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WATER TREEING AS A CAUSE
OF POLYETHYLENE POWER CABLES REPEATED FAILURES

1. Introduction

It has been known from in service experiences that presence of mois-
ture in contact with various types of insulation can greatly accelerate
its deterioration [1, 2]. The extent of insulation deterioration occurs
because of water treeing, independently on species of polyethylene (ther-
moplastic, crosslinked) and kind of cable construction. Water treeing
have been found to cause premature cable failure [3, 4]. It has been also
observed that after first failure, irrespective of its cause, there are
other successive break-downs after some months in service [5, 6]. Labora-
tory tests has been performed to explain this phenomenon.

2. Environmental exposure of cable insulation under service and test
conditions

There are some the most important factors affecting destructively on
polyethylene insulation under moist conditions:
    1) temperature, its gradient and fluctuation;
    2) electric field, its frequency and gradient;
    3) mechanical stress
    4) compounds dissolved in water.
Each of these factors exerts an influence on water treeing and this is
impossible to describe its interaction by theoretical way.
    Insulation temperature depends on conductor load current. This current
should be near to the rated one in a correct designed and used power line.
The natural temperature drop exist between conductor and outer insulation
layer under steady-state. The lengthwise temperature difference can be
observed in some particular cases too. Insulation temperature fluctuations
are caused by load current variations and environmental temperature char-

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ging. It has been assumed that the operating temperature of thermoplastic polyethylene cable insulation should not exced 70°C, and 150°C under short-circuit conditions near by inner conductor as well as 250°C near by outer one.

Electrical stress is practically constant in service and its average value for Polish cables varies from 1.4 MV/m at rated voltage 3.6/6 kV to 2.25 MV/m at voltage 18/30 kV. This stress amounts to 1.7 MV/m and 2.6 MV/m respectively for maximum admissible power line operate voltage. Furthermore, we can observe overvoltages existence caused by switching processes or earth fault. Switching surge duration is too short (a few miliseconds) to make an influence on water treeing growth. Earth fault overvoltage, having longer duration (1-2 s) can involve some water treeing effect.

Electric field distribution in cable insulation depends on its geometry. Usualy we have a single-core polyethylene insulated cables with radial electric field distribution. Electric field gradient always exists in this kind of insulation form and its quantity depends on conductor diameter (cross-section). Electrical stress difference between inner and outer insulation layer doesn't exceed a few teens of percent for all rated conductor cross-sections (50÷625 mm²).

Electric field frequency is constant in service conditions. Mechanical stress may occur in some moments of cable life. The first and probably the most dangerous mechanical stress can be formed in insulation during cabling using too much bending and tensile forces. Microcracs made by this stresses will render under service insulation life. Moreover, mechanical stress may appear in cable insulation because of soil layer displacement especially in mining and urban area.

Chemical constitution of water which affects on polyethylene insulation is unknown. Undoubtedly, it is mineral compound solution rinsed out from soil and their concentration varies in every case.

3. Results

Basing on this analysis and previous experiences, insulation ageing program was elaborated. Ageing process consist of mechanical, electrical and thermal stresses. Thermal stress is produced by loading conductor current. Three current values have been selected to make three different insulation temperatures. Measured on the conductor shield it was respectively 36, 54 and 75°C for current 100, 180 and 270 A.

Other measured temperatures are shown in Table 1.

The maximum temperature value at this samples is near to the admissible operating temperature of thermoplastic polyethylene insulation.

T a b l e 1

Sample	Current	Temperature °C			
Nr	[A]	1	2	3	4
K8	100	36	34	31.9	35
K9	100	36.4	34.4	32.1	35.4
K3	180	54.2	46.1	43.5	50.2
K4	180	51.4	45.7	43.2	48.6
K7	180	53.8	46.5	43.6	50.2
K10	270	74.3	53	50.2	63.7
K11	270	74.8	52.6	50.6	63.7

Measuring points:
1 - conductor shield;
2 - insulation shield;
3 - covering jacket;
4 - average value be-
    tween 1 and 2 po-
    ints

The voltage applied during laboratory test had a value to generate o-
verage electrical stress:
- approximatively twice higher than maximum operating stress, namely
  4.4 MV/m,
- $\sqrt{3}$ times less then former one, namely 2.5 MV/m.
For this reasons, applied voltage had value respectively 20 and 12 kV.

