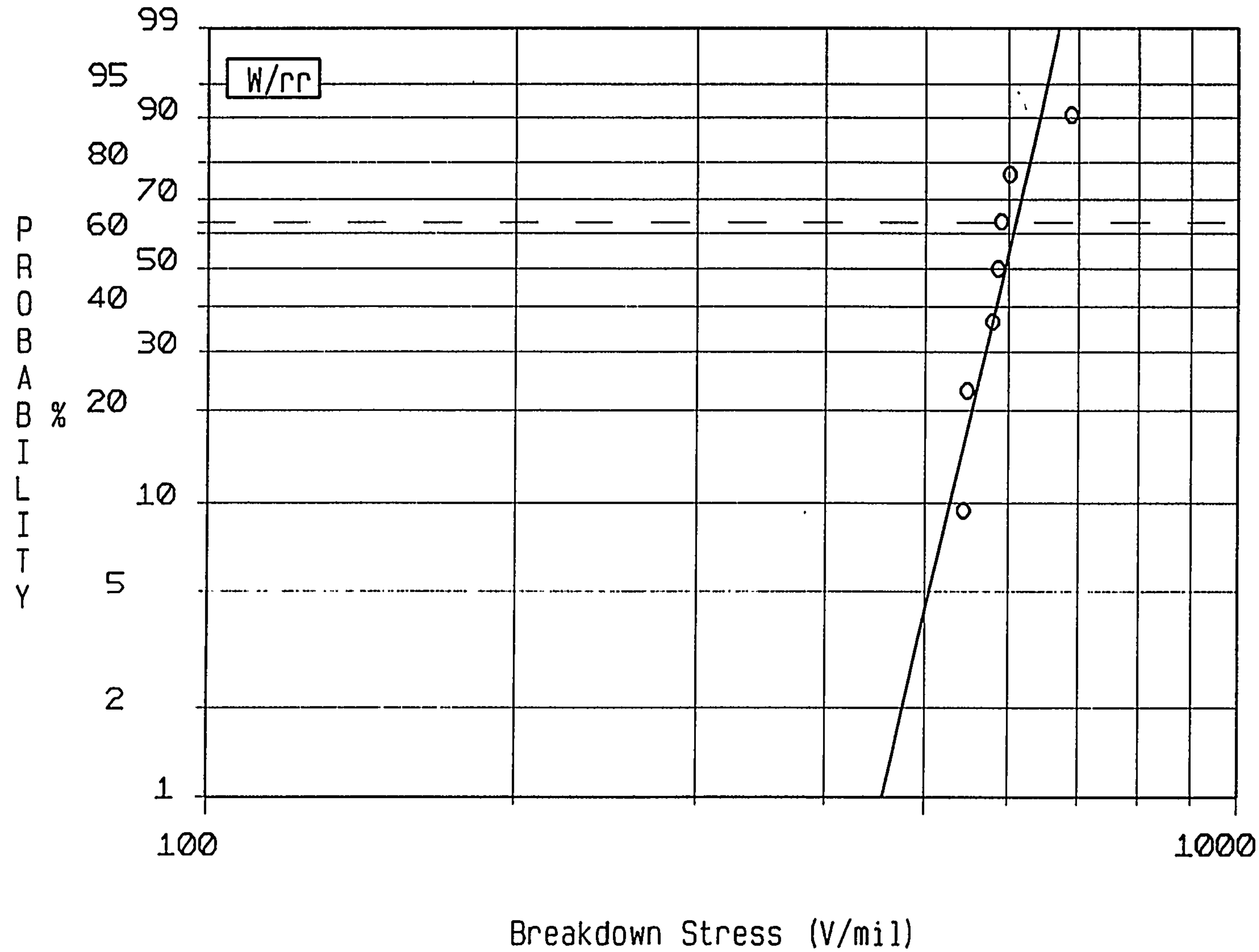


Fig. 42

Model Cable Aged 26 Weeks
A.C. Breakdown Test Results (16 Hour Steps)



The Weibull probability distributions of a.c. voltage breakdown stress are given in Figs. 43 and 44 for 1 and 5 minute steps. Comparing this data with similar data on the 26 weeks aged cables (Figs. 35 and 36) demonstrate the effectiveness of drying cable to increase its dielectric strength and thereby extend the life of the cable.

7.3 Measurement of Threshold Voltage Stress of Aged XLPE 15 kV Cable

The test and analysis procedures to establish threshold voltage were the same as described in Section 4.2. The Weibull probability distribution of impulse breakdown voltage and of impulse breakdown voltage stress for different levels of d.c. pre-stressing are given in Figs. 45 to 50 for cable aged 26 weeks. The tests were conducted at ambient temperature.

The dependence of impulse, breakdown voltage stress on the d.c. pre-stressing voltage is shown in Fig. 51.

7.4 Measurement of A.C. Breakdown of Aged XLPE 15 kV Cable

The a.c. breakdown tests were conducted at ambient temperature. The length of the sample tested was 10 feet. The step voltage procedure was used and the voltage was

Fig. 43

Model Cable Aged 26 Weeks & Dried
A.C. Breakdown Test Results (1 Minute Steps)

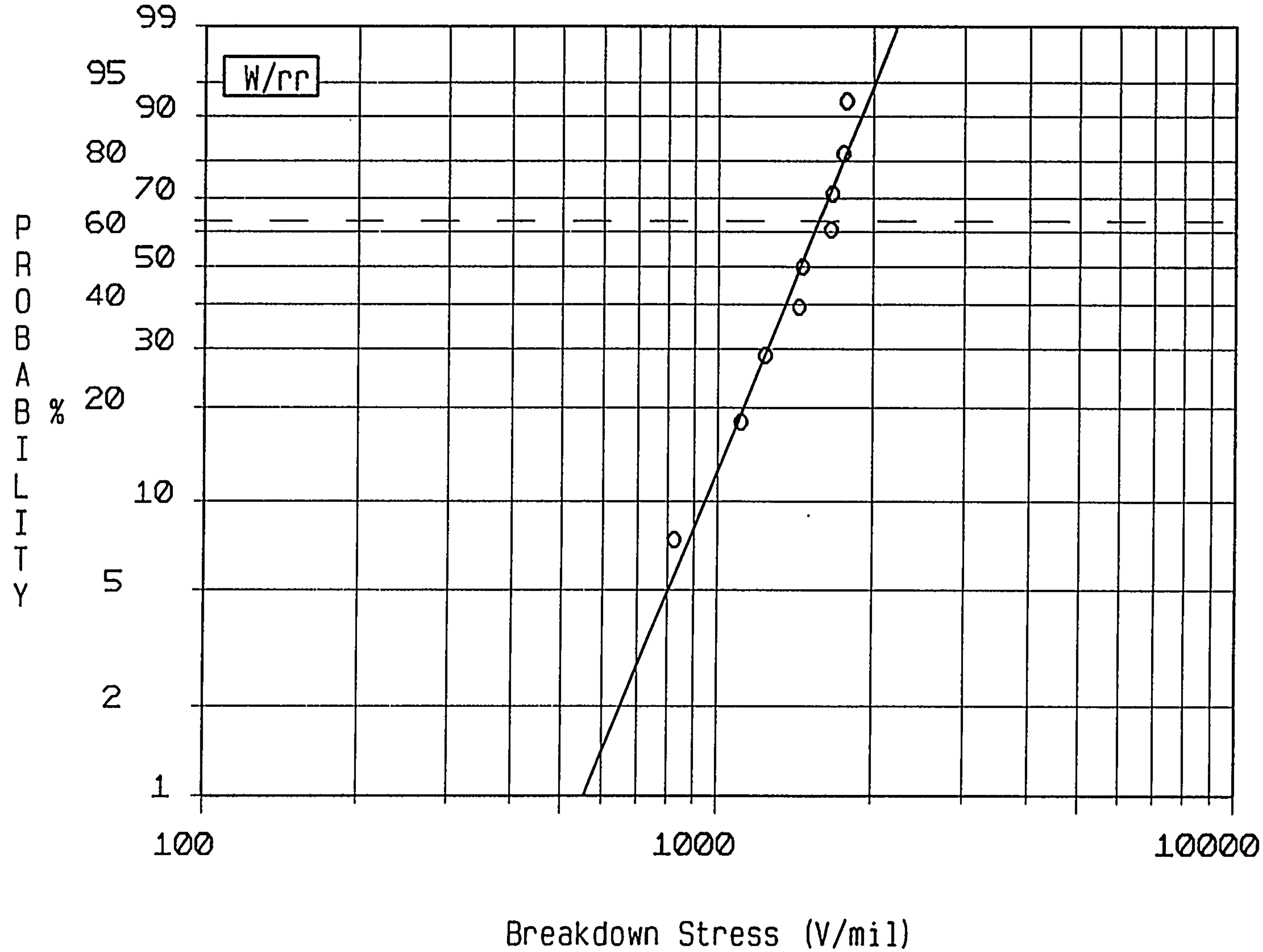


Fig. 44

Model Cable Aged 26 Weeks & Dried
A.C. Breakdown Test Results (5 Minute Steps)

