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MOISTURE PERMEATION AND ITS EFFECT ON COMMUNICATION CABLE

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FIFTEENTH ANNUAL WIRE AND CABLE SYMPOSIUM
ATLANTIC CITY, NEW JERSEY
DECEMBER 7, 1966

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ABSTRACT

~~This~~ paper covers certain aspects of the problem of water in buried telephone cables. In the first part of the paper the permeation of water vapor through plastic sheath is discussed and the concept of the permeation time constant is introduced. A permeation pumping mechanism which can accumulate significant amounts of liquid water in buried cables is described. This mechanism depends on air flow rate and temperature changes in pressurized cables.

In the second part of the paper the effects of small amounts of water on the capacitance and conductance of polyethylene insulated cable at voice and carrier frequencies are reported. In addition, some estimates are given of the likelihood of conductor cutoff by electrochemical corrosion in wet PIC cable.

Finally, the problem of the junction of pressurized PIC and pulp cables is considered and the effect of humid air from the PIC cable on the electrical properties of the pulp cable are reported.

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Introduction

The problem of keeping water out of cables has occupied designers, manufacturers and users alike since the beginning of the art. If an operator finds water in one of his cables there is a very high probability that the water entered the cable through a hole in the sheath or a faulty splice closure. However, in the case of a cable with plastic sheath water can, under certain circumstances, get into the cable core through an intact sheath by a permeation mechanism. We shall describe in the first part of this paper such a mechanism and present means for estimating the amount of water which will accumulate under given conditions. In the second part of the paper we shall show the effect of liquid water on the capacitance and conductance of PIC cable. In the situation where PIC cable is joined to pulp insulated cable we shall show the effect of humid air from the PIC cable on the electrical properties of the pulp cable.

Moisture Permeation Through Plastic Sheath

Let us consider, for example, a fifty pair, 19 gauge, plastic insulated cable buried in moist earth. Let us further assume that the sheath on this cable consists of double polyethylene jackets separated by an aluminum tape overlapped but not sealed. This is commonly known as PAP sheath. In any unprotected area the outer jacket will, in the course of time, be punctured by lightning, allowing water or humid air to come in contact with the inner jacket. When a cable is buried in the earth the relative humidity surrounding the sheath is almost always 100%

and the vapor pressure is identical with that which would exist if the cable were immersed in water. Since the vapor pressure outside the jacket exceeds that inside, there will be a movement of water vapor into the cable core. The moisture content in the core will be a time varying function. If one overlooks the amount of moisture absorbed by the sheath material, the expression for vapor pressure in the core becomes a function of the jacket thickness, the permeation constant of the jacket material and the volume of air in the cable core. One can write the following differential equation for the system.

$$dV_t = (V_s - V_t)(1/t_c)\, dt$$

This equation has the solution:

$$V_t = (V_s - V_o)(1 - e^{-t/t_c}) + V_o \qquad (1)$$

where

V_t = vapor pressure in core at time t

V_s = vapor pressure at saturation, i.e., vapor pressure at 100% R.H.

V_o = vapor pressure in core at time zero

t = the time the cable is exposed to 100% R.H.

t_c = permeation time constant.

The formula for V_t is quite similar to that for voltage on a capacitor of a series resistance and capacitance circuit which is connected to a constant voltage source. While this formula does not take into account the moisture absorbed by the sheath material it does approximate the actual situation quite well when the cross sectional area of the sheath is less than the cross sectional area of the core.

Considering again the electrical analogy, the time constant for such a circuit is given by RC, the product of resistance and capacitance. In the moisture permeation formula the time constant is given by: $t_c = C/Q$ where C is the capacity of the air space in the cable core to hold water vapor and Q is the rate of permeation of water vapor through the jacket. The capacity of the air space in the cable core to hold water vapor is given by

$$C = (Vol)\ W/V_s \text{ gms/cm Hg} \qquad (2)$$

where

Vol = air volume in the length of core in cc

W = weight of water in unit volume at saturation

V_s = vapor pressure at saturation

The rate of permeation of the water vapor through the jacket is given by

$$Q = \frac{2\pi\ PDL}{\log_e R} \text{ gms/sec/cm Hg} \qquad (3)$$

where

P = the permeation constant of the jacket material

D = the density of water vapor

L = length of the section of core in cm

R = the ratio of the outside to inside jacket diameter.

The permeation constant, P, is expressed in cc(STP)/cm/sec/cm Hg. It varies with jacket material and with temperature. In the attached Figure 1 values of log P for two jacket materials are plotted versus reciprocal of the absolute temperature. Both materials contain 2.75% carbon black by weight but are different density polyethylenes. Note that the 0.945 density material is about one quarter as permeable as the 0.92 density material. The permeation constant data were furnished by R. W. Hamilton[1].

The density of water vapor is, of course, given by the gram molecular weight of water divided by the gram molecular volume: $D = \frac{18}{22.4 \times 10^3} = .000804$ gms/cc. The weight of the water in unit volume at saturation is given by the following:

$$W = \frac{273}{T} \times \frac{V_s}{76} \times D$$

W is equal to 18.4×10^{-6} gms/cc at the temperature of 70°F.

The fifty pair 19 gauge cable that we are considering has a jacket which is 0.84" in diameter and 0.053" thick. The jacket material is 0.92 density polyethylene with a permeation constant of 0.73×10^{-8} cc/sec at 70°F. The space in a unit length of core not occupied by conductors is 1.73 cc. The capacity C is calculated from Equation (2) as follows:

$$C = 1.73 \times 18.4 \times 10^{-6}/1.88 = 1.72 \times 10^{-5} \text{ gms/cm Hg}$$

The rate of permeation from Equation (3) is equal to:

$$Q = \frac{2\pi \times 0.73\times10^{-8} \times .804\times10^{-3}}{\log_e .946/.84} = 3.11 \times 10^{-10} \text{ gms/sec/cm Hg}$$

Using these parameters the time constant can be calculated as follows:

$$t_c = \frac{C}{Q} = \frac{1.72 \times 10^{-5}}{3.11 \times 10^{-10}} = 0.553 \times 10^{5} \text{ sec}$$

$$t_c = 15.4 \text{ hours.}$$

After one time constant, that is, t = 15.4 hours, the vapor pressure of the moisture inside the core is given by

$$V_t = (V_s - V_o)(1-e^{-1}) + V_o$$

If the initial vapor, V_o, is small

$$V_t = V_s\ (1-.36)$$

or

$$V_t/V_s = .64$$

Thus in a little over 15.4 hours the relative humidity can reach 64%. In a matter of a few days the air in the cable can approach complete saturation. In the absence of any temperature changes the amount of water in the cable would remain very small, namely 18.4 micrograms per cc, the amount in saturated air.

Stationary Air Moisture Pumping Mechanisms

Small amounts of water can, however, accumulate if the cable goes through a temperature cycle, for instance a daily cycle. One such pumping mechanism has been described by Hladik[2]. With a drop in temperature the water vapor inside the cable condenses instantaneously but as the temperature rises it evaporates very slowly. Thus, during the rising half of the temperature cycle, the vapor pressure is lowered permitting the entrance of additional water vapor. This mechanism accumulates water very slowly. In a typical case the upper bound is about one gram per foot in 30 years.

There is another mechanism described by Lechleider[3] involving the difference between the sheath temperature and the core temperature during the daily cycle. During rising part of the temperature cycle the sheath is warmer than the core and during the falling half the opposite is true. Since the permeation constant of the jacket is a direct function of temperature and the permeation is inward during the rising half of the cycle, there is a net accumulation of water. This mechanism, produces even less water than that described by Hladik.

A Moving Air Moisture Pumping Mechanism

In the previous section an expression for vapor pressure in a cable core as a function of time was arrived at under the assumption that the air was stationary. Now we are going to describe a slightly different variation of this mechanism, which under special circumstances, can produce larger quantities of water in localized sections of cable. In pressurized cables there is normally a flow of gas due to inadvertent leaks at splices and elsewhere. As the gas (air) flows through the cable in a direction away from the air dryer it gradually accumulates the moisture which permeates through the jacket. In the situation where the flow rate is small and hence the pressure drop low, the expression for vapor pressure is that derived earlier in Equation (1):

$$V_t = (V_s - V_o)(1 - e^{-t/t_c}) + V_o.$$

Since the air is flowing through the cable, there is no change in the moisture content of the sheath material, at any given location, once the steady state condition has been reached. Hence the expression for vapor pressure is exact from that standpoint.

The length of time that an incremental element of air is in the cable is now determined by length of the cable, the flow rate and the cross section area of the air space.

$$t_\ell = A\ell/f = P_o A\ell/P_a F \text{ hours}$$

where

A = the cross section area of air space in cable in sq. ft.

ℓ = length of the section of cable in ft.

f = flow rate of air in cu. ft./hr.

F = flow rate of air in std. cu. ft./hr.

P_a = standard pressure in psia

P_o = absolute pressure at beginning of the section in psia.

For the 50 pair 19 gauge cable considered earlier, $A = 1.9 \times 10^{-3}$ square feet. Hence the transit time, t, will equal 1.9 hours per 100C feet for a flow rate of one cubic foot per hour. Such a flow rate is not unreasonable.

