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# INSULATION CUT-THROUGH ON WIRES

H. Tracy Hall and A. M. Bueche

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Abstract: From a study of the interdependence of insulation thickness, bare wire diameter, and load on the cut-through of wires crossed at right angles, it has been established that a threshold load exists. That is, a given wire tested at fixed temperature would cut through above a certain load but would not cut through below this load, even if the load were maintained on the wires indefinitely. It has been established for polychlorotrifluoroethylene on aluminum that maximum resistance to cut-through is obtained when the ration on "build" to total wire diameter is 1:7. However, a ration of 6:100 supports 90 percent of maximum load. An equation relating threshold cut-through load, bare wire diameter, coating thickness, and yield value of insulation has been determined. This work points out that basic data relating wire diameter, "build," and load cannot be obtained from the joint Army-Navy "JAN-W-583, 7 April 1948, Specifications for Magnet Wire" test. Tests of the type described in this work are necessary to obtain basic cut-through information. These tests simultaneously apply various loads to many crossed wired held at fixed temperatures to determine the threshold cut-through load.

# INSULATION CUT-THROUGH ON WIRES

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This investigation was instigate to determine the relevant factors in the cut-through of thermoplastic insulation on wire. There is a joint Army-Navy specification for magnet wire: JAN-W-583 7 April 1948. Concerning thermoplastic flow, Section F-4c (10)A of this specification states the following:

> "Thermoplastic flow of a resin-type insulation film on round wire shall be determined by placing one wire horizontally on a steel plate, with another wire placed across the first at right angles to it. The two wires shall be pressed together with a 1000-gram weight. They shall be connected to a 110-volt a.c. supply through an argon lamp, and then placed in an oven at 25° C. The temperature shall be raised uniformly at the rate of 1° C per two minutes until the conductors are shorted and cause the lamp to light. The temperature of the plate directly beneath the sample shall be determined with thermocouples and shall be taken as the temperature of the insulation."

Wire size, insulation thickness, and load are not considered in the JAN test. Certainly, a wire that fails under a 1000-gram load will stand up under a smaller load and would be suitable for some purposes. With this in mind, experiments were designed to discover the effect of bare wire diameter, insulation thickness, and load on the cut-through of thermoplastic insulation on crossed wires.

The mechanical properties of a particular thermoplastic material are often deduced form stress-strain (load elongation)curves obtained by loading test pieces of the material in tension, compression, or shear. Figure 1 shows a typical tensile stress-strain curve. Along OP, a linear relation between stress and strain exists (Hooke's law region). As the applied stress increases, a point P is reached beyond which the linear relationship between stress and strain no longer holds. Point P marks the proportional limit. The deformation continues to be elastic, however, until the yield point or elastic limit Y is reached. For stresses up to Y the strain disappears promptly and completely on release of the stress. Beyond Y the material is no longer an elastic body but is behaving as a plastic solid. The particular curve being considered indicates considerable elongation from Y to C, where the material is ductile and flowing under nearly constant stress. Beyond C, the stress required to effect further elongation again increases (strain hardening) until a maximum called the ultimate tensile strength at T is reached.

A crossed-wire cut-through test at fixed temperature is a complicated stress-strain measurement. It is complicated by the geometry of the system. At the start of a cut-through test, the area of contact of two round wires crossed at right angles is a point. Consequently, the pressure is infinite. As the weight pushes the center of the wires closer together, the area of contact increases and the pressure per unit area decreases. When the insulation cuts through and the conductors touch, the area of contact will have reached its greatest value and the pressure per unit area its smallest value. Different parts of the material in