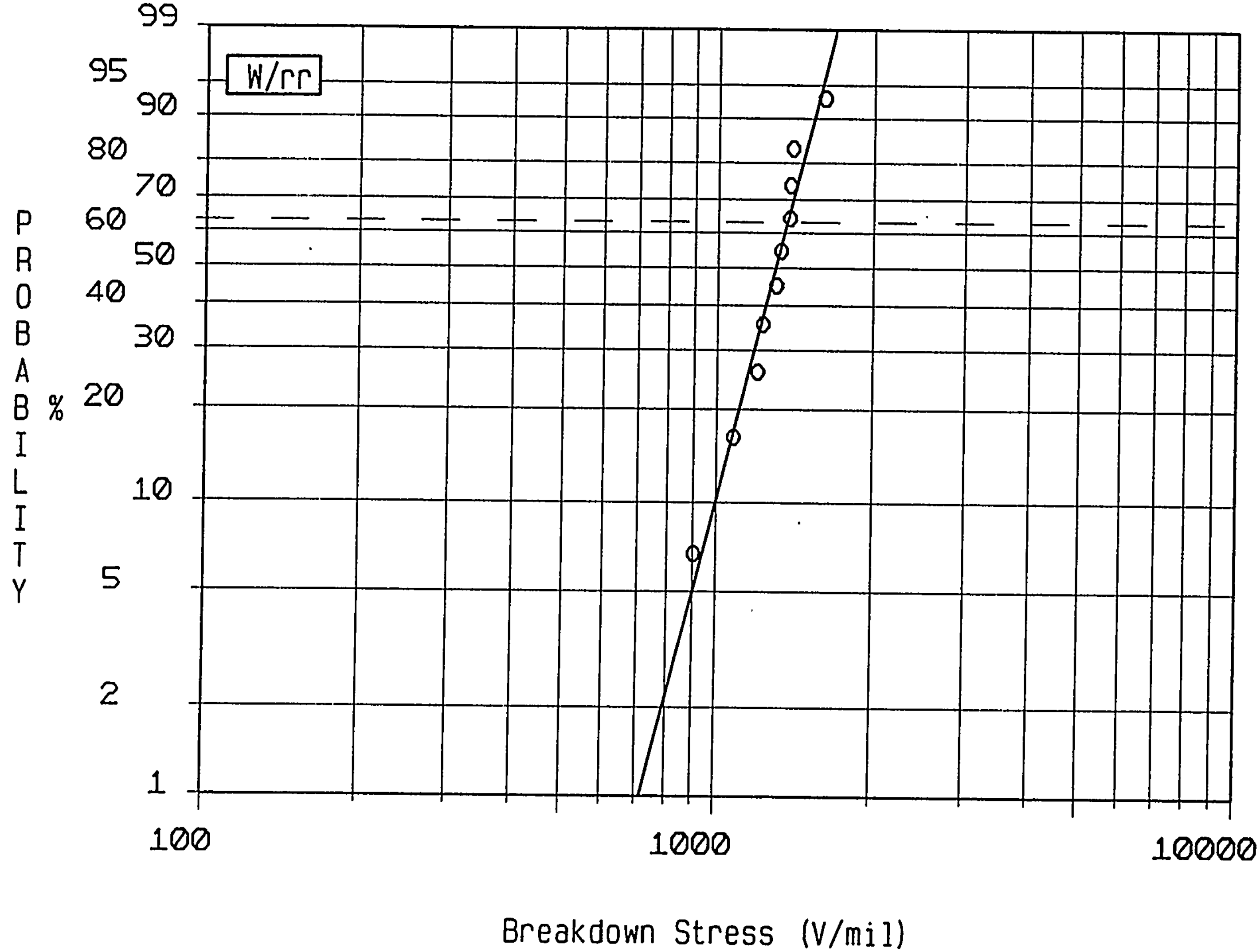


Fig. 45

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results

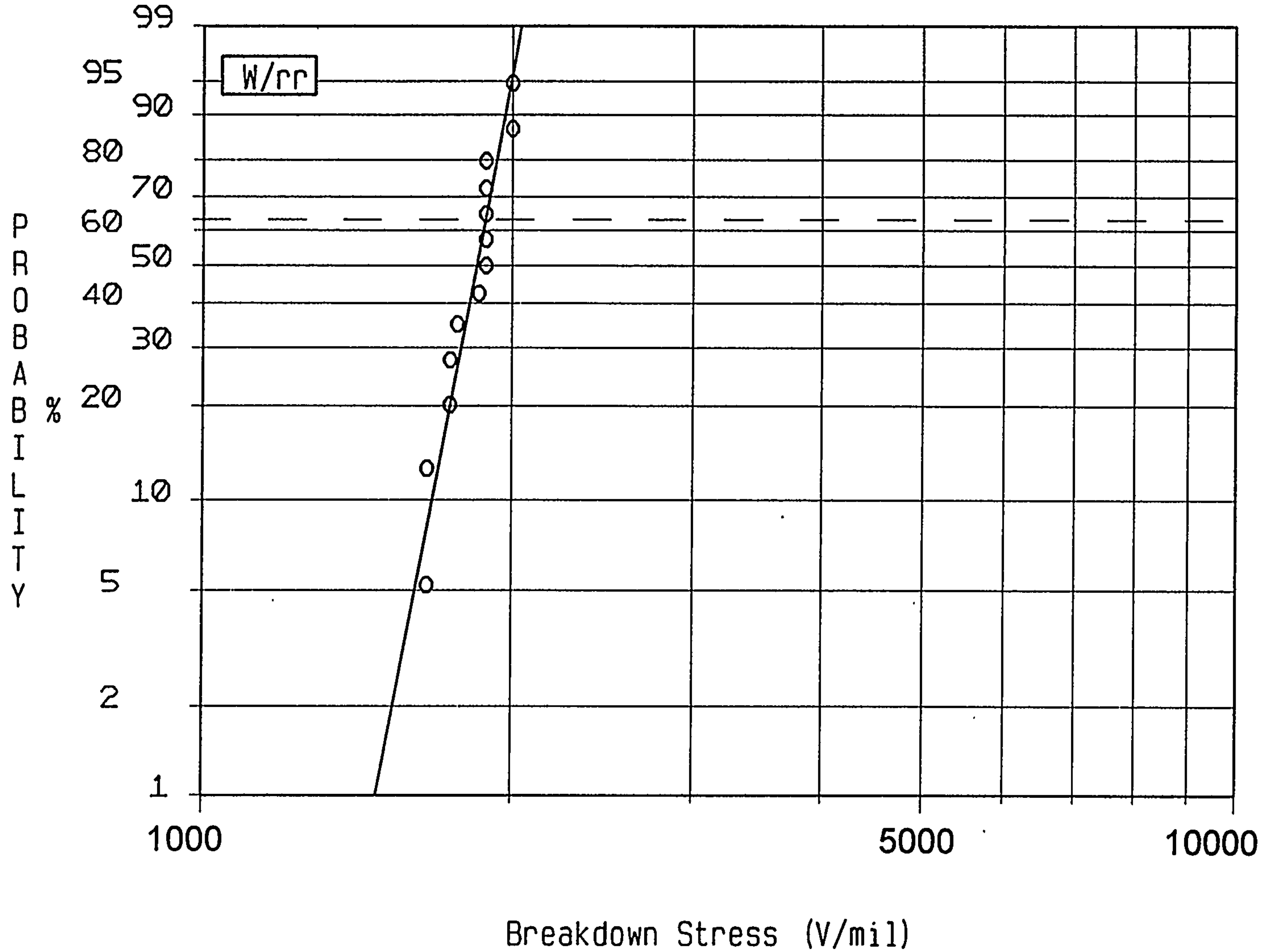


Fig. 46

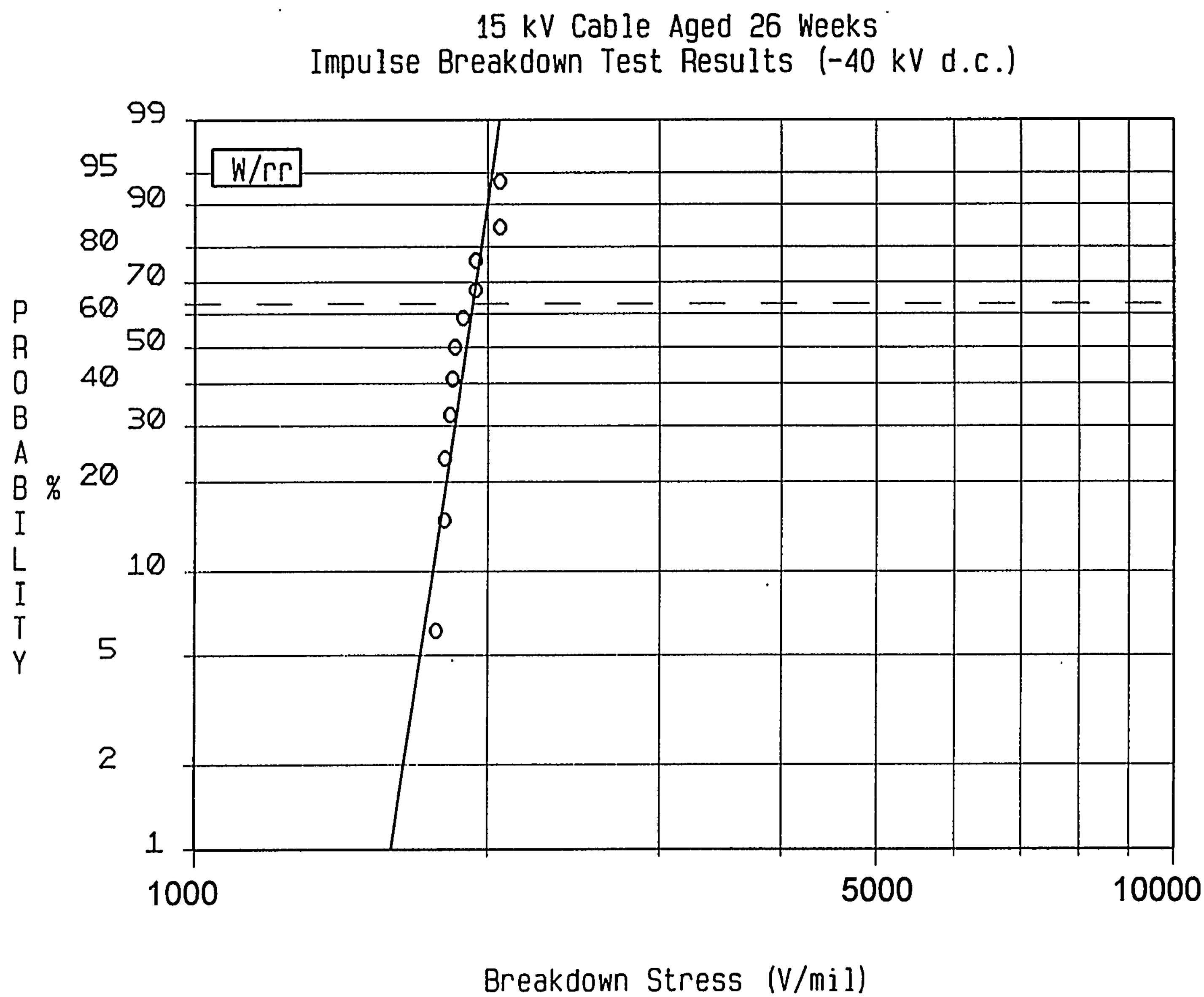

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results (-40 kV d.c.)