Some tested cybles were exposed to overvoltages modelling earthing
process. This overvoltages were applied periodicaly twice an hour for
2 seconds, increasing voltage $\sqrt{3}$ times in relation to 20 kV. The increa-
sed overvoltage frequency in comparson to service conditions was applied
to intensify their influence on water treeing, if any.

Some samples were exposed to mechanical stress before voltage applying.
These stresses were produced by cable six-couple winding up around a drum
500 mm diameter. Two cables were stressed at 20°C a d te next one at 0°C
temperatures.

Polyethylene insulation was wet by putting distilated water or 0.3%
and 5% NaCl solution under outer cable jacket just before applying vol-
tage.

Table 2 shows ageing conditions list for all samples

Considering the above criteria, ageing tests were performed on full
size 15 kV, 3 m long, LDPE, Al single-core cables, which had extruded
conductor shield and tape-graphite insulation shield.

During the test, at the certain time intervals, 30 cm long sections
were cut from the part of the cable which was submerged in water. The
samples were cut into 0.2 mm thick slices and dyed in methylene blue so-
lution. After 16 hours dyeing process in 90°C temperature the samples
were microscopically examined. The number of trees and volume of examined
samples were noted.

Insulation samples of cables removed from service were microscopically
examined this way too.

This samples were removed from cables after their second failure. The second break-down place was near to the first one on this cables (a few meters distance).

T a b l e 2

Sample Nr	Voltage kV		Load current A				NaCl solution density %			Over-voltage 20 3 kV 2 s	Mechanical stress at	
	12	20	0	100	180	270	0	0.3	3	kV 2 s	0°C	20°C
K1		+	+				+					
K3		+			+		+					
K4		+			+				+			
K5		+	+						+			
K6		+	+					+				
K7		+			+			+				
K8		+		+				+				
K9		+		+				+		+		
K10		+				+		+		+		
K11		+				+		+		+		
K12	+		+					+		+		
K13	+		+					+		+		
K14	+		+				+					
K15		+	+							+	+	
K16		+	+					+		+	+	
K17		+	+					+		+	+	
K18		+	+					+			+	
K19		+	+							+		+
K20		+	+					+				+

3.1. Laboratory aged cables

Fig. 1. 2 and 3 show water trees density in cables, aged laboratory, is a function of time of voltage application. Basing on this diagrams we can describe:

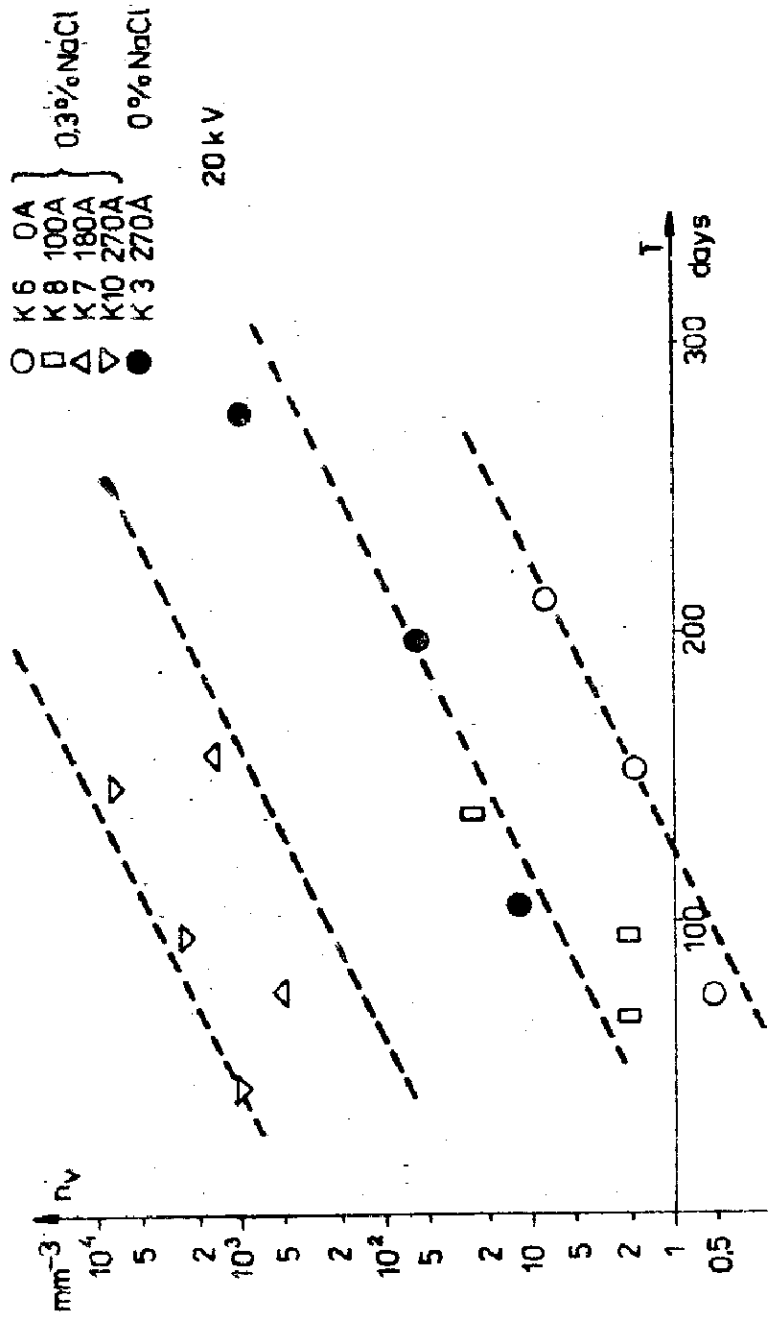$$n_v = b \cdot a^{c \cdot t} \qquad (1)$$

or

$$\log n_v = A \cdot t + \log b \qquad (2)$$

where:

n_v — water trees density (mm^{-3}),
$A = c \cdot \log a = const.$ — material constant.

Expressions log b value should be dependent on ageing conditions, temperature, type of water solution, overvoltages existence, etc.