Let us consider now a buried cable that runs through an open field where the earth is warmed by the sun during the day. Let us suppose that the warm section extends for several thousand feet and that the cable then enters a shaded area where the earth is relatively cool. Let us assume that air is flowing through cable from the warm section toward the cool section and that there are no leaks in the warm section. Under these conditions, if the warm section of cable is long enough and the moisture permeation rate high enough, the vapor pressure of the moisture in the air coming out of the warm section will be more than that required for saturation in the cool section. The excess amount of water vapor will be condensed in the cool section. Assuming that the vapor pressure of the air when it enters the warm section is very low yields the following equation for the moisture collected at the leading edge of the cool section:

$$M = (V_\ell - V_{sc})\, f = (V_\ell - V_{sc})\, F\, P_a/P_o$$

$$M = [V_{sw}(1 - e^{-A\ell/ft_c}) - V_{sc}]\, f \text{ gms/hr.} \qquad (4)$$

where

V_{sw} = vapor pressure at saturation in the warm section

V_{sc} = vapor pressure at saturation in the cool section

V_{ℓ} = vapor pressure in cable at end of warm section.

For our purposes the expression for moisture is only of interest for positive values of M. Negative values of M only mean that moisture is not being deposited at the beginning of the cool section.

Earlier in this section it was assumed that the flow rate would be low enough so as not to cause a sizeable pressure drop as the gas flowed through the warm section of cable. We would like now to consider the situation where there are sizeable pressure drops. For our purposes the pressure drop in lbs. per square inch is related to flow by the following equation.

$$\Delta P = R\ell F/1000$$

where

R = penumatic resistance - a cable structure constant

ℓ = length in feet

F = flow in standard cubic feet

For 50 pair 19 gauge cable R = 0.7. Hence sizeable pressure drops can occur with lengths in the neighborhood of several miles. Cables are normally pressurized at a gauge pressure of 10 psi. Clearly, the pressure drop cannot exceed this value. However, even for smaller pressure drops, the effect is one of placing an upper bound on the rate at which moisture can enter a given cable regardless of the length of the warm section. The expressions for the quantities V_{ℓ}, and M, containing correction terms for a linear pressure drop, are derived in the Appendix. The results for V_{ℓ} and M are as follows:

$$V_\ell = V_{sw} b(1-a\ell) e^{-b(\ell - \frac{1}{2} a\ell^2)} \int_0^\ell e^{b(x - \frac{1}{2} ax^2)} dx \qquad (5)$$

and

$$M = \frac{(V_\ell - V_{sc})\ F\ P_a}{(1-a\ell)\ P_o} \qquad (6)$$

where

$$a = -\frac{1}{P_o}\frac{dP}{dx} = \frac{RF}{1000\ P_o}$$

$$b = \frac{P_o A}{P_a F t_c} = \frac{t_\ell}{t_c \ell}$$

These equations reduce to those used earlier when $\frac{dP}{dx}$ is assumed to be zero. The expression for V_ℓ features an integral which is an error function in disguise. It can also be handled by means of numerical integration.

Numerical Results for Moving Air Mechanism

Let us consider now some numerical results obtained from the above formulas. Assume that the warm section temperature is 70°F and that the cool section temperature is 65°F. Also assume an initial pressure, P_o, of 25 psia. The amount of water in saturated air at 70°F is .521 grams per cubic foot, while the amount in 65°F saturated air is .445 grams per cubic foot. The maximum amount of water that can be deposited is, then, .521 - .445 = .076 grams per cubic foot. The amount of water accumulated per hour will be obtained by multiplying the amount accumulated per cubic foot by the flow rate at the beginning of the cool section. The curves shown in Figure 2 are results obtained from Equation (6). Each curve represents moisture accumulation versus flow rate for a given warm section length. The curves all coincide near the origin. This is explained by the fact that for low flow rates the moisture accumulation is a function only of the product of the difference in saturated vapor pressures and the flow rate. However, as flow rates increase, the curves one by one drop into the negative region. This means that the vapor pressure of the air has not reached a level sufficiently high to cause saturation when going into the cool section. The fact that the 25,000 foot curve drops into the negative region before the 20,000 foot curve does, is explained by effect of

the linear air pressure drop. Note also that there is a "pessimum" flow rate for each warm section length. This is explained by the fact that the degree of saturation is an inverse function of flow rate, that is, flow rate appears in the denominator of the exponential argument. Finally, the maxima of the various curves are bounded from above. That is, beyond a certain length the maximum of the moisture curve no longer increases with length.

It will be noted that significant amounts of water can accumulate. During the night and on cloudy days, however, the temperatures tend to equalize throughout the cable length. Also during the winter the average temperatures are lower than those assumed. Since the curve of water content vs temperature tends to be much flatter at lower temperatures, the effect will be much reduced in the winter.

Refer again to Figure 2. The maximum accumulation is 20 mg per hour. This amounts to 175 grams per year but since the mechanism does not operate full time it would probably be somewhat less than this amount. In any case this is an easily visible amount of water. It will accumulate initially at the leading edge of the cool section, but will flow, under the influence of gravity, to any nearby low point in the cable. It is interesting to note that at the rate of 20 mg per hour it would take 4 months to completely fill one foot of a 50 pair, 19 gauge cable which can hold about 50 grams of water when the air space is filled. Carrying the arithmetic a little further, it would take 33 years to fill 100 feet of cable. It is clear then that large amounts of water cannot be accounted for by permeation mechanisms but are more likely the result of sheath breaks or faulty splice closures.

Improved Sheath Design

Several means for decreasing the rate of moisture ingress are possible. One of these is a higher density polyethylene. It was pointed out earlier that 0.945 density material has one quarter the permeability of 0.92 density material. The effect is that the time constant, t_c, of equation (1) is increased by a factor of four. Using a better sheath design will increase the time constant by many times and result essentially in no pumping under any conditions. One such sheath design has an aluminum tape adhered to the inner jacket. This tape acts as a moisture barrier which drastically reduces the permeation rate. The aluminum tape may be adhered to either the inner

or outer surface of the inner jacket. Figure 3 shows an experimental design known as APAP sheath in which an aluminum tape is adhered to the inner surface to provide a low permeability moisture barrier. The aluminum tape which is normally present between the two jackets is retained in order to provide electrical conductivity. Since it is not adhered it can be more easily bonded at splices.

The Effect of Moisture in PIC Cable

Having demonstrated that measurable amounts of water can enter a cable it is of interest to examine what effects a given amount of water has on the primary constants of PIC cable. It was demonstrated by Eager et al[4] that the resistance and inductance of PIC cable pairs are affected very little by the presence of moisture. However, moisture has a substantial effect on the capacitance and conductance of PIC cable. An experiment was performed recently in our laboratory to obtain a quantitative measure of these effects. This experiment involved the core of a 50 pair, 19 gauge PIC cable. This core was pulled into a brass tube so as to eliminate the possibility of moisture getting behind the core wrap as would be the case in conventional sheath design. A ten foot length of cable was used in the experiment. The amount of moisture in the core at each instant was determined by weighing the cable assembly on a balance scale of sufficient resolution. Conductance and capacitance measurements were made on 2 pairs in each unit, or a total of 12 pairs. The measurements were made at frequencies extending from 1 to 300 kHz.

The experimental procedure started with an initial weighing and initial measurements of conductance and capacitance on the dry cable. The cable was then filled with water. This was done by applying a vacuum to the cable and allowing it to draw in the water. The filled cable was weighed to verify that it had been completely filled. The cable was then suspended vertically overnight allowing most of the water to drain out under the influence of gravity. This reduced the moisture content in the core from a full value of about 50 grams per foot down to about 1.69 grams per foot. A second set of conductance and capacitance measurements were made at this point. Additional increments of moisture were removed by blowing dry nitrogen through the cable core. Conductance and capacitance measurements were made after each drying interval.

The ability of a given nitrogen flow rate to remove moisture uniformly over the ten foot section of cable was studied at some length. The objective was to use a flow rate great enough to insure that the gas would not be appreciably saturated by the time it passed out the far end but not so great as to cause the moisture droplets to migrate in the direction of flow. An upper bound for the possible range of flow rates was established by pulling a section of wet core into a glass tube and observing the flow rate at which droplet migration set in. A flow rate somewhat lower than this value, about 250 cu. ft./hr. was proven by means of a supplementary experiment to be satisfactory for the drying procedure.

Experimental Results with PIC Cable

The results of the experiment are illustrated by two families of curves, Figures 4 and 5. The first set of curves deals with conductance as a function of water content in grams per foot. These curves are plotted on semilog paper to allow placing the whole family on one page. The variation of conductance versus water in grams per foot is actually an almost linear relationship for moisture levels less than one gram per foot. From the spacing of the various conductance curves, it is obvious that conductance varies as the first power of frequency over the entire range of moisture levels as it does for dry cable. In other words, conductance is proportional to the first power of frequency. In summary, the presence of one gram of moisture per foot in 50 pair 19 gauge PIC cable causes conductance to go up by a factor of 45.

Figure 5 is a family of curves showing the percent increase in capacitance as a function of water content in grams per foot. The curves of Figure 5 all have the same shape with the higher frequency curves having lowest slope. From the uniform spacing between the curves pertaining to the various frequencies it appears that, for any given moisture level, capacitance variation with frequency is proportional to the logrithm of frequency.