W/rr
PROBABILITY %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
1000
5000
10000
Breakdown Stress (V/mil)

Fig. 47

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results (-60 kV d.c.)

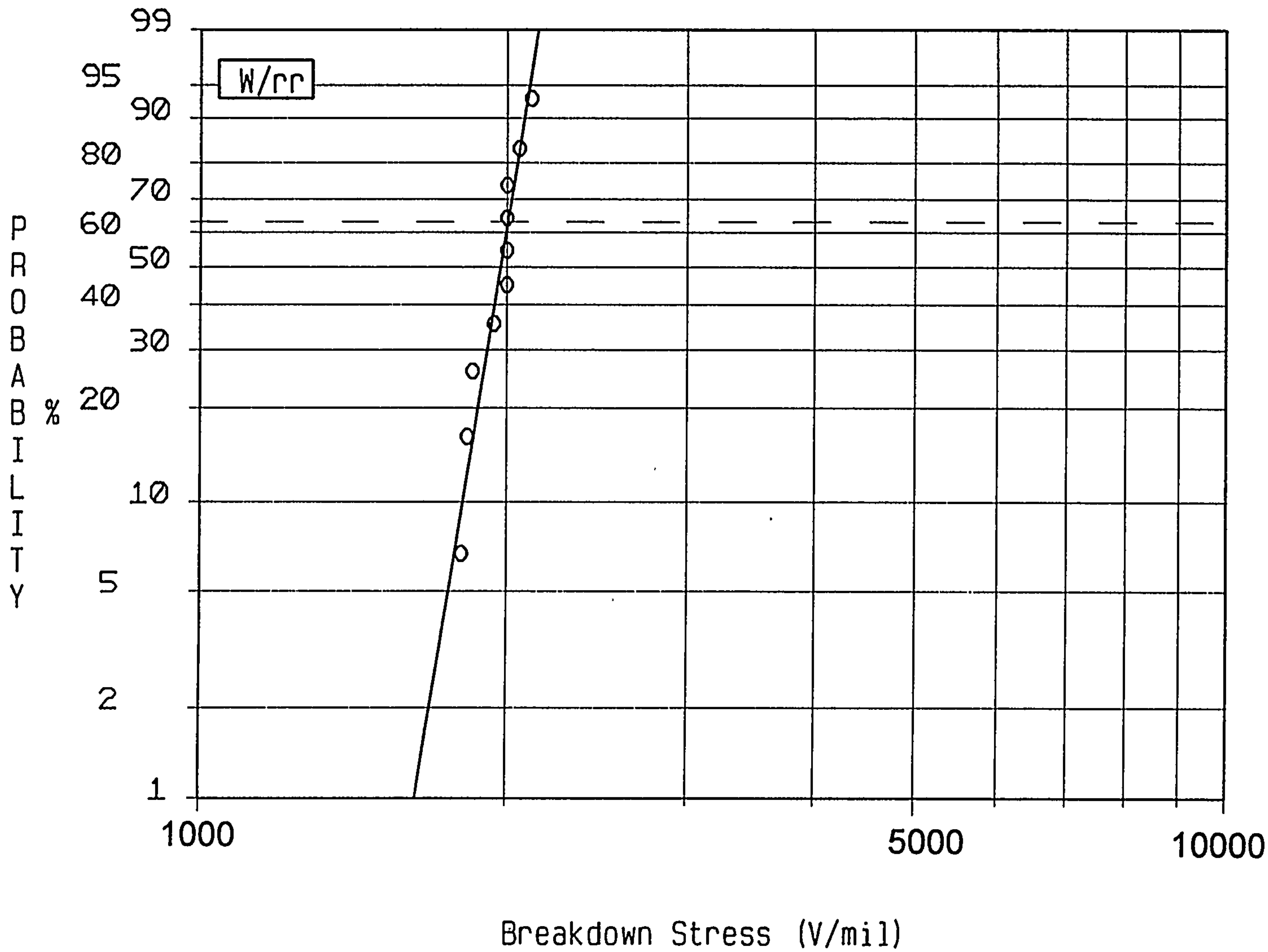
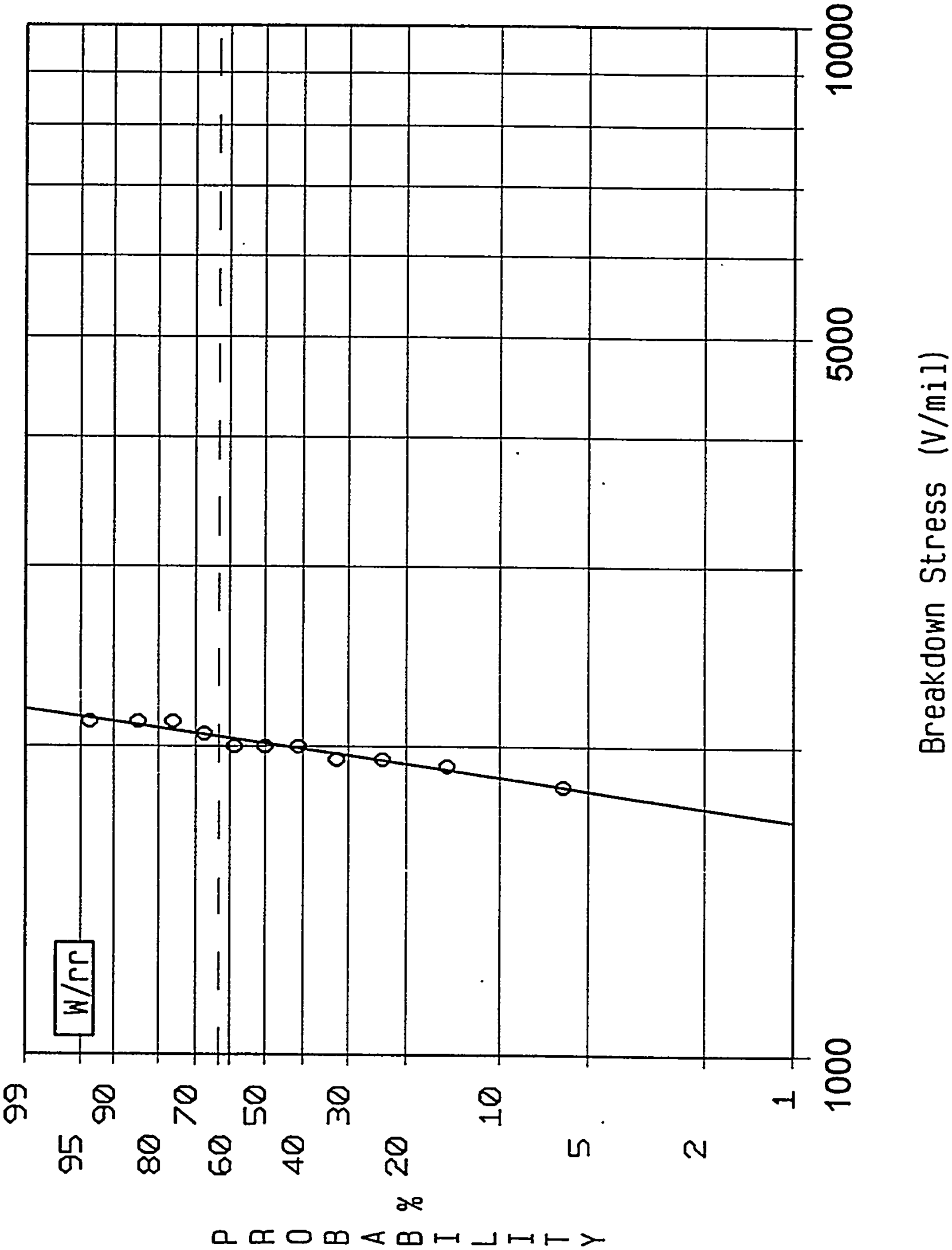