Fig. 1

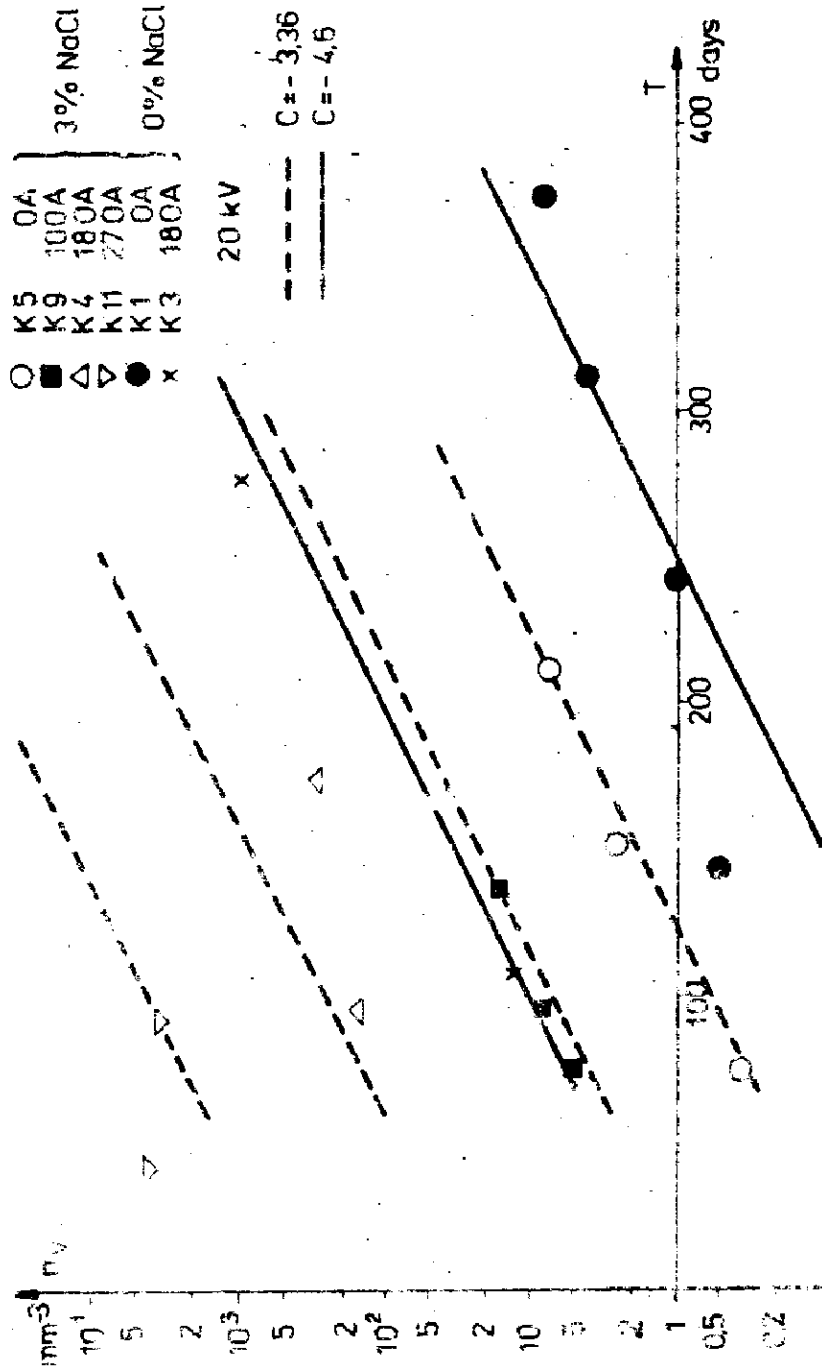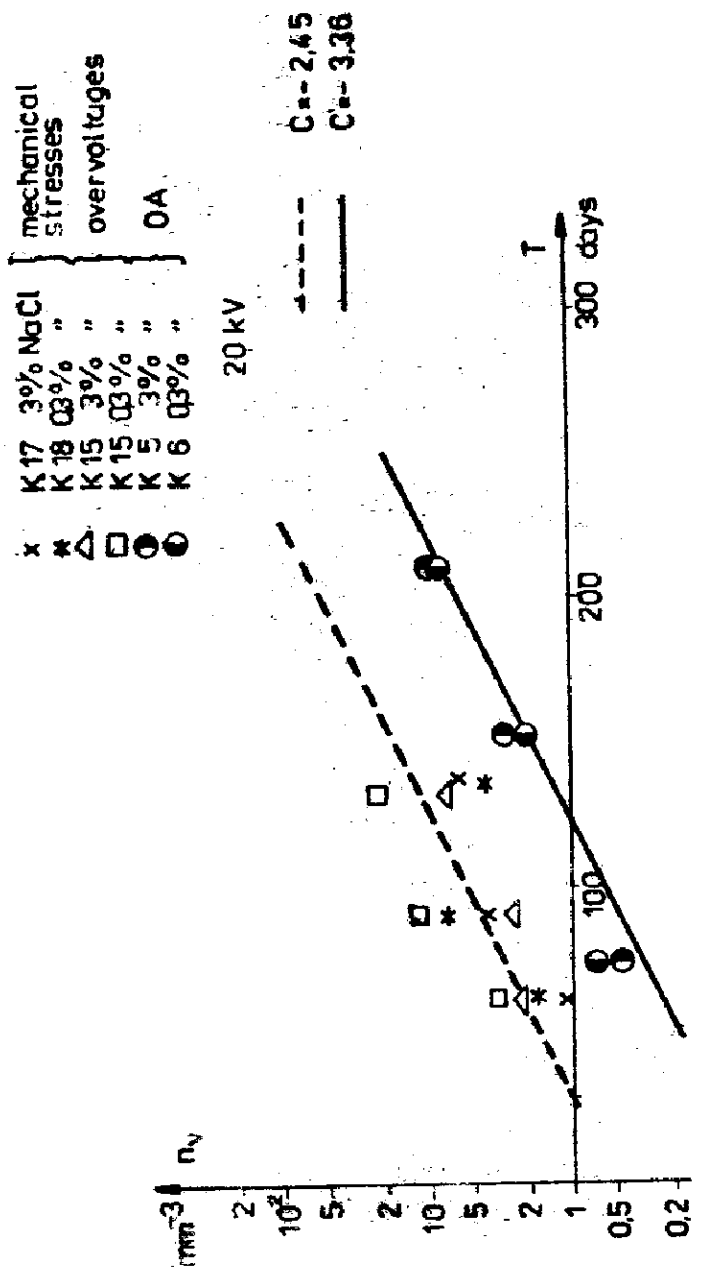Fig. 2