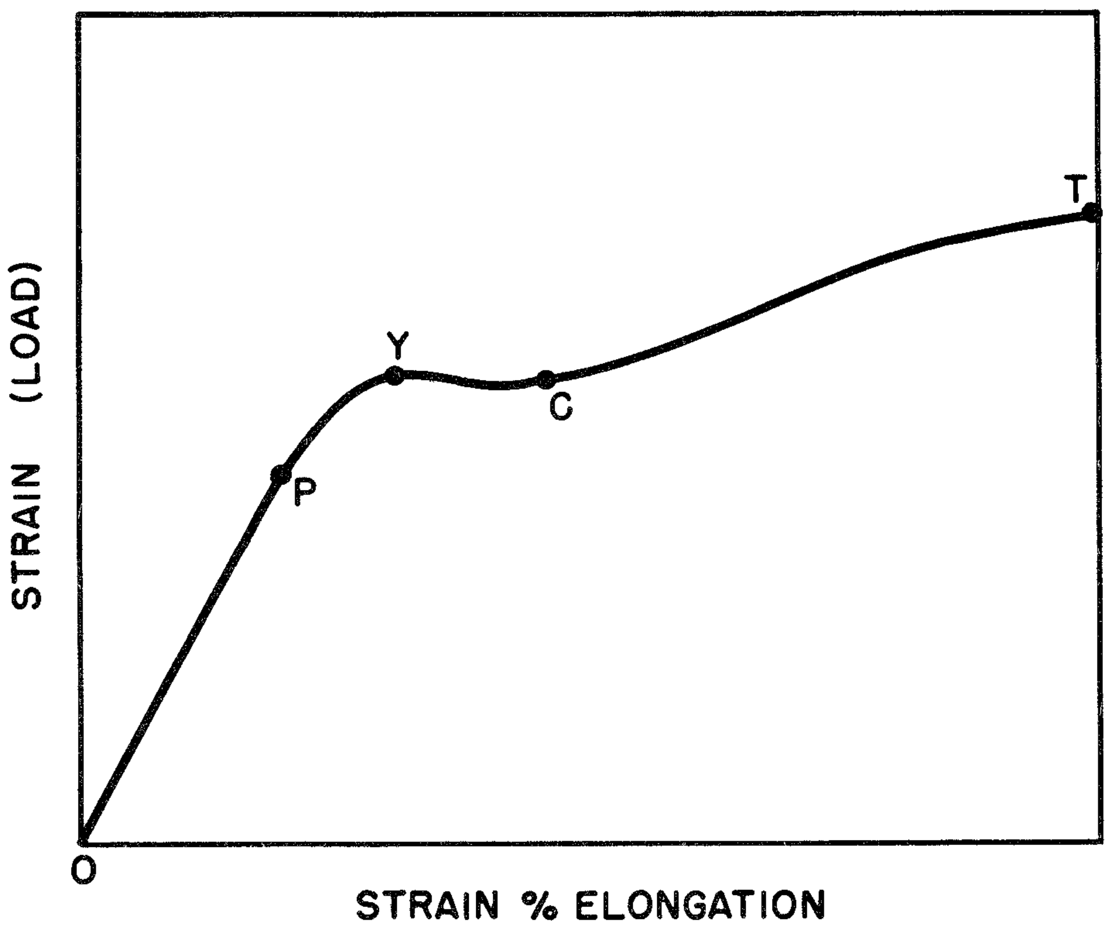


Fig. 1 A typical tensile stress-strain curve.

and near the cut-through area are subjected to entirely different stresses. The insulating material located close to a line perpendicular to the centers of the two crossed wires has at cut-through been subjected to the greatest stress. Some of the material here will flow plastically. At distances further away from this perpendicular line, near the edge of the contact area, the deformation will be so small that Hooke's law will be obeyed. Near the point of contact of the conductors at cut-through, some of the insulation must necessarily have been stressed beyond the ultimate tensile strength.

Regardless of the complex situation discussed above, one property of the thermoplastic material will be most important in determining whether or not cut-through will take place. That quantity is the yield strength Y. The greater the value of Y at a particular temperature, the greater the force required to cause cut-through at that temperature. The force necessary to cause cut-through will also depend on the area of contact of the two insulated wires just as cut-through occurs. The larger the area over which the stress is distributed, the greater the force required to cut through.

The shape of the contact area between crossed wires is approximately a circle. This can be seen from a consideration of Fig. 2. From the figure, $h = R - \tau$; so $r^2 = (R + \tau)^2$, or $r^2 = 4 R\tau$. Rotation of 180 degrees about the symmetry axis S leaves the figure unchanged. Rotation of 90 and 270 degrees just exchanges the role of the top and bottom wires. Thus, there are four places where $r^2 = 4 R\tau$. In between these four places, experiment and rigorous mathematical derivation show that $r^2 \cong 4 R\tau$ for $\tau$ small compared to R. In other words, the projection of r on a plane perpendicular to S as r swings through 360 degrees is a circle of area $A = 4\pi R\tau$.