All of the data thus far has dealt with small amounts of moisture, that is, up to 1.7 grams per foot. It is of interest to consider what happens to a water filled PIC cable. In a water filled cable each wire is in effect shielded by a cylinder of water. The mutual capacitance between a pair of wires is one half that obtained from the coaxial formula $C = 0.0359\varepsilon/\log \frac{DOD}{d}$ μf/mile, where DOD is the diameter over

the dielectric and d is the wire diameter. Using $\varepsilon = 2.26$, DOD = 60 mils and d = 35.9 mils, yields C_{mut} = .197 microfarads per mile. Hence the full of water value of mutual capacitance is about 2.38 times that of the nominal .083 microfarads per mile value for dry cable. This factor was substantiated experimentally by a few measurements. Figure 6 is a plot of capacitance increase versus water content with the points from Figure 5 shown in the lower left corner and the point in the upper right representing the capacitance increase with the cable full of water. Little is known about the region between the lower left hand corner and the point in the upper right hand corner except that the curve somehow has to pass through it. The sketched-in curve in Figure 6 does illustrate that the average slope of the curve in the region to the right of the cluster of points in the lower left hand corner is considerably lower than the slope near the origin. This means that the first portion of moisture to enter the core causes a relatively important increase in capacitance. One possible explanation here is that water clings to the interstices of the pair more readily than to other portions of the insulation surface. When water is added to this region it is most effective in increasing capacitance.

A few comments might be made about the effect that changes in capacitance and conductance have on attenuation of PIC cable. Inasmuch as attenuation at both voice and carrier frequencies varies only as the square root of capacitance, changes in capacitance will have a relatively small effect on cable attenuation. For instance, there will be about a 5% increase in the series component of attenuation, α_R, for moisture levels of one gram per foot. The story on the effect of increased conductance is more complex. At carrier frequencies the attenuation due to conductance, normally designated α_G, is relatively independent of gauge size and is proportional to conductance. At 300 kHz a dry 19 gauge PIC cable has an attenuation of 10 db per mile. The α_G portion of this 10 db is about .013 db per mile. Now if the cable has a moisture level of one gram per foot conductance is up by a factor of 45 and α_G is about .6 db or about 6%. If one considers a frequency of 3 MHz, α_G is about 0.13 db per mile for dry cable. Increasing the conductance by a factor of 45 raises α_G to 6 db or 17% of a total of 36.

Conductor Cutoff Due to Electrochemical Corrosion

In a section of cable containing liquid water, if there are insulation faults, and the conductors have battery voltage on them, there will be electrochemical corrosion which may proceed to wire cutoff. By Faraday's law the copper will be

removed at the rate of 1.18 gms per ampere - hour. The current will be determined by the ratio of the battery voltage divided by the resistance between faults. The resistance involved depends on the distance between faults, the conductivity of the water and the extent to which corrosion products build up in the areas of the fault.

The distance between faults is a statistical function of fault count level and cable length[5]. For instance, with a fault count level of 100 faults per million conductor feet the probability of finding two faults of opposite polarity less than ten feet apart in a 100 foot length of 50 pair cable is about 0.015. An important point to remember is that the resistance between faults will be too high to produce conductor cutoff in any reasonable time unless the length of cable (in our example, 100 feet) is completely filled with water. The resistance of polyethylene surfaces with discontinuous films or droplets of water is normally in the order of hundreds of megohms or more. This may be the explanation of why there is no history of massive conductor cut-off in "wet" cable. Nevertheless a finite probability of conductor cutoff remains and is a compelling reason for keeping water out of cables.

Moisture in Pulp Insulated Cables

From the discussion of the effect of moisture on PIC cable parameters it is evident that it is water in liquid form inside the cable that causes an increase in capacitance and conductance. This is demonstrated by the fact that as the amount of water in the core is reduced, the PIC cable parameter values approach the normal dry values. Humid air alone has very little effect on PIC cable parameters. In pulp insulated cable the situation is entirely different. The presence of moist air does affect the conductance and capacitance of pulp insulated cable. When moist air of a given relative humidity (R.H.) flows through a pulp cable, the moisture content of the pulp insulation equilibrates until there is no change with time in R.H. of the effluent air. The pulp insulation is capable of absorbing large amounts of moisture. Polyethylene insulation by comparison absorbs very little moisture.

To evaluate the effects of moisture in pulp cable an experiment was performed in our laboratory. This experiment involved the core of a six foot length of 22 gauge, 50 pair pulp insulated cable. The length of core was pulled into a sheath consisting of a brass tube with the appropriate inside diameter. The brass tube sheath had previously been perforated with small holes spaced several inches apart. The holes were provided to allow the injection of controlled amounts of water into the core at equally spaced intervals. A method of sealing the holes was provided.

Ten representative pairs were selected for the conductance, capacitance and IR measurements. These pairs were brought out at one end through an epoxy plug to eliminate drying out end effects. The remaining pairs were grounded.

The experimental procedure consisted of observing the effect that a given moisture content had on the electrical properties. Liquid water was injected at the holes. Initially the water soaked the pulp insulation in the vicinity of the hole but after a period of time appeared to be well distributed throughout the insulation. This dispersion was observed both visually and by time sampling the insulation resistance. In general, the insulation resistance, as observed from the end, would drop to a low value upon introducing the water. Then it would increase in value, until perhaps 24 hours later it had, for practical purposes, reached a stable value. Conductance and capacitance values behaved in a similar manner but did not vary over as wide a range. The fact that the resistance change was more pronounced can be understood by considering a parallel arrangement of large and small resistors or wet and dry sections of pulp. The small resistors are controlling.

In this presentation the measured values of insulation resistance, conductance and capacitance are actually plotted versus percent relative humidity of the air in the cable instead of moisture content. The main reason for doing this is that it is easier to measure moisture in terms of relative humidity in a fibrous material such as pulp insulation. When air of a known relative humidity is forced through a container filled with pulp, the pulp either picks up or loses moisture until the relative humidity of the effluent air is the same as that at the inlet. Moisture is not usually present in pulp cable in liquid form as was the case in PIC cable.

Experimental Results on Pulp Cable

The relationship between the moisture content of pulp and % R.H. was determined experimentally many years ago by A. C. Walker[6]. This relationship is displayed graphically by Figure 7 for virgin sulfate wood pulp. For low values of R.H. the moisture content is a linear function of R.H. on a log-log basis. However, as the R.H. approaches 100% the moisture content approaches the saturation moisture content of the pulp fibers. To relate a given quantity of water being introduced into the cable to % R.H. both the weight of the water and the weight of the pulp must be known. For a 50 pair 22 gauge pulp cable the insulation weighs about 11.3 grams per foot.

The results of the insulation resistance measurements are shown in Figure 8. Basically the insulation resistance is inversely related to R.H. over the entire range of R.H. In the telephone plant a cable will normally become inoperable if the insulation resistance falls below 10,000 ohms. In a one mile length this value would be reached when the pulp insulation equilibrates with 60% R.H. air.

Figure 9 is a plot of conductance versus % R.H. The conductance when plotted on semilog paper increases fairly linearly over the range of R.H. extending from 20 to 70%. Above 80% R.H. the conductance appears to increase quite rapidly. It will be noted that for low R.H. values the conductance changes less rapidly at 100 kHz than at 1 kHz with increase in R.H. The implication is that the higher the frequency the smaller the effect of R.H. on conductance.

A curve showing the percent increase in capacitance as a function of % R.H. is plotted in Figure 10. The capacitance changes relatively slowly up to about 40% R.H. and increases more sharply thereafter. The capacitance increase is much less at high frequencies than at low frequencies when high values of R.H. are considered.

We would like now to consider the effect of moisture on the attenuation of pulp cable. As mentioned earlier, the series component of attenuation, α_R, varies as the square root of capacitance. For R.H. levels around 25% the increase of α_R will be about 5%. For higher values of R.H., especially those above 50%, increases in attenuation due to capacitive changes become more significant. The effect of increased conductance is also of importance. At 100 kHz dry 22 gauge pulp cable has an α_G of 0.25 db per mile. At 50% R.H. this quantity increases to 1.0 db per mile which is 10% of a total of 9.5 db per mile. The effect of moisture on attenuation is somewhat greater at higher frequencies.

A few words about the reliability of the results of the pulp cable experiment may be in order. The experiment was first performed by increasing the R.H. in steps of 15%. The core was then dried and the procedure repeated with points spaced about 5% R.H. apart in the 0 to 30% range and 10% R.H. apart for higher values. The two runs indicate that repeatability is very good. The results of this experiment covered R.H. ranging from 0 to 85%. A similar experiment, using a different means to introduce the moisture was performed by Walker in 1927.

His range extended from 0 to 32%. The capacitance measurements made in our experiment check those of Walker's results quite well over this range. However, the conductance curve has a somewhat higher slope. Similarly, the insulation resistance curve has a lower slope than Walker's results indicated. This difference would be explained if present day pulp were to exhibit a higher impurity content than that of 40 years ago. On the other hand, the results of our experiment may be somewhat pessimistic because of the way the moisture was introduced.

Comparison of PIC and Pulp

It might be of interest at this point to compare the PIC and pulp cables for a given moisture content/cross sectional area density. It will be recalled that for a 50 pair 19 gauge PIC cable a moisture content of 1 gram per foot caused a 10% increase in capacitance and a conductance increase of about 45 times at 1 kHz. The 50 pair 22 gauge pulp cable has about half as much cross sectional area as the 50 pair 19 gauge PIC cable. The pulp insulation weight is 11.3 grams/ft. Hence a moisture content of .5 grams/ft. corresponds to an R.H. of 22%. This means a 10% increase in capacitance and double the value of conductance. It is apparent that for small quantities of water the effect is about the same in pulp as in PIC cable.