Fig. 48

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results (-80 kV d.c.)



It is assumed that the inverse power law applies for the time-span of aging that the XLPE model cable was tested.

$$C = E^n t \quad \text{(Inverse power law)}$$

where: E = voltage stress applied between conductor and ground

t = time voltage is applied until breakdown

n = voltage endurance coefficient, assumed constant

C = a constant for each type of insulation

Figure 56 shows the time to breakdown for different magnitudes of a.c. voltage applied to the XLPE model cable. When the voltage breakdown stress falls below a certain level the cable's useful life is ended.

As may be expected the cable aged for 26 weeks in water has a shorter projected remaining life than the projected life of the cable aged for only one week.

The voltage endurance coefficient "n" has been calculated by putting the measured values of a.c. breakdown stress at various times in the inverse power law and assuming "C" to be a constant value. It appears that the value for "n" of 12 fits the data reasonably well.

10.0 CONCLUSIONS

- The results of dual polarity impulse tests on XLPE cable aged in water show a significant drop in threshold voltage stress with time of aging.

- The threshold voltage stress in terms of a.c. voltage was found to be 70 V/mil (rms) for the XLPE model cable and 42 V/mil (rms) for the XLPE 15 kV cable after aging in water. Since most XLPE 15 kV cable operate at approximately 50 V/mil when in service this indicates partial discharges may occur in XLPE cables while in service.

- The results of dual polarity impulse tests on XLPE model cable aged in water and subsequently dried by flushing the conductor with dry gas show a marked increase in threshold voltage. This increase occurs because the flushing process removes moisture from the insulation of the cable. It was found that drying increased the threshold voltage stress from 70 V/mil to 597 V/mil a.c. (rms).

- The results indicate that drying a XLPE cable while in service can extend its life. Distribution cables rated up to 35 kV operate at 32 to 58 V/mil, depending on the rated cable voltage. Aging of XLPE cables in this project reduced the threshold voltage down to the range of 42 to 70 V/mil which overlaps the operating voltage range. The results show that drying increases the threshold voltage between 8 and 9 times which should eliminate partial discharges, thereby extending cable life.

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2. Determination of Threshold and Maximum Operating Stress for Selected High Voltage Insulations, DOE/RA/50156-61 - Progress Report No. 2.

3. Determination of Threshold and Maximum Operating Stress for Selected High Voltage Insulations, DOE/RA/50156-61 - Progress Report No. 3.

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6. Department of Energy, Evaluation of the Economical and Technological Viability of Various Underground Transmission Systems for Long Feeds to Urban Load Areas, Report HCP/7-2055/1, December 1977.

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8. "Basic Study of Transient Breakdown Voltage of Solid Dielectric Cables." Final Report DOE/ET/29303-1.

9. Dakin, T.W., and Studniarz, S.A. "The Voltage Endurance of Cast and Molded Resins." (In Electrical/Electronics Insulation Conference, 13th, Chicago, 1977. Proceedings. New York, Institute of Electrical and Electronics Engineers, 1977. pp. 318-21).

10. Pattini, G. and Simoni, L. "Discussion on Modeling of Voltage Endurance." (In International Symposium on Electrical Insulation, 3d, Boston, 1980. Conference record. New York, Institute of Electrical and Electronics Engineers, 1980. p.15).

Fig. 49

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results (-100 kV d.c.)