According to Hertz,[1] the mean pressure P between two geometrical objects forced together (such as a ball against a plate or two rods crossed at right angles) is equal to a constant times the yield value for the material of which the objects are constructed. The constant depends on the geometry of the system.

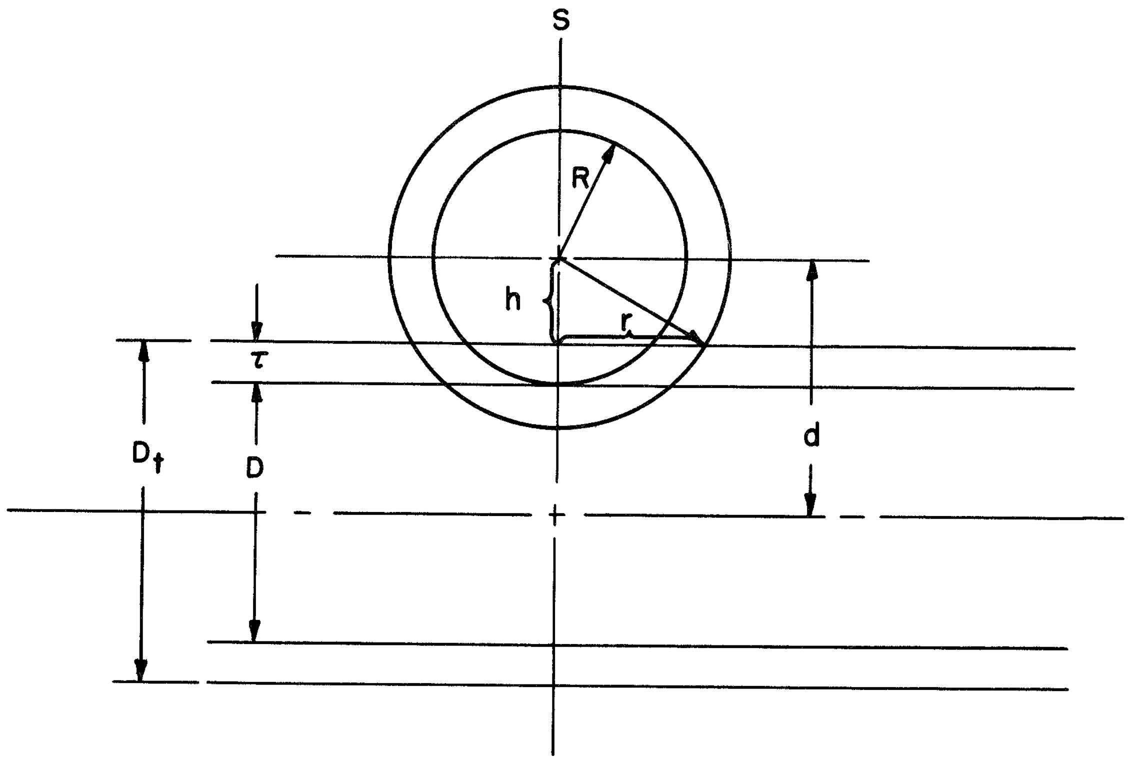


Fig. 2 Phantom view of two insulated wires crossed at right angles with conductors touching (extrusion of insulation not considered).

Experiment has shown Hertz's relationship to be approximately true. Consequently, yield-testing machines that press a ball or some other shape against a block of specimen with a flat face are a commercial product.

By using Hertz relationship and neglecting the increase in contact area between the crossed wires due to extrusion of thermoplastic material, the following equation is obtained:

$$P = W/4\pi R\tau = C' Y; W=CDBY \tag{1}$$

where W is the weight forcing the crossed wires together. The weight W is just sufficient to cause cut-through after infinite time. The above equation states that the weight just necessary to cut through is proportional to the product of bare wire diameter D, build B, and yield value Y of the insulation.

Equation (1) was used as a guide in designing the experiments to be described later.