Fig. 3

stresses etc. Equation (2) suggests that log n_v = f(t) lines in diagram should be seen as a straight lines with a slope A. These lines should be paralelly displaced dependent on ageing conditions. Experimental results are in a good agreement with equation (2) for A = 0.01 (1/day).

The second term of equation (2) is the most dependent on temperature, as we can conclude from experimental results in Fig. 1-3. Fig. 4 shows water tree density temperature dependence after 150 days of cables ageing. This is logarithmic correlation too, so we can write:

$$\log n_v = A \cdot t + B \cdot T + C \qquad (3)$$

where:

A, B, C — parameters,

t — ageing time (days),

T — temperature (^{o}C).

A quick numerical analysis shows that B = 0.092 (1/^{o}C). The coefficient C value would depend on other ageing conditions (mechanical stresses, overvoltages, existance etc.).

Basing on experimental results it could be calculate that:

C_1 = -3.36 — for salted water (0.3 and 3% salutions),

C_2 = -4.6 — for destilated water,

C_3 = -2.45 — in presence of mechanical stresses or overvoltages.

Fig. 1-3 show experimental data (points) and calculated from eqn. (3) results (lines) which are with a good agreement in spite of experimental points scatter. Now, transforming eqn. (3), it is possible to calculate order of magnitude of water tree density in aged cables as:

$$n_v = 10^N \qquad (4)$$

where:

$$N = A \cdot t + B \cdot T + C$$

Equation (4) give an easy possibility to watch progress in water treeing in service and laboratory ageing test. So, it could be imagine that a triple change of average insulation temperature induce 10^3 times (some thousands) change in water trees density; water salting increase that number $10^{1.24}$ times (over a dozen or so) because of difference $C_1 - C_2$; and mechanical stress give $10^{0.91}$ times (several times) change in water trees density caused by $C_3 - C_1$ difference. It is clear that temperature influenced the most effects on water trees density.

Conversely proceeding, it is possible to estimate a wet condition time for in service cable knowing water treeing density on its insulations