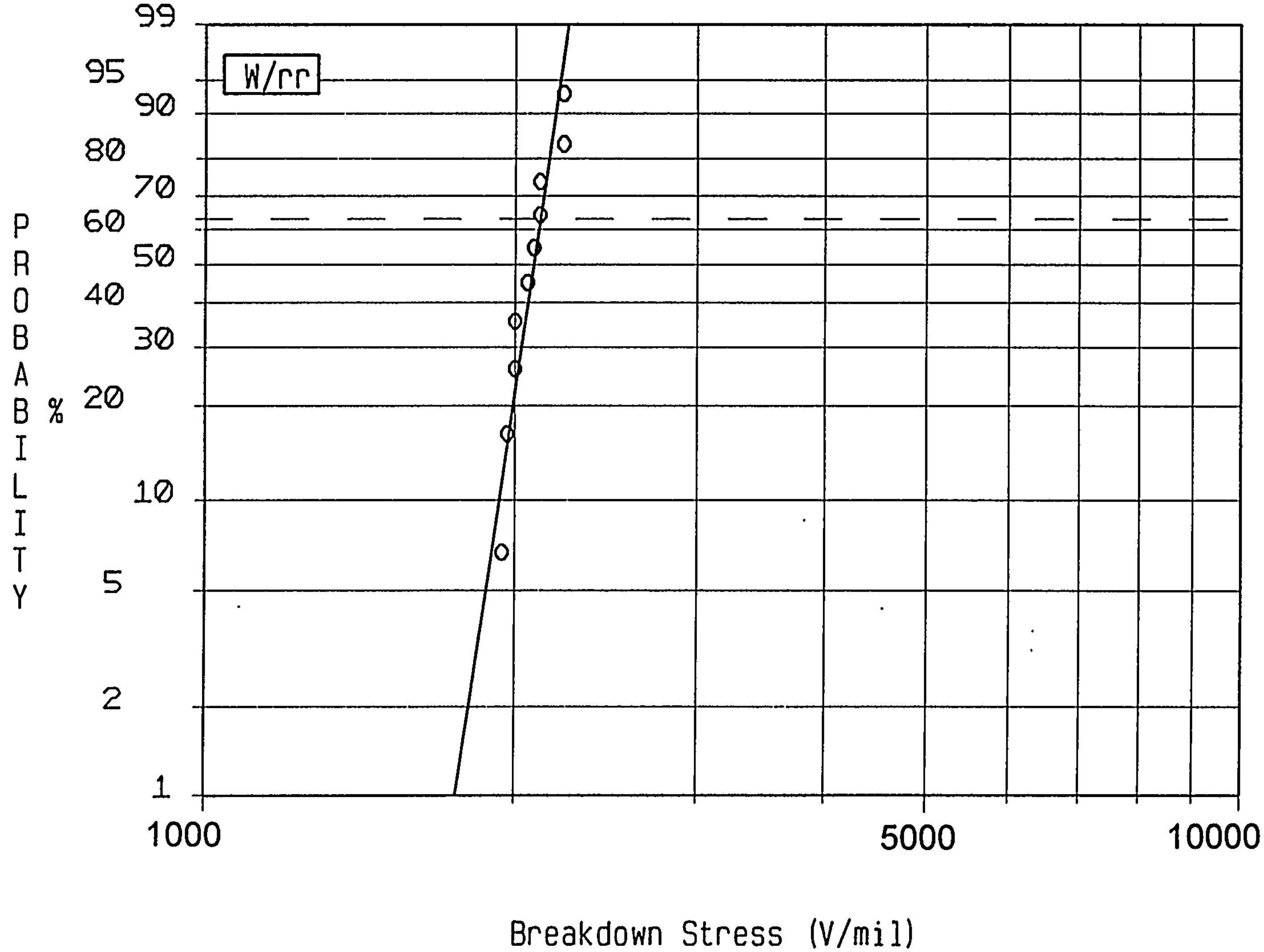
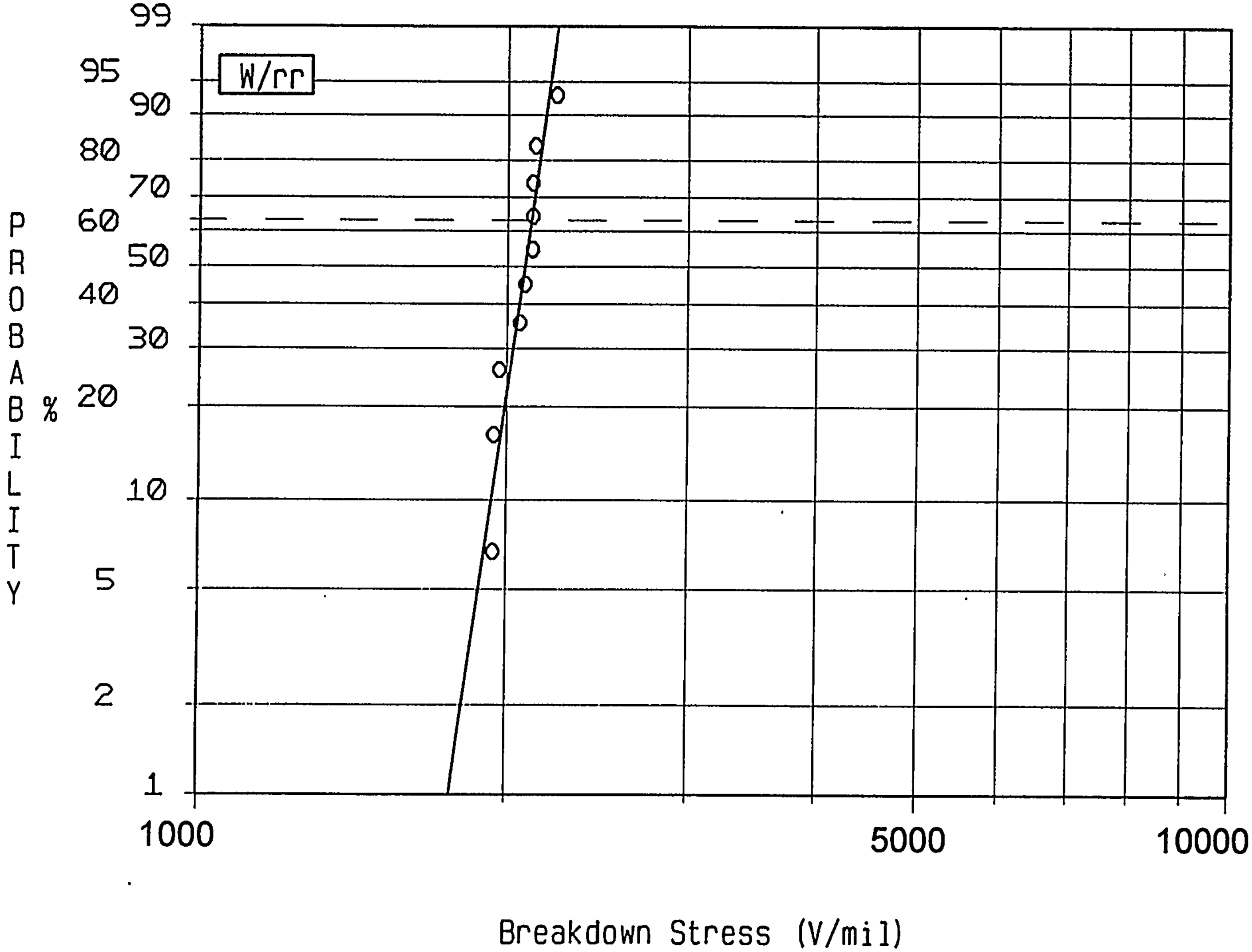


Fig.50

15 kV Cable Aged 26 Weeks
Impulse Breakdown Test Results (-150 kV d.c.)



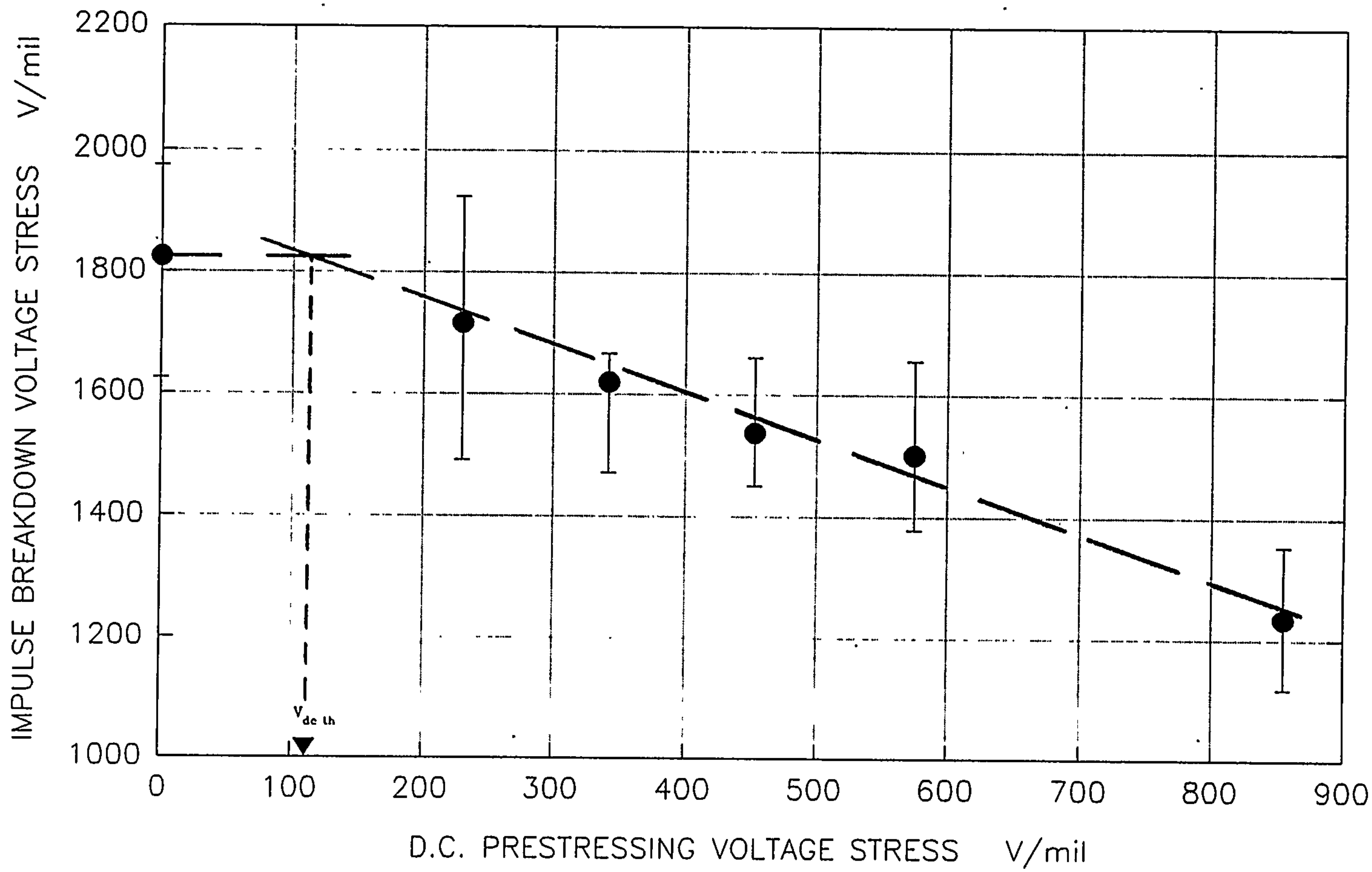


Fig. 51 Determination of Threshold Voltage Stress of XLPE 15 kV Cable Aged 26 Weeks.

increased 10% at each 1 minute step. The initial voltage was about 50% of the expected breakdown value. The breakdown voltage was plotted on Weibull probability graph paper. The Weibull probability distribution of a.c. voltage breakdown stress is given in Fig. 52. Comparing this data with data presented in Fig. 17 (before aging) two effects can be noted: a) the large decrease in breakdown strength over the 26 weeks of aging and b) the increased spread of the individual breakdown strength data.