EXPERIMENTAL

A. Cut-through Tester

Figures 3, 4, and 5 show various aspects of the cut-through tester. Figure 3 shows the binding posts that hold 25 pairs of crossed wires is place over the anvils. Push-rods with various weights attached are simultaneously lowered onto the crossed wires by pulling a wedge (shown in detail in Fig. 5). Figure 4 shows the complete assembly mounted in the oven. A panel of 25 neon lamps corresponding to each pair of crossed wires is mounted above the oven. The electrical circuit is arranged so that a neon lamp lights when the insulation cuts through and the conductors

[1] H. Hertz, J. Reine Angew. Math., **92**, 156 (1886); see F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids (1950), Oxford University Press, London.

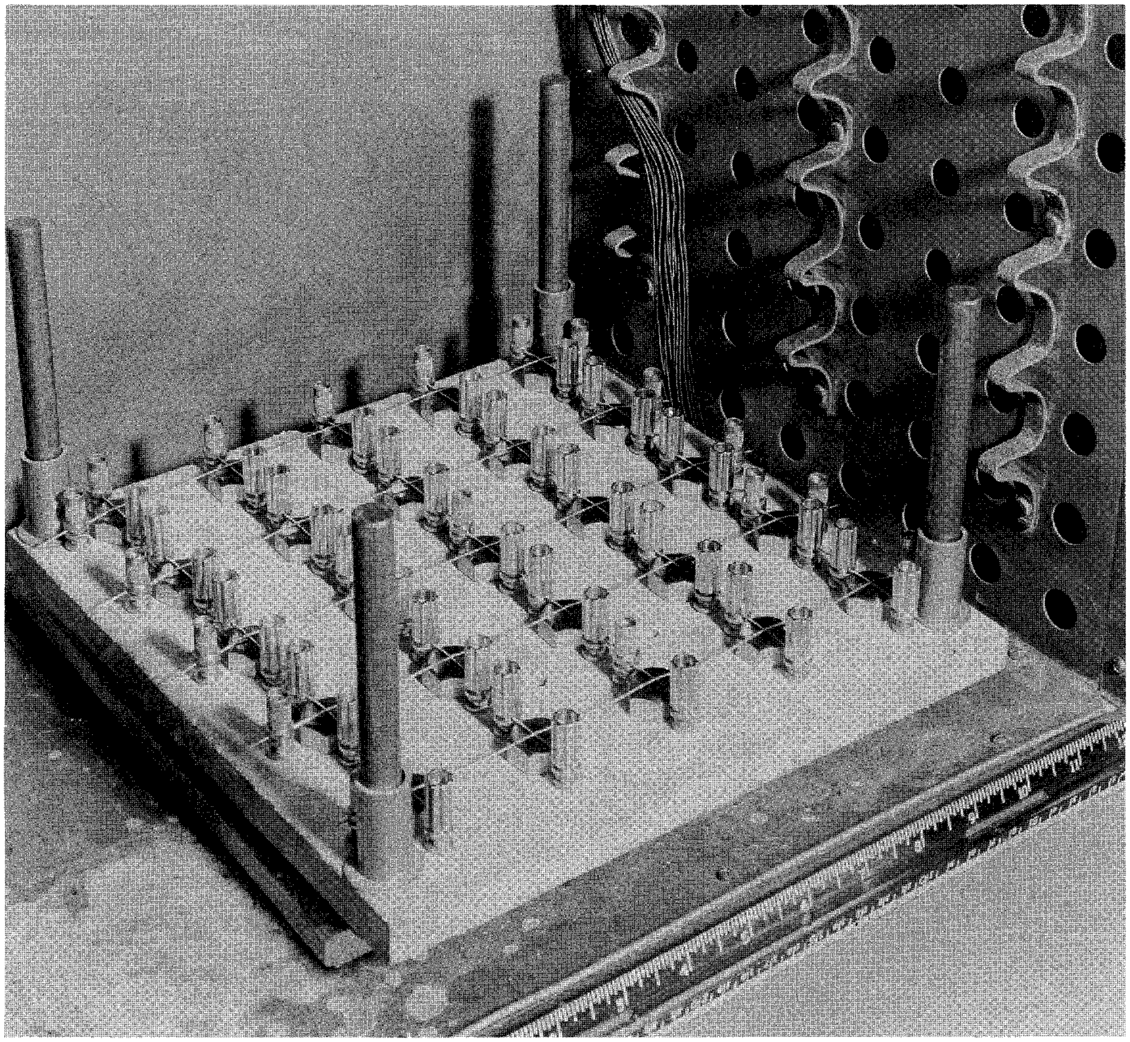

Fig. 3 Cut-through tester--view of binding posts that hold crossed wires in place over the anvils.