When all available space in the core is flooded with water the situation is very different. In PIC cable as mentioned before, the capacitance increases by 238% and the conductance increases only a slight amount at low frequencies. In a flooded pulp cable on the other hand, the insulation becomes highly conductive and the cable will no longer function.

PIC-Pulp Junctions

The situation where a pulp cable is pressurized via a PIC cable, i.e., there is a length of PIC cable between pulp cable and the air dryer, may lead to trouble in the pulp cable. If there is a substantial length of PIC cable and the rate of air flow from the dryer is low, the R.H. of the air will build up to a point where it can degrade the electrical properties of the pulp cable and make it unusable. It will be noted that there is no liquid water involved, only high humidity air with which the pulp insulation equilibrates. One solution to this problem is to plug the PIC-pulp cable junction and supply air to the pulp cable from another source.

Summary

It has been shown that, under certain circumstances, liquid water can accumulate in buried PIC cable with intact sheath and that this problem can be eliminated by improved sheath design. Data on the effect of liquid water on the capacitance and conductance of PIC cable and the effect of humid air on the electrical properties of pulp cable have been presented. In the case of PIC cable, for instance, one gram of water per foot will increase the capacitance 11% and the conductance 45 times.

For pulp cable the convenient parameter is the R.H. of the air with which it has equilibrated. With 40% R.H. the capacitance goes up 25% and the conductance increases 16 times. Above 40% the situation rapidly becomes worse. The insulation resistance falls sharply to such a low value that the cable is unusable.

Information with regard to electrochemical corrosion in wet PIC cable has been presented in an attempt to aid users in estimating the likelihood of conductor cut-off. It appears that the probability of conductor cutoff is small unless substantial lengths of cable are completely filled with water or the fault count is very high. Nevertheless there is a finite probability of some conductors being cut off which emphasizes the importance of keeping water of cables.

Acknowledgement

The authors are indebted to Mr. C. E. Jones for the measurements made on the pulp cable and to Messrs. J. T. Early and R. P. Guenther for helpful comments on the manuscript.

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APPENDIX

Derviation of Moisture Permeation Formula

A simplified formula for moisture permeation, Equation (1), was arrived at in the first part of the paper. This equation held for the situation where the air was stationary, if one neglected the moisture absorbed by the sheath material. In the section where a moving air mechanism was considered it was pointed out that if vapor pressure at any point down the cable did not change with time, the capacity of the sheath material to hold moisture could indeed be neglected. However, it was pointed out that Equation (1) would hold as an approximation only for situations where the flow rate was low and hence the air pressure drop was low for the length of the line being considered.

To derive an expression for the situation where sizable air pressure drops occur, we begin by considering the differential equation which led to Equation (1). Written in incremental form we have:

$$\Delta V_t = [(V_{sw}-V_t)/t_c]\ \Delta t$$

where

V_t = vapor pressure in core at time t

V_{sw} = vapor pressure in the warm section at saturation, i.e., vapor pressure at 100% R.H.

t_c = permeation time constant which is the capacity of the air space in the cable core to hold water vapor divided by the rate of permeation of water vapor through the jacket

Δt = length of time needed to traverse the segment of cable, Δx.

At this point is is desirable to relate the increment of vapor pressure to the increment of length Δx. In the section where small pressure drops were considered, the time required to traverse a length ℓ was linearly related to ℓ by:

$$t_\ell = A\ell/f$$

where

A = the cross section area of air space in cable in sq. ft.

ℓ = length of section of cable in ft.

f = flow rate of air in cu. ft./hr.

In this case, since pressure drops with distance, the flow rate increases with distance. Hence the increment of time, Δt, required to traverse a given length, Δx, varies with position. Assuming a linear pressure drop one can write an expression for flow rate at a point x distance from the beginning of the warm section length of cable:

$$f = FP_a/P_x$$

$$f = FP_a/(P_o + \frac{dP}{dx}\, x)$$

$$f = FP_a/P_o(1-ax)$$

where

F = flow rate of air in std. cu. ft./hr.

P_a = standard pressure in psia

P_x = air pressure at point x in psia

P_o = air pressure at x=0 in psia

$a = -(1/P_o)dP/dx = RF/1000\ P_o$

R = pneumatic resistance

Now one can write the following expression for the length of time required to traverse a distance Δx:

$$\Delta t = [AP_o(1-ax)/FP_a]\ \Delta x$$

The resulting expression for ΔV is:

$$\Delta V_x = [(V_{sw}-V_x)AP_o(1-ax)/FP_a t_c]\ \Delta x$$

where V_x is vapor pressure at point x.

The above expression, however, does not take into account the fact that the pressure exerted on the moist air is dropping as it traverses the incremental length, Δx. By Dalton's Law of Partial Pressures* it is evident that the vapor pressure changes in a manner proportional to the change in total pressure. The pressure at the beginning of the increment Δx is:

$$P_o + \frac{dP}{dx}\,x = P_o(1-ax)$$

The pressure at the end of the segment is:

$$P_o + \frac{dP}{dx}\,(x+\Delta x) = P_o\ [1-a(x+\Delta x)]$$

The change in vapor pressure due to this pressure drop is the ratio:

$$[V_x\,\frac{dP}{dx}/(P_o+\frac{dP}{dx}\,x)]\Delta x = [-a\ V_x/(1-ax)]\ \Delta x$$

The final expression for ΔV_x is:

$$\Delta V_x = [(V_{sw}-V_x)AP_o(1-ax)/FP_a t_c - aV_x/(1-ax)]\Delta x$$

Taking the limit of ΔV_x as Δx goes to zero and regrouping, results in the following differential equation:

$$dV_x + [b(1-ax) + a/(1-ax)]\ V_x dx = V_{sw} b(1-ax)dx$$

where

$$b = AP_o/FP_a t_c$$

This is a differential equation of the form:

$$dy+M(x)ydx = N(x)dx$$

*Pauling, L., College Chemistry, W. H. Freeman and Company, San Francisco, 1952, p. 170.

The left hand side can be made exact by multiplying by the factor $e^{\int M(x)dx}$

where $$\int M(x)dx = \int [b(1-ax) + a/(1-ax)]\, dx$$

$$= b(x - \tfrac{1}{2} ax^2) - \log_e(1-ax)$$

Multiplying through by the integrating factor results in:

$$\frac{e^{b(x-\frac{1}{2}ax^2)}}{1-ax}\left[dV_x + [b(1-ax) + \frac{a}{(1-ax)}]\right]V_x dx = V_s b e^{b(x-\frac{1}{2}ax^2)} dx$$

Integrating both sides we have:

$$V_x \frac{e^{b(x-\frac{1}{2}ax^2)}}{1-ax} = V_{sw} b \int e^{b(x-\frac{1}{2}ax^2)} dx$$

Giving some thought to what happens to the constant of integration (when $x=0$, $V_x=0$) allows one to write:

$$V_\ell = V_{sw} b(1 - a\ell) e^{-b(\ell - \frac{1}{2}a\ell^2)} \int_0^\ell e^{b(x-\frac{1}{2}ax^2)} dx$$

The integral involved in this expression is a candidate for numerical integration. It can also be transformed into the error function which is a tabulated function. The form of the solution is of interest. In general $a \ll 1$. If one considers the case where $a = 0$ then:

$$V_\ell = V_{sw} b\, e^{-b\ell} \int_0^\ell e^{bx}\, dx$$

$$= V_{sw}\, (1-e^{-b\ell})$$

This expression is similar to Equation (1) except that V_o is assumed to be zero and the variable is x instead of t.

Finally the expression for moisture is arrived at by multiplying the difference of the vapor pressure at the end of the warm section and that required for saturation in the cool section, by the flow rate.

$$\dot{M} = (V_\ell - V_{sc})f$$

$$M = (V_\ell - V_{sc})\ FP_a/P_o\ (1-a\ell)$$

where V_ℓ is the complex expression arrived at earlier.

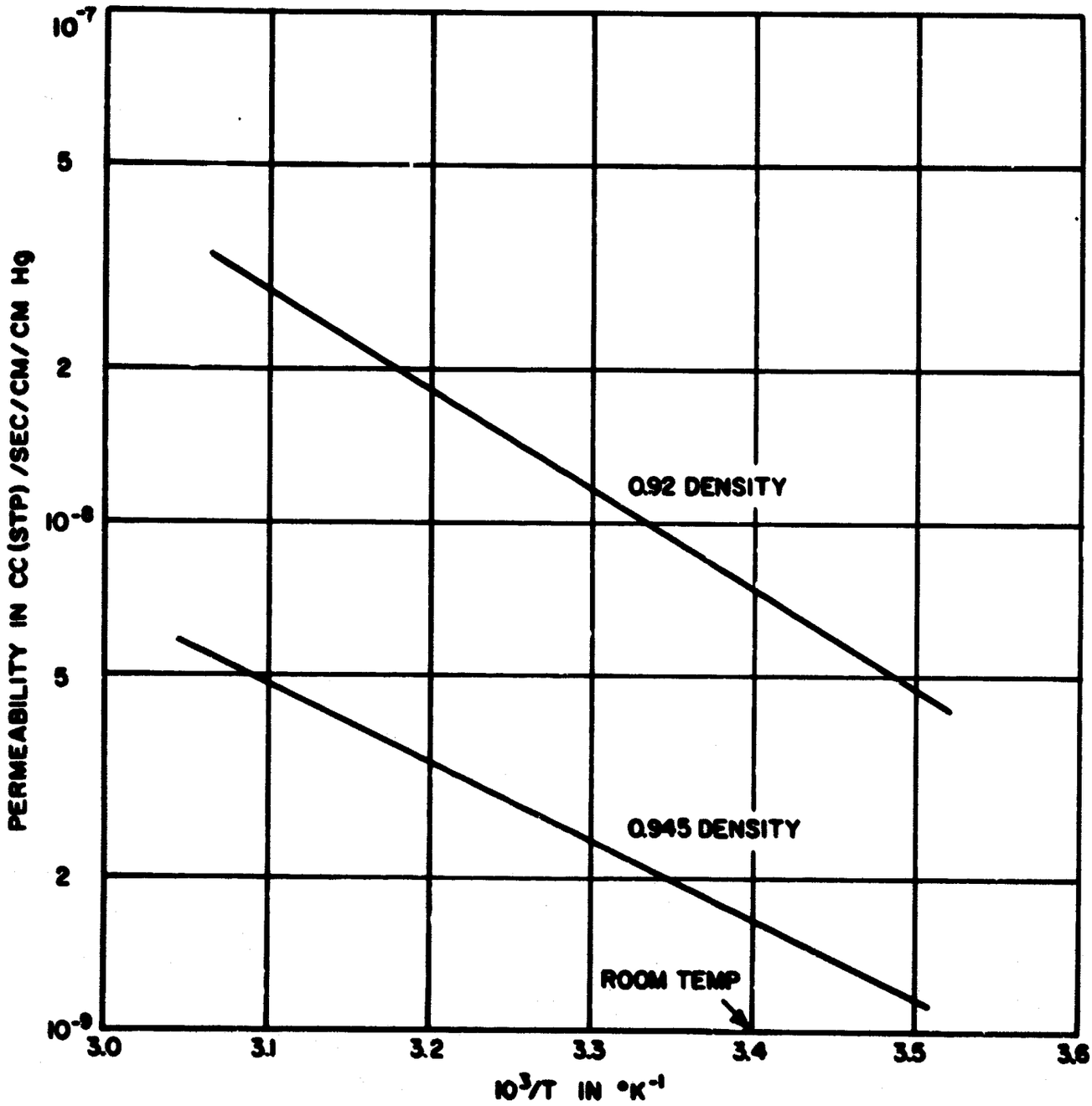

FIG. I PERMEABILITY OF SHEATH JACKET MATERIAL AS A FUNCTION OF TEMPERATURE

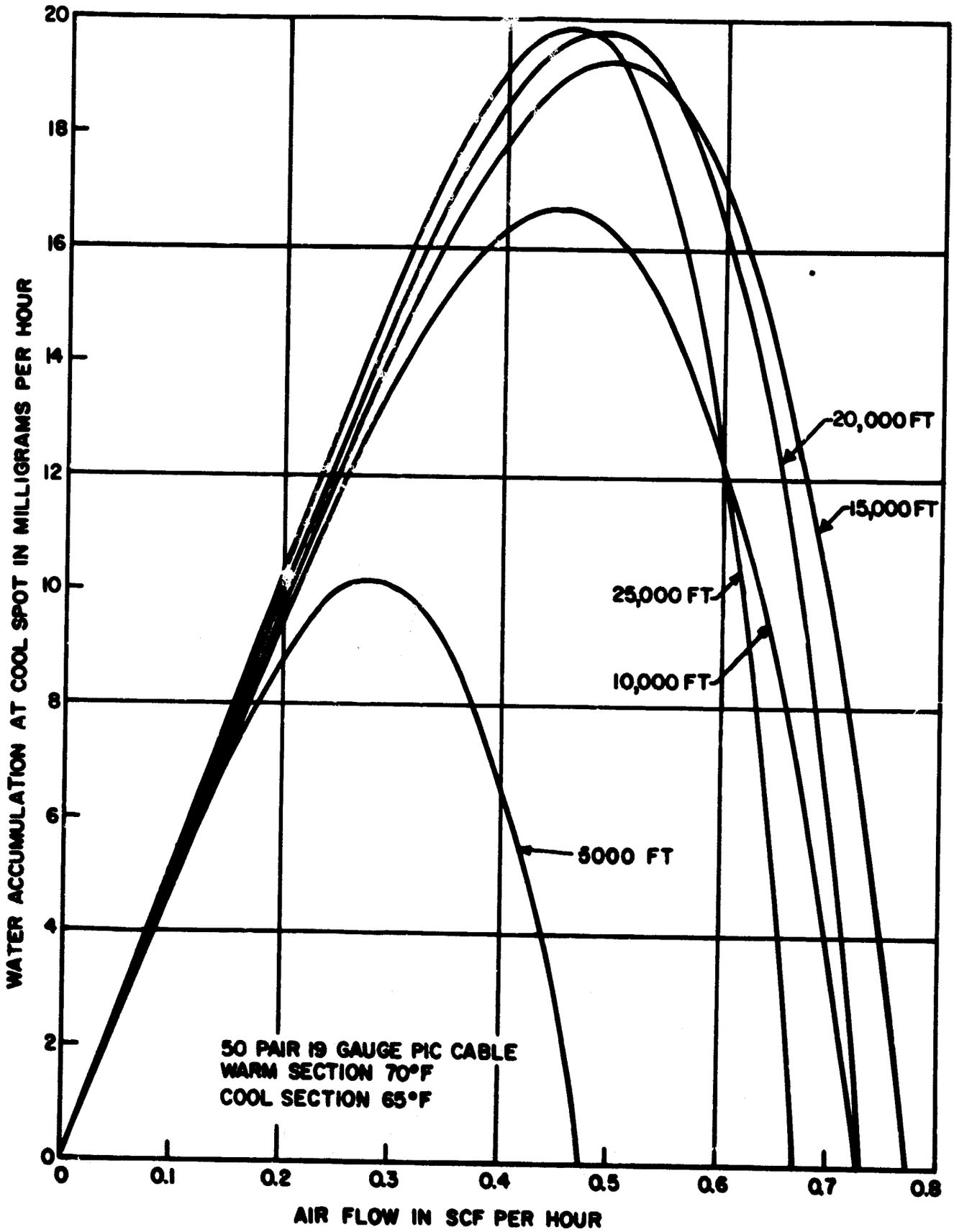

FIG. 2 WATER ACCUMULATION IN COOL SECTIONS OF CABLE FOLLOWING WARM SECTIONS OF VARIOUS LENGTHS

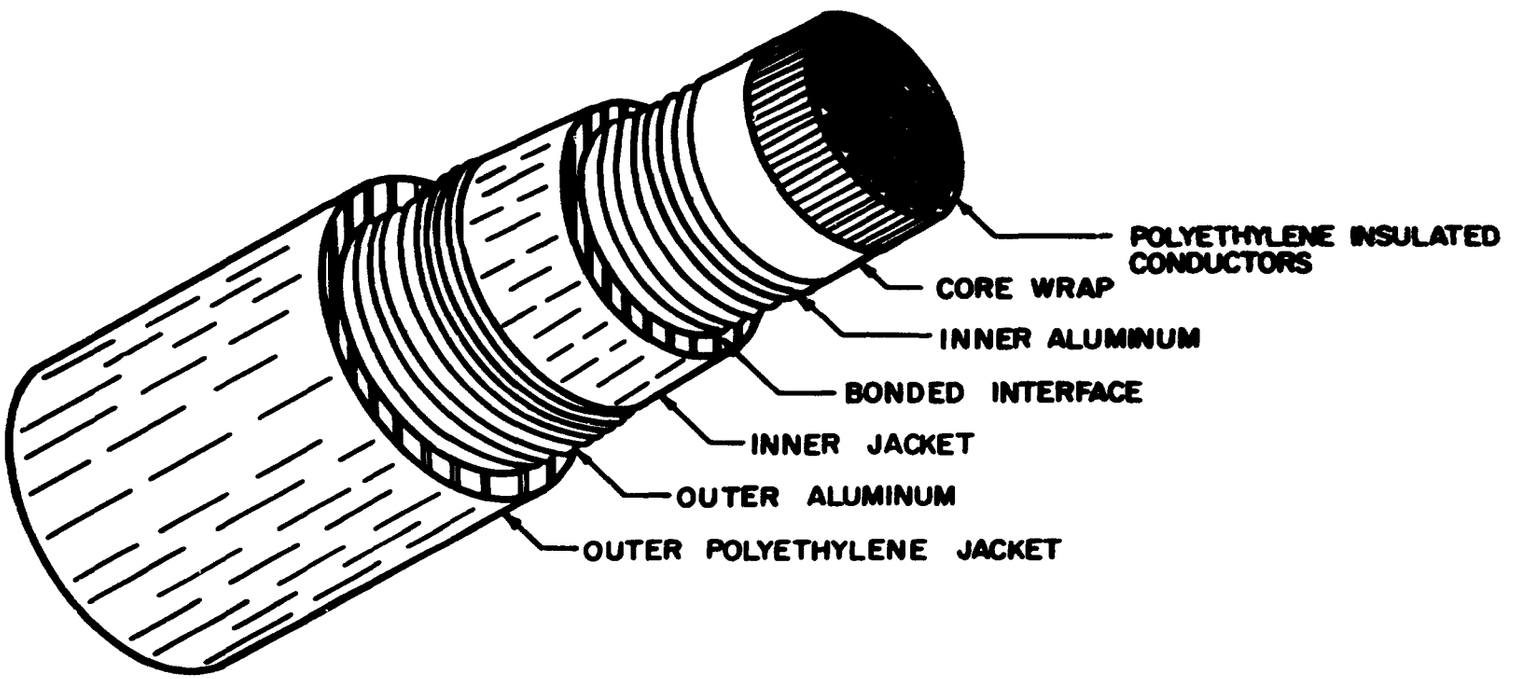