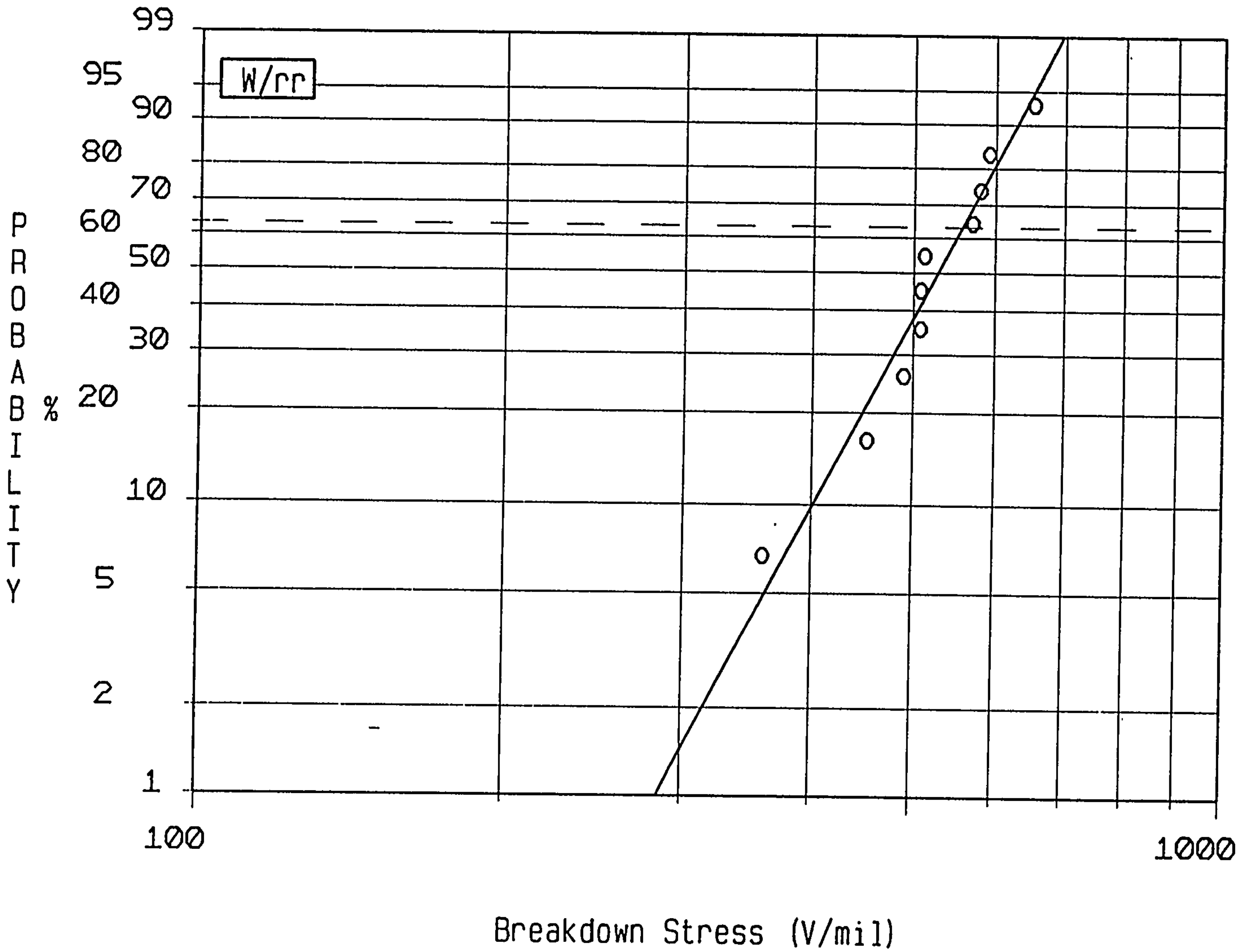
8.0 MEASUREMENT OF D.C. BREAKDOWN OF XLPE MODEL CABLE

Similar to a.c. breakdown tests, determinations were made at ambient temperature. The initial voltage was applied at about 50 percent of the expected breakdown level and the voltage was increased in 10 percent steps each one minute, until breakdown. Tests were conducted on approximately 10 different cable samples. Negative polarity was placed on the conductor.

Tests were conducted after the XLPE model cable was aged 1 and 26 weeks; and after it was aged 26 weeks and dried for 13 weeks by passing dry nitrogen through the conductor interstices.

Fig. 52

15 kV Cable Aged 26 Weeks
A.C. Breakdown Test Results (1 Minute Steps)



The breakdown voltage was plotted on Weibull probability graph paper. The Weibull probability distribution of d.c. voltage breakdown stress is given in Figs. 53, 54 and 55.

9.0 DISCUSSION

9.1 XLPE Model and 15 kV Cables

The measurements show the dependence of both the a.c., d.c. and impulse breakdown voltage stress and the threshold voltage stress on the presence of moisture in the cable. The original value of all four parameters are lowered by the presence of water and the reduction increased with time of aging in water. Table 5 shows the correlation of these parameters as the XLPE model cable aged.

When the moisture in the XLPE model insulation is removed by drying the measurements show that the dual polarity threshold voltage, and the a.c. and impulse voltage stresses are significantly restored. The recovery of the impulse voltage stress is virtually complete.

Less data were taken on the XLPE 15 kV commercial cable but the findings were similar to those found with the XLPE model cable. Table 6 shows that both the a.c. and impulse breakdown voltage stress and the dual polarity threshold