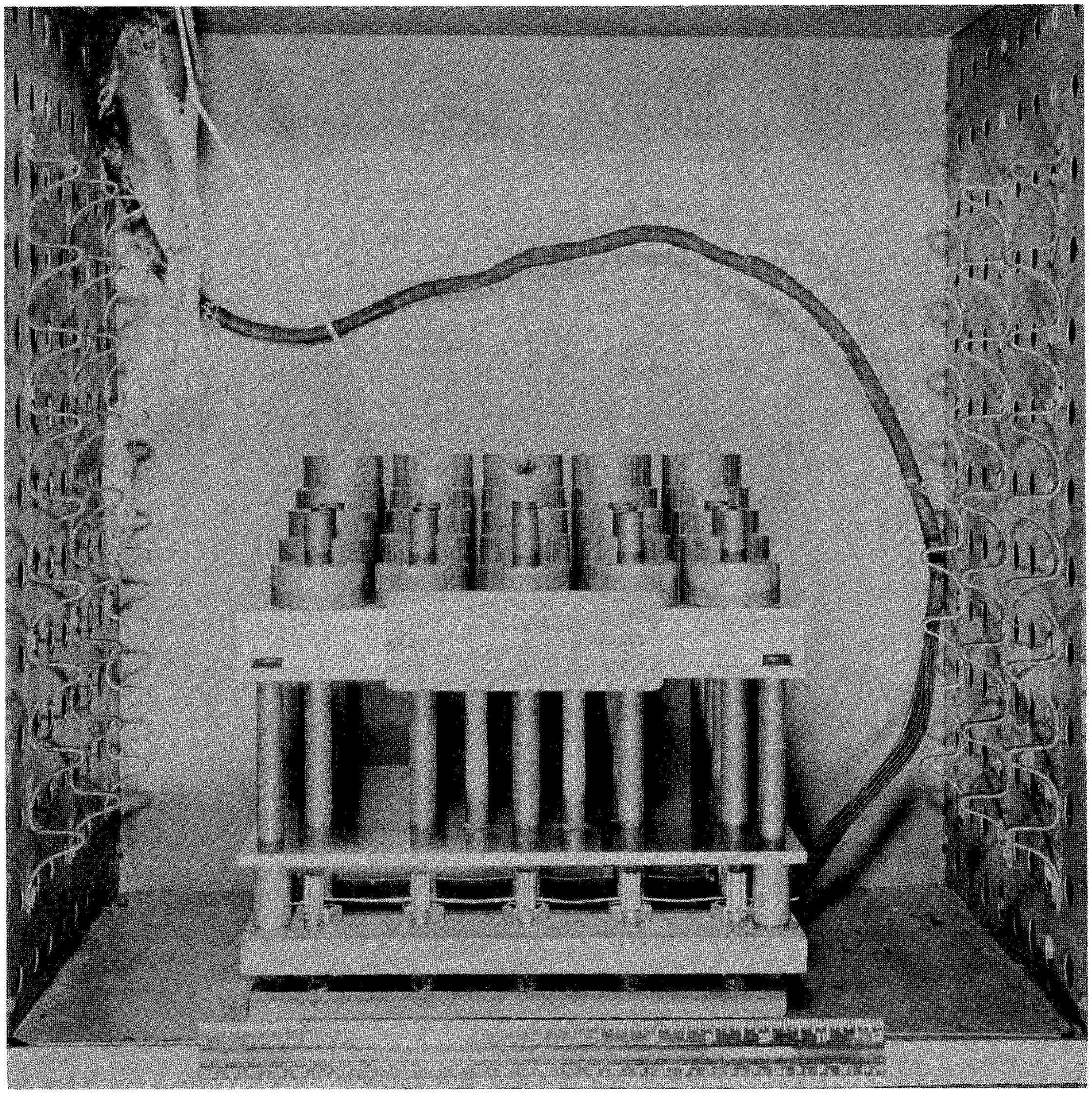

Fig. 4 Cut-through tester--complete assembly mounted in oven.