FIG. 3 EXPERIMENTAL APAP SHEATH DESIGN

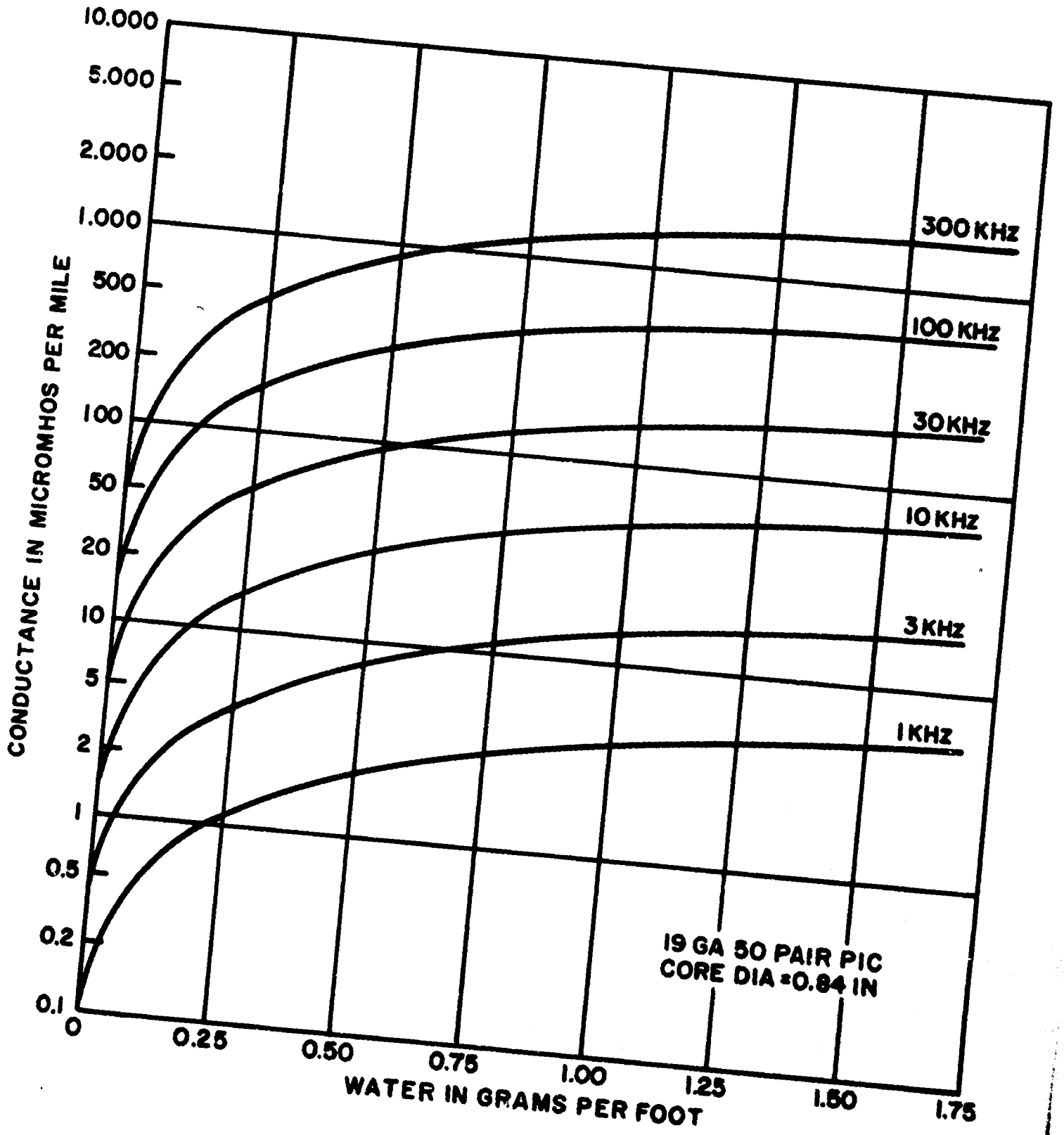

FIG. 4 CONDUCTANCE OFF PIC CABLE AS A FUNCTION OF WATER IN THE CORE

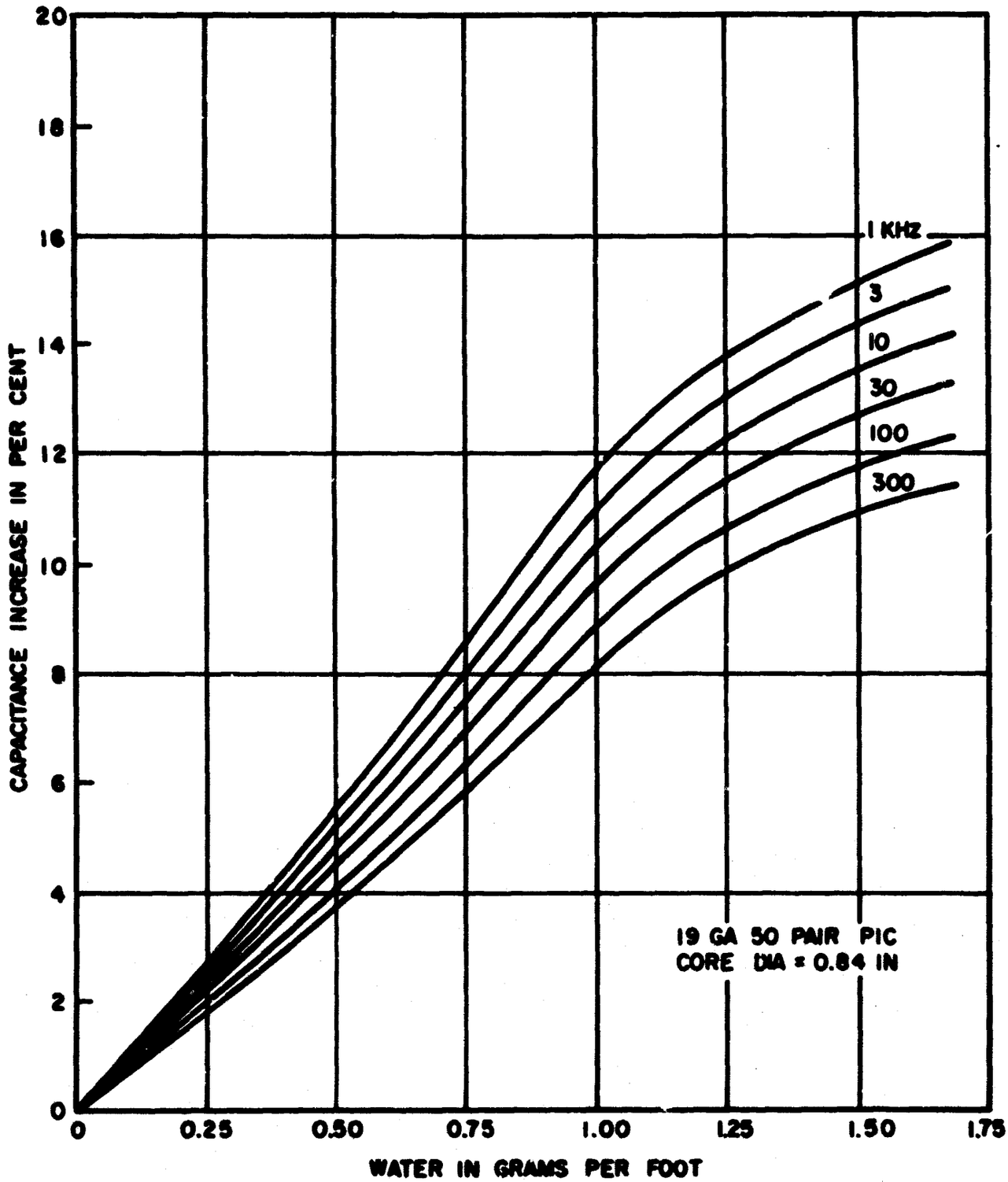

FIG. 5 CAPACITANCE INCREASE OF PIC CABLE AS A FUNCTION OF WATER IN THE CORE

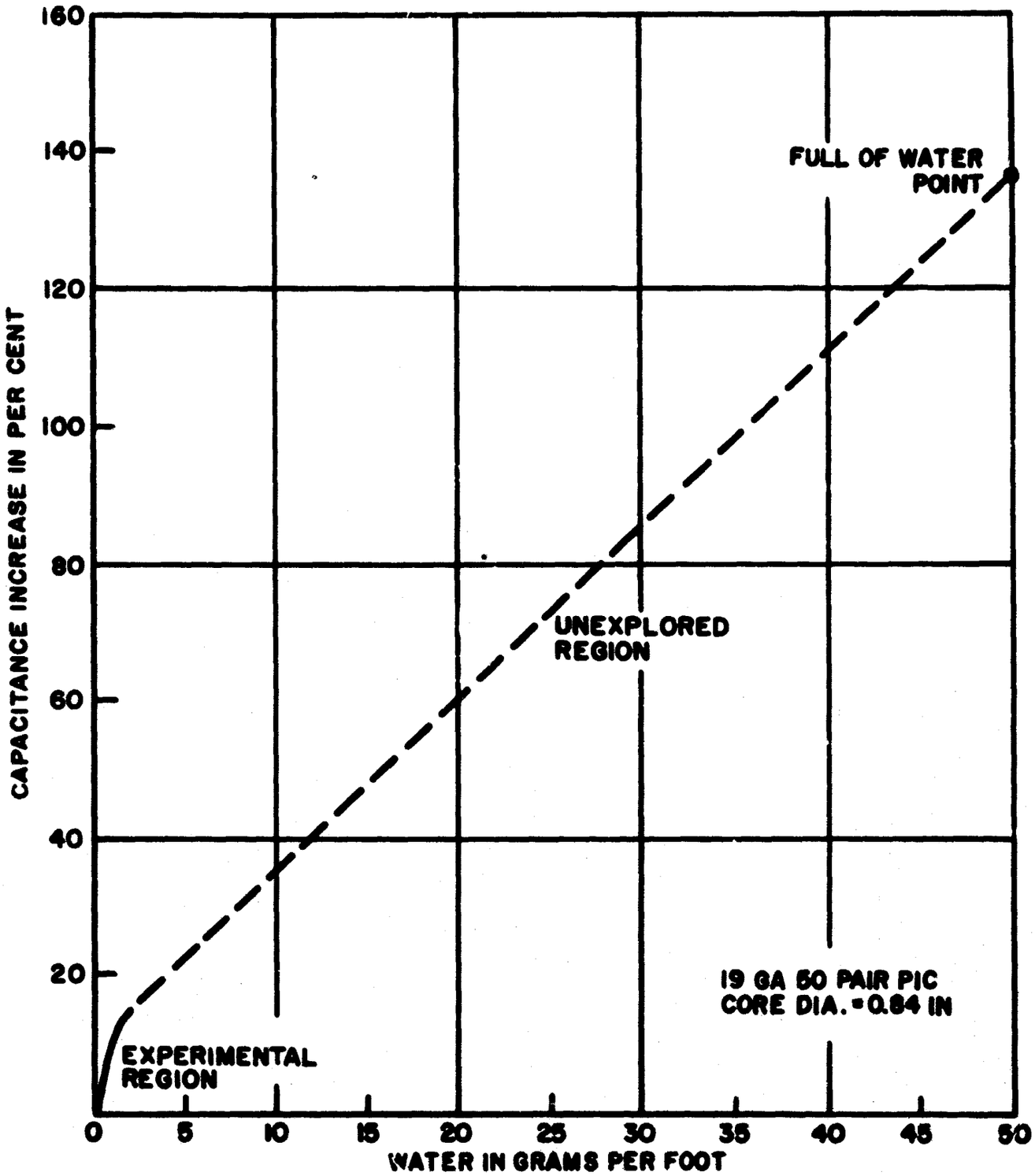

FIG. 6 CAPACITANCE INCREASE OF PIC CABLE AS A FUNCTION OF WATER IN THE CORE

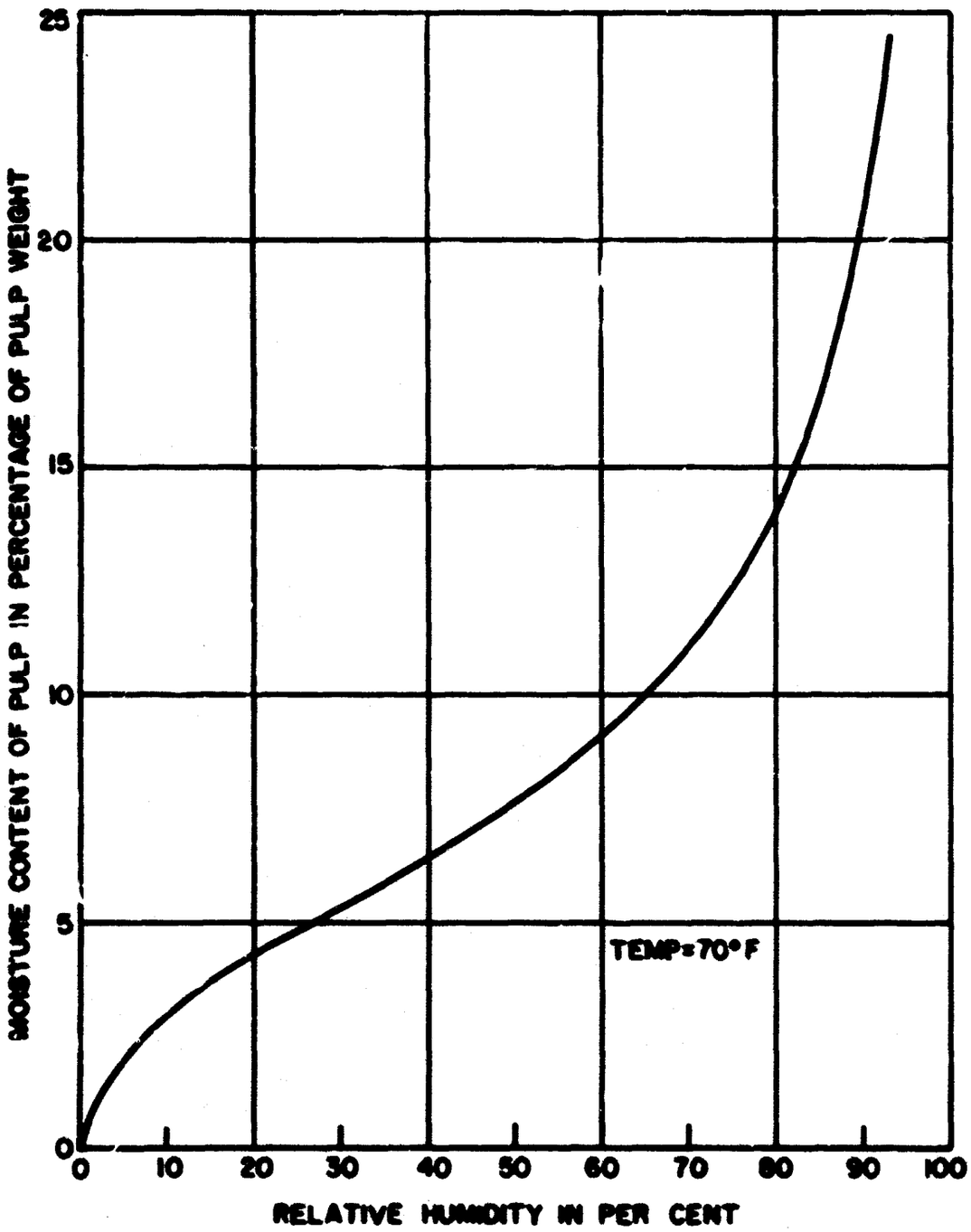

FIG. 7 MOISTURE CONTENT OF PULP AS A FUNCTION OF RELATIVE HUMIDITY

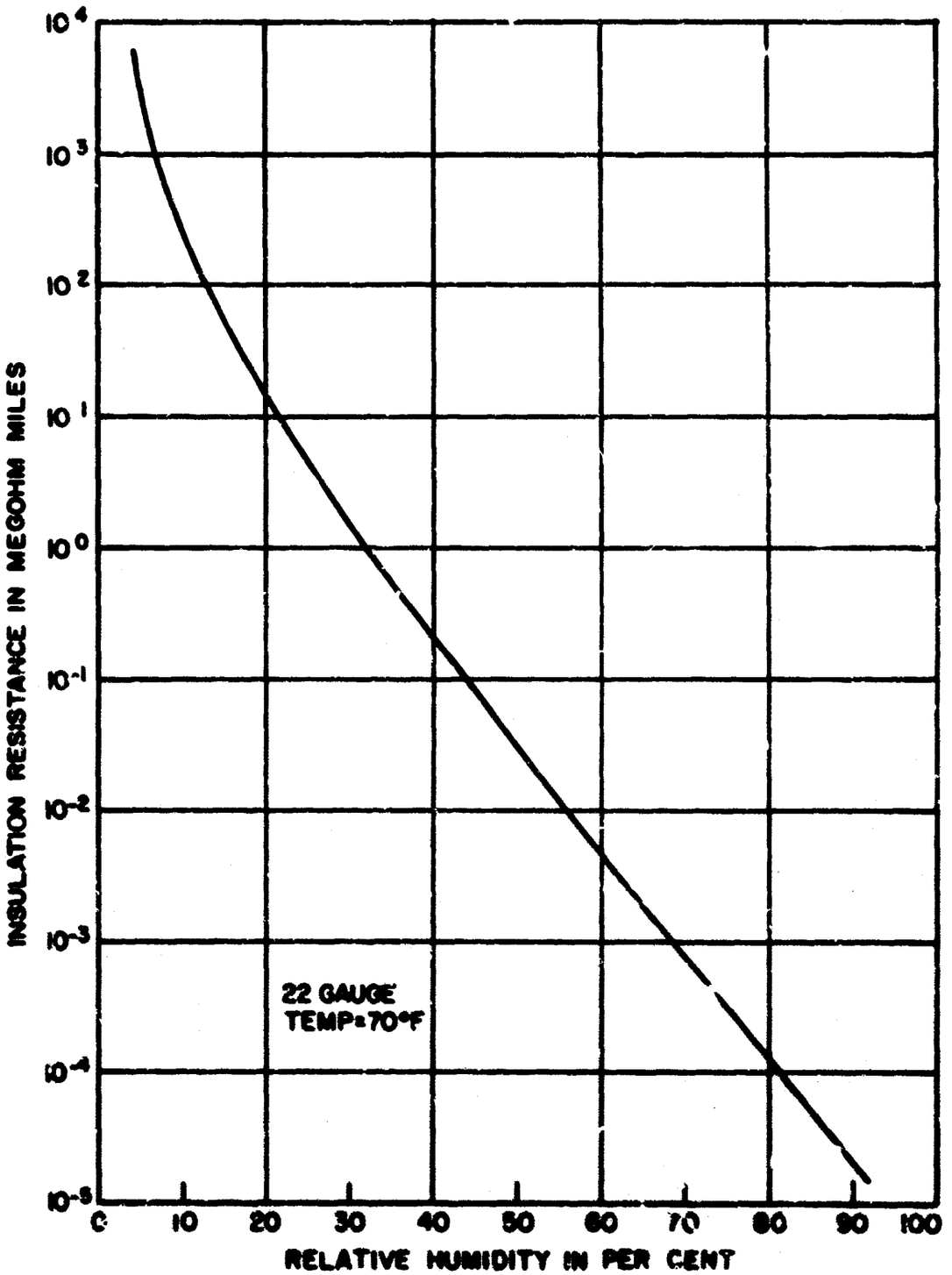