Fig. 53

Model Cable Aged 1 Week
D.C.Breakdown Test Results

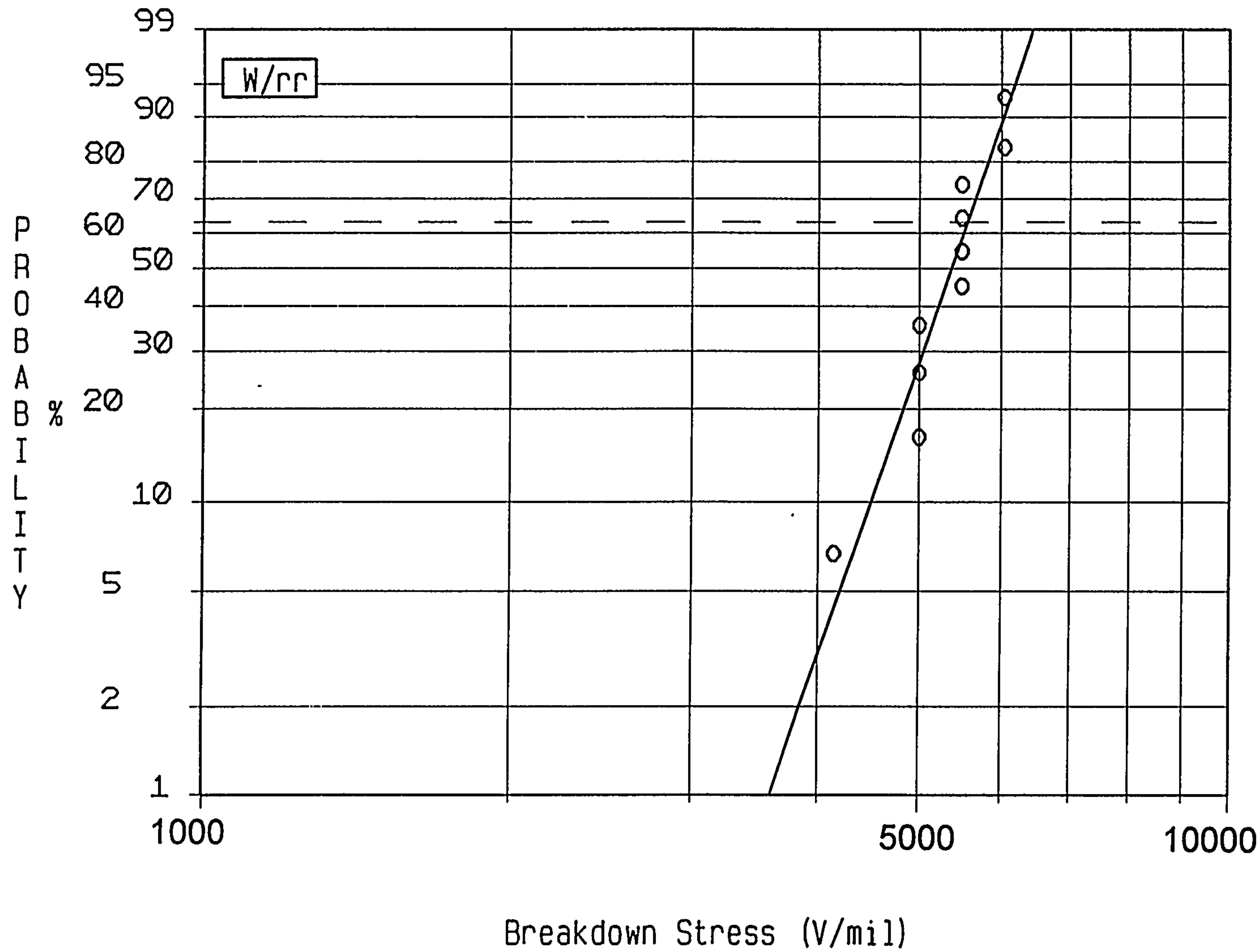


Fig. 54

Model Cable Aged 26 Weeks
D.C. Breakdown Test Results

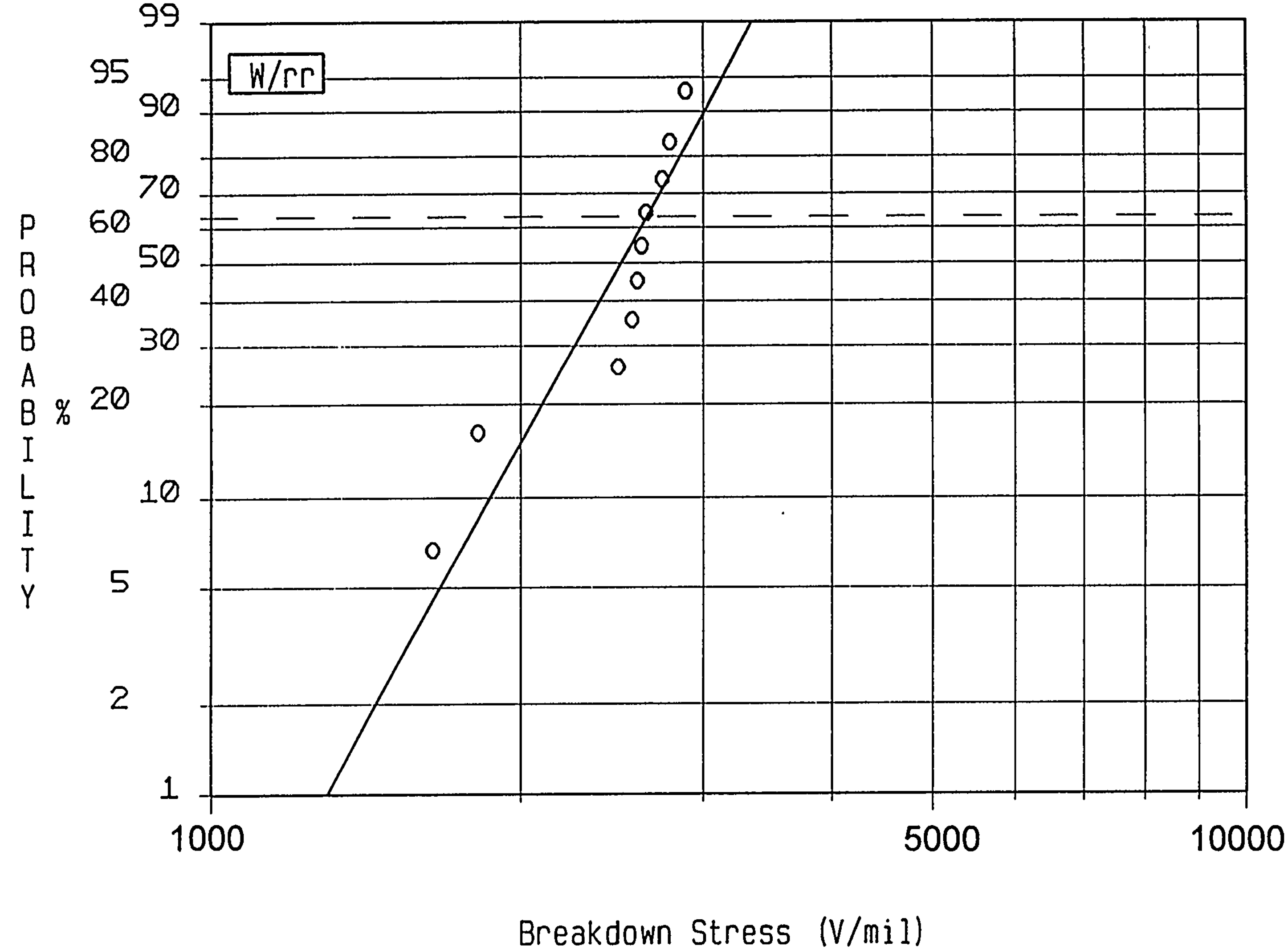


Fig. 55

15 kV Cable Aged 26 Weeks & Dried
D.C. Breakdown Test Results

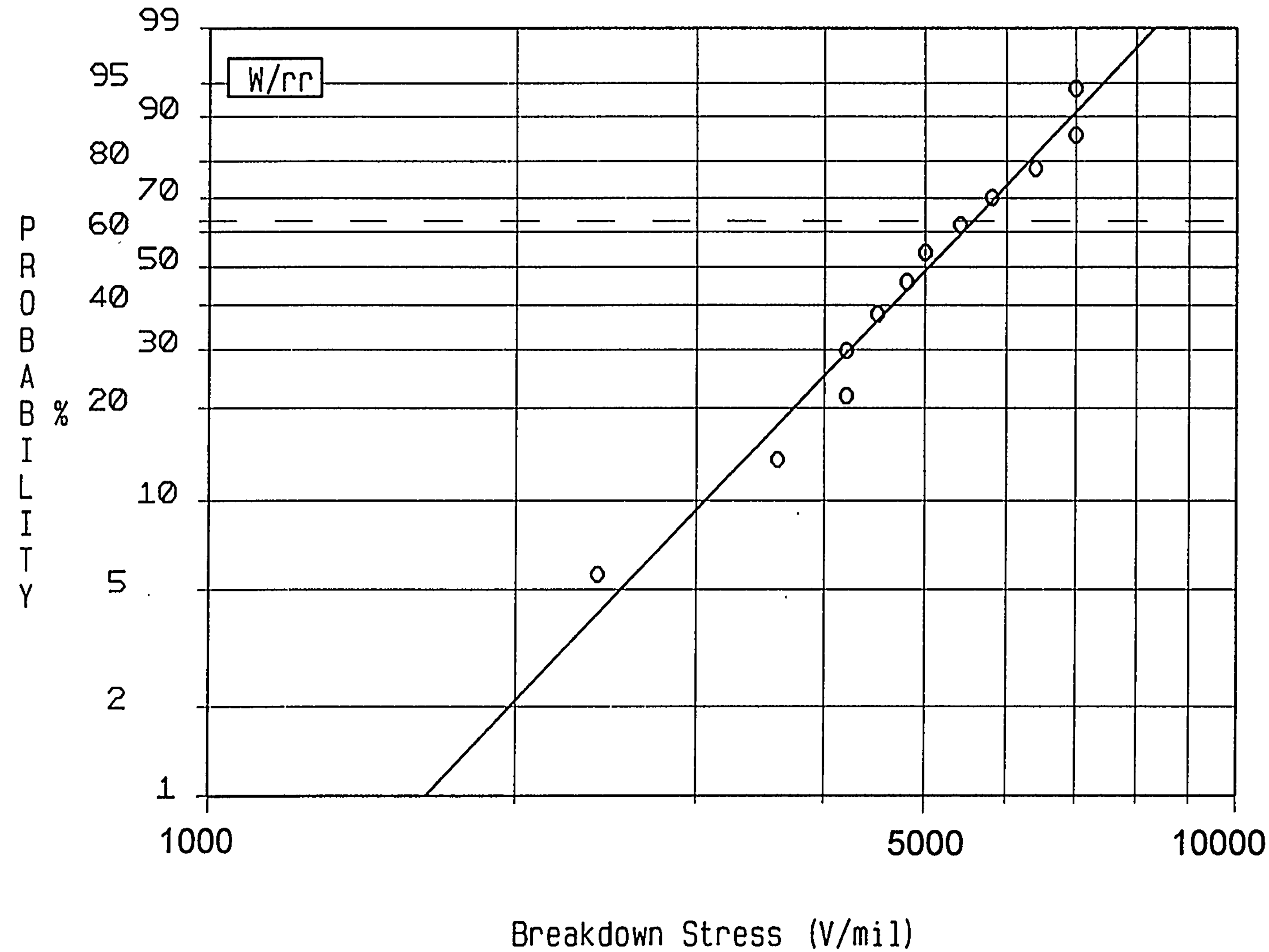


TABLE 5

THRESHOLD VOLTAGE STRESS OF XLPE MODEL CABLE

COMPARED TO A.C. AND IMPULSE BREAKDOWN STRESS

Aging Time Week	Threshold Voltage			Breakdown Voltage			
	Dual Polarity		A.C. (rms)	A.C. (1 min.step)		Impulse	
	V/mil	%	V/mil	V/mil	%	V/mil	%
0	2900	100	1020	1730	100	4710	100
1	1000	35	350	1380	80	3570	76
26	200	7	70	770	44	2600	55
26 Plus Drying	1690	58	600	1570	90	4350	92

Note. Cable aged in water at voltage stress 175 V/mil.