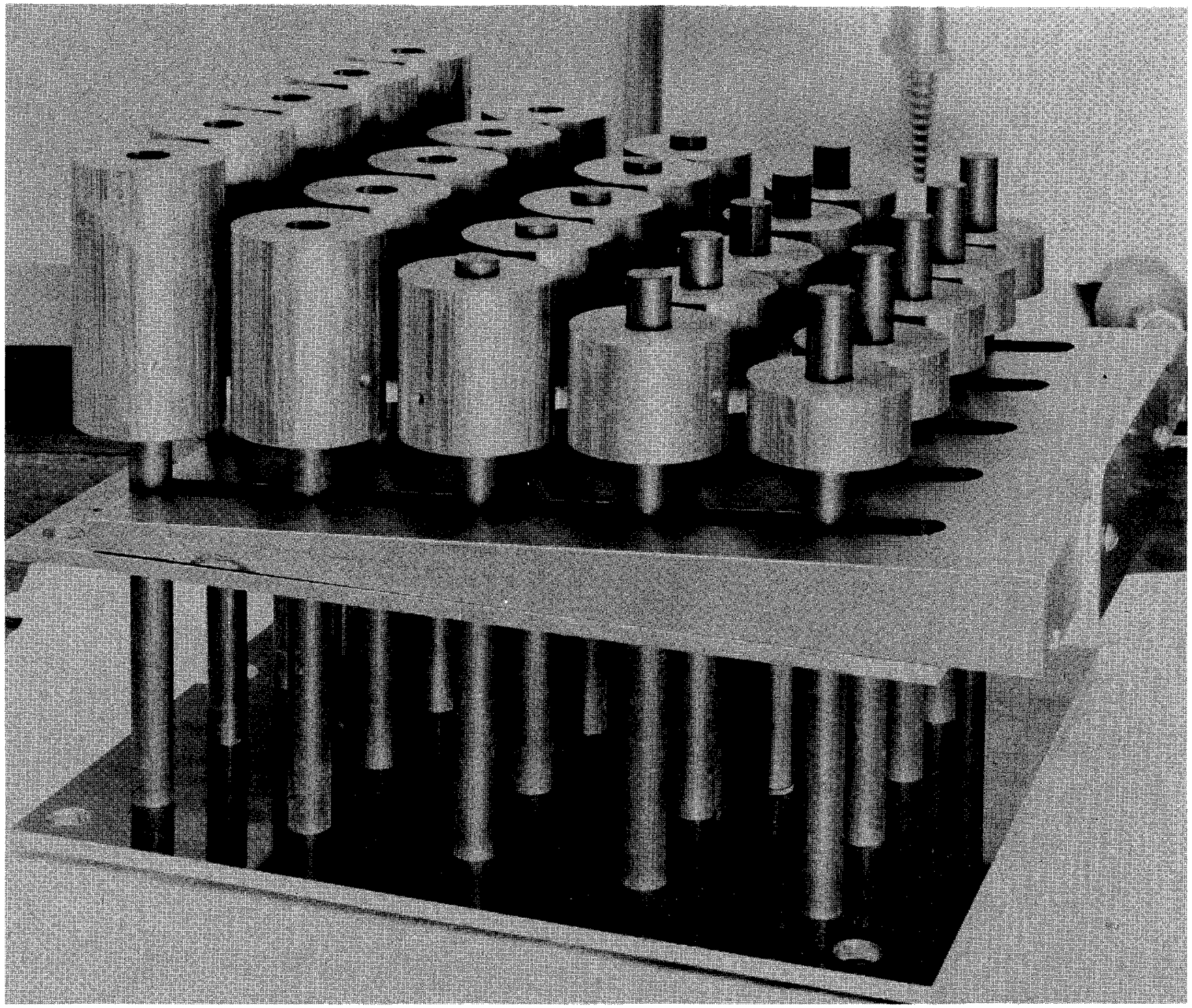

Fig. 5 Cut-through tester--detail of wedge arrangement for lowering weights.