FIG. 8 INSULATION RESISTANCE OF PULP CABLE AS A FUNCTION OF RELATIVE HUMIDITY

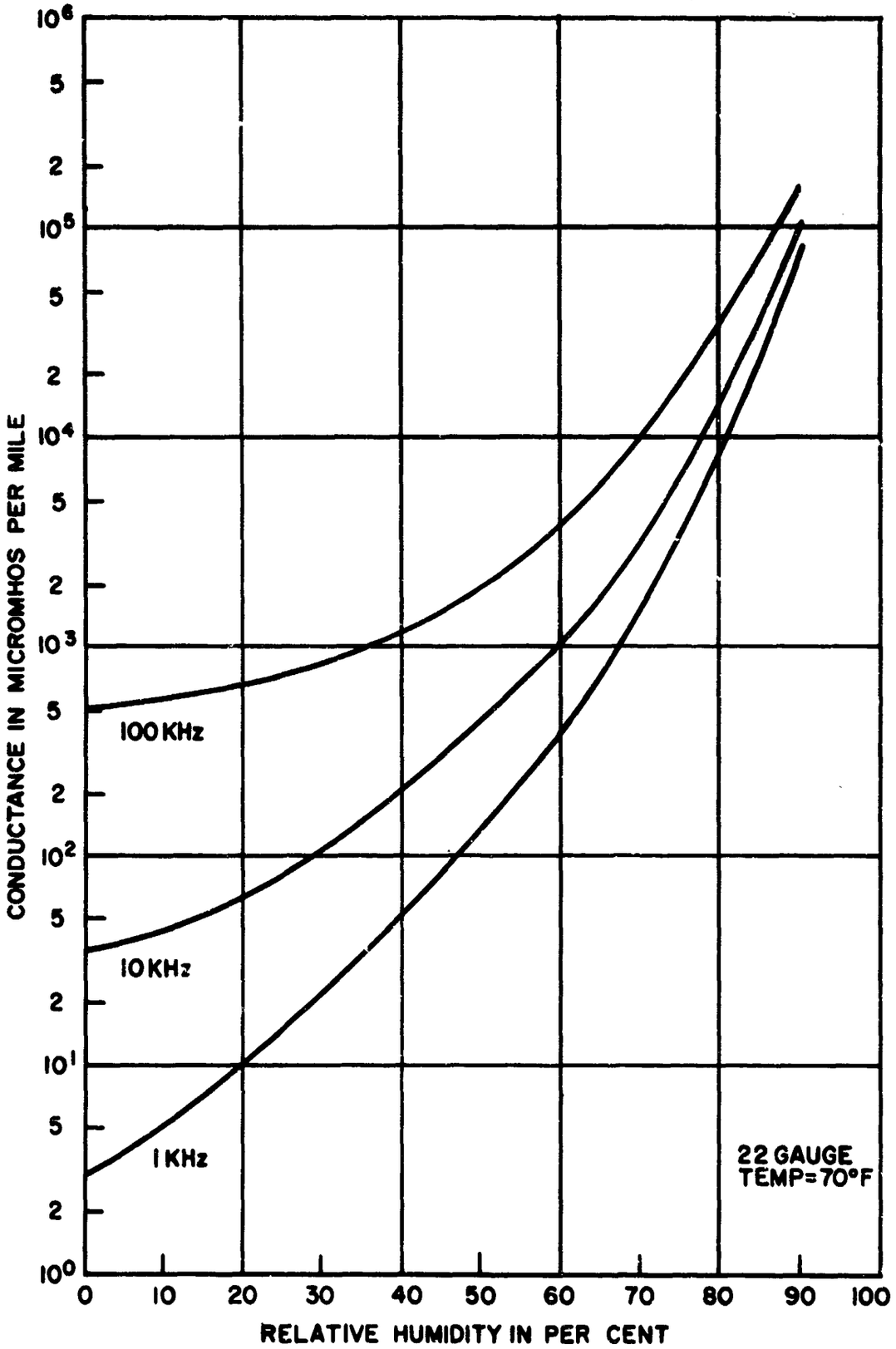

FIG. 9 CONDUCTANCE OF PULP CABLE AS A FUNCTION OF RELATIVE HUMIDITY

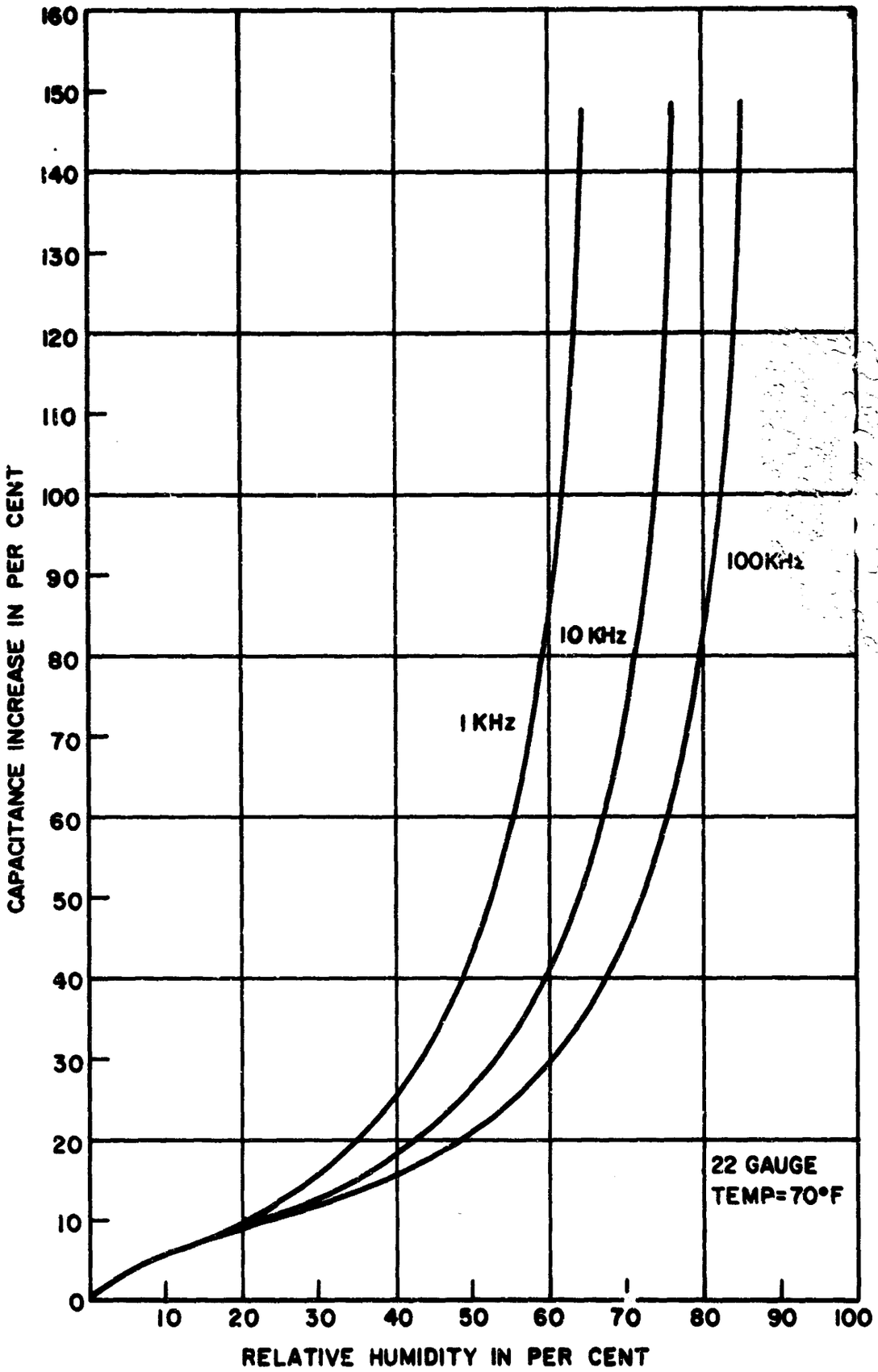

FIG. 10 CAPACITANCE INCREASE OF PULP CABLE AS A FUNCTION OF RELATIVE HUMIDITY