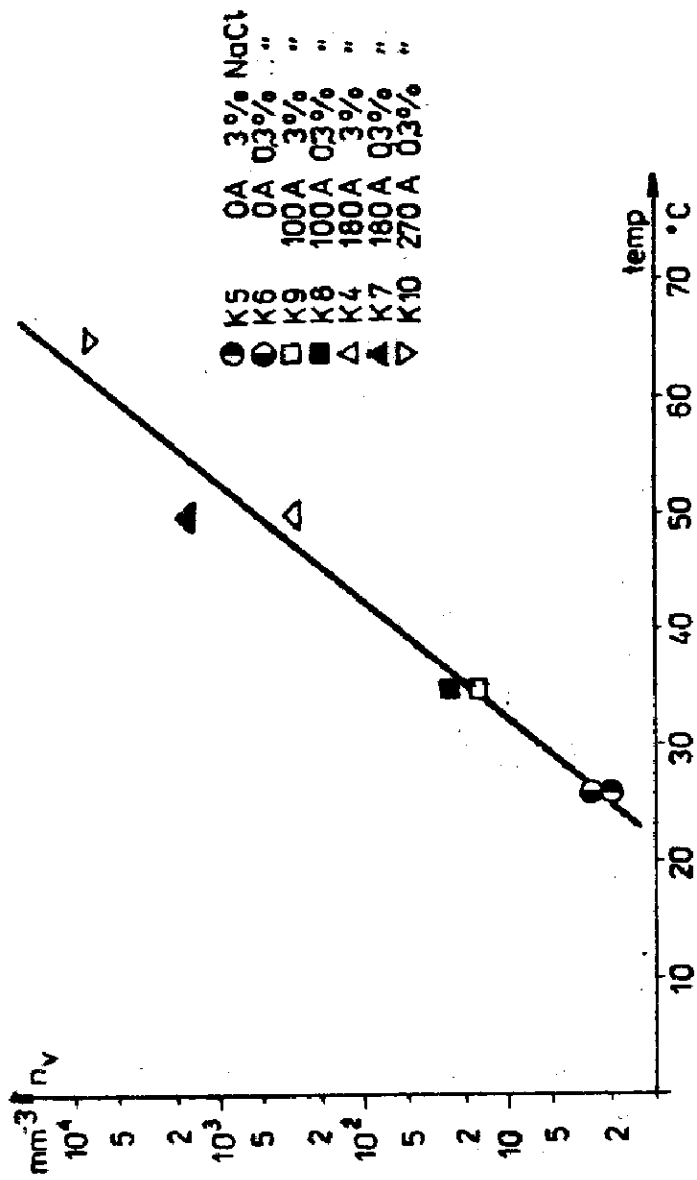It was observed during laboratory tests, some thousand of water trees

Fig. 4

growing in 1 mm^3 polyethylene insulation, aged at the temperature some-
where round to admissible one. This water tree density produce serious
insulation degradation.

3.2. Cables recorved from the field

As it was said before, cables after their second failure were microsco-
pically examined. The second break-down places were found near to the
first one, in a few meter distance. This kind of cables failure happens
about 1 year after the first one, which have been observed by Białystok
Power Plant Cable Service. This observation may suggest that the water
penetrates into the cable after the first failure. The water trees growth
degrade an insulation, leading to its second break-down.

The following cables have been tested:

K101 - YHAKX 15 kV, 1x240 mm^{2}Al, 1979-83 in service,
K102 - YHAKX 15 kV, 1x120 mm^{2}Al, 1976-85 in service,
K104 - YHAKX 15 kV, 1x120 mm^{2}Al, 1977-85 in service.

It was concluded above, that counting water trees density in insula-
tion, it is possible to estimate a wet condition time for examined cables.
Making an assumption that the average value of insulation temperature in
above-mentioned cables ranged 30-35°C, determination of wet condition
time have been made. It has been also asummed that the water had a salt
solution property at this process.

Effect of overvoltage and mechanical stress were neglected. Results
of calculations are shown in Table 3.

T a b l e 3

Cable	n_v (mm^{-3})	Service time (years)	Calc. wet time (days)	Assumed coefficients
K101	1850	4	386-340	A = 0.01
K102	294	9	307-261	B = 0.092
K104	-132	7	272-226	C = -3.36

Although these results can be taken as an approximate values, it is clear,
however, that the cables insulation wetting time was app. one year. It
corresponds with service observations.

4. Conclusions

The quantitative investigations of water treeing in laboratory aged and recovered from service polyethylene insulation show that the water treeing phenomenon could be a reason of power cables repeated failures. Water penetrates into the cable after the first break-down and insulation degradation caused by water treeing leads to the second damage in a short time.

In order to prevent cables from repeated failure water retardant polyethylene should be used in a new products as an insulation. The lifetime of buried cables could be extended by permeating a liquid dielectric into the insulation via the conductor or by drying insulation with an inert gas.

An investigations of this methods should be undertaken for Polish cables.

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