TABLE 6

THRESHOLD VOLTAGE STRESS OF XLPE 15 KV CABLE

COMPARED TO A.C. AND IMPULSE BREAKDOWN STRESS

Aging Time Week	Threshold Voltage			Breakdown Voltage			
	Dual Polarity		A.C. (rms)	A.C. (1 min.step)		Impulse	
	V/mil	%	V/mil	V/mil	%	V/mil	%
0	1800	100	640	1610	100	2940	100
26	120	7	40	540	34	1880	64

Note. Cable aged in water at voltage stress 150 V/mil.

voltage stress are reduced by aging the cable in water.

The data on the aged XLPE model cable show that the dual polarity threshold voltage decreases with cable aging more than the a.c. and impulse voltage breakdown strength implying that the cable becomes more sensitive to partial discharges and thereby to degradation by ionization.

For the tested cable, the a.c. voltage breakdown decreases with cable aging more than the impulse voltage breakdown. This indicates that the impulse breakdown voltage is less sensitive than the a.c. voltage breakdown to changes caused by aging XLPE cable in water.

One objective of this project was to establish the relation between the breakdown voltage and the time of voltage application for aged XLPE cable. In order to accomplish this objective impulse and a.c. voltage step breakdown tests were conducted as indicated in Tables 2 and 3. The a.c. voltage steps for 1, 5, 60 minutes and 16 hours were used to determine the breakdown voltages at these times. The impulse voltage breakdown was used to determine the breakdown voltage at the micro-second range. Table 7 and Figure 56 show the data obtained for the XLPE model cable after 1 week and after 26 weeks aging.

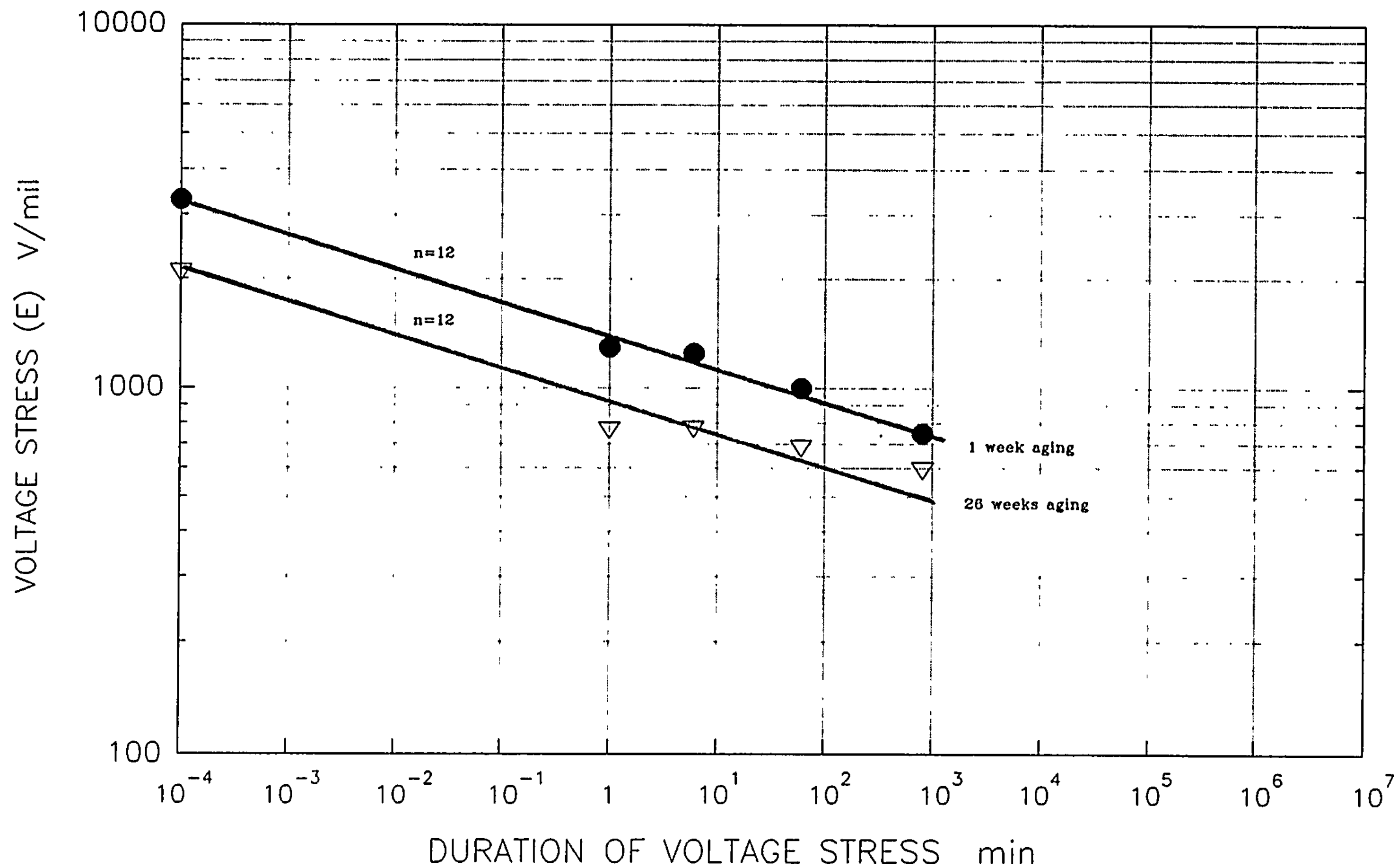
TABLE 7

A.C. VOLTAGE BREAKDOWN OF AGED XLPE MODEL CABLE AT DIFFERENT TIMES OF VOLTAGE APPLICATION

Time of Aging Week	A.C. Voltage Step Time (t) minutes	Equivalent A.C. Voltage Stress (E) Applied Continuously V/mil
Unaged	1	1730
1	1	1380
1	5	1410
1	60	1090
1	960	730
26	1	770
26	5	820
26	60	680
26	960	610
26+ drying*	1	1570
26+ drying*	5	1360

*By flow of nitrogen and current heating. See Section 6.0

Figure 56
BREAKDOWN VOLTAGE OF AGED XLPE MODEL CABLE
AT DIFFERENT TIMES OF VOLTAGE APPLICATION



DOE6

It is assumed that the inverse power law applies for the time-span of aging that the XLPE model cable was tested.

$$C = E^n t \quad \text{(Inverse power law)}$$

where: E = voltage stress applied between conductor and ground

t = time voltage is applied until breakdown

n = voltage endurance coefficient, assumed constant

C = a constant for each type of insulation

Figure 56 shows the time to breakdown for different magnitudes of a.c. voltage applied to the XLPE model cable. When the voltage breakdown stress falls below a certain level the cable's useful life is ended.

As may be expected the cable aged for 26 weeks in water has a shorter projected remaining life than the projected life of the cable aged for only one week.

The voltage endurance coefficient "n" has been calculated by putting the measured values of a.c. breakdown stress at various times in the inverse power law and assuming "C" to be a constant value. It appears that the value for "n" of 12 fits the data reasonably well.

10.0 CONCLUSIONS

- The results of dual polarity impulse tests on XLPE cable aged in water show a significant drop in threshold voltage stress with time of aging.

- The threshold voltage stress in terms of a.c. voltage was found to be 70 V/mil (rms) for the XLPE model cable and 42 V/mil (rms) for the XLPE 15 kV cable after aging in water. Since most XLPE 15 kV cable operate at approximately 50 V/mil when in service this indicates partial discharges may occur in XLPE cables while in service.

- The results of dual polarity impulse tests on XLPE model cable aged in water and subsequently dried by flushing the conductor with dry gas show a marked increase in threshold voltage. This increase occurs because the flushing process removes moisture from the insulation of the cable. It was found that drying increased the threshold voltage stress from 70 V/mil to 597 V/mil a.c. (rms).

- The results indicate that drying a XLPE cable while in service can extend its life. Distribution cables rated up to 35 kV operate at 32 to 58 V/mil, depending on the rated cable voltage. Aging of XLPE cables in this project reduced the threshold voltage down to the range of 42 to 70 V/mil which overlaps the operating voltage range. The results show that drying increases the threshold voltage between 8 and 9 times which should eliminate partial discharges, thereby extending cable life.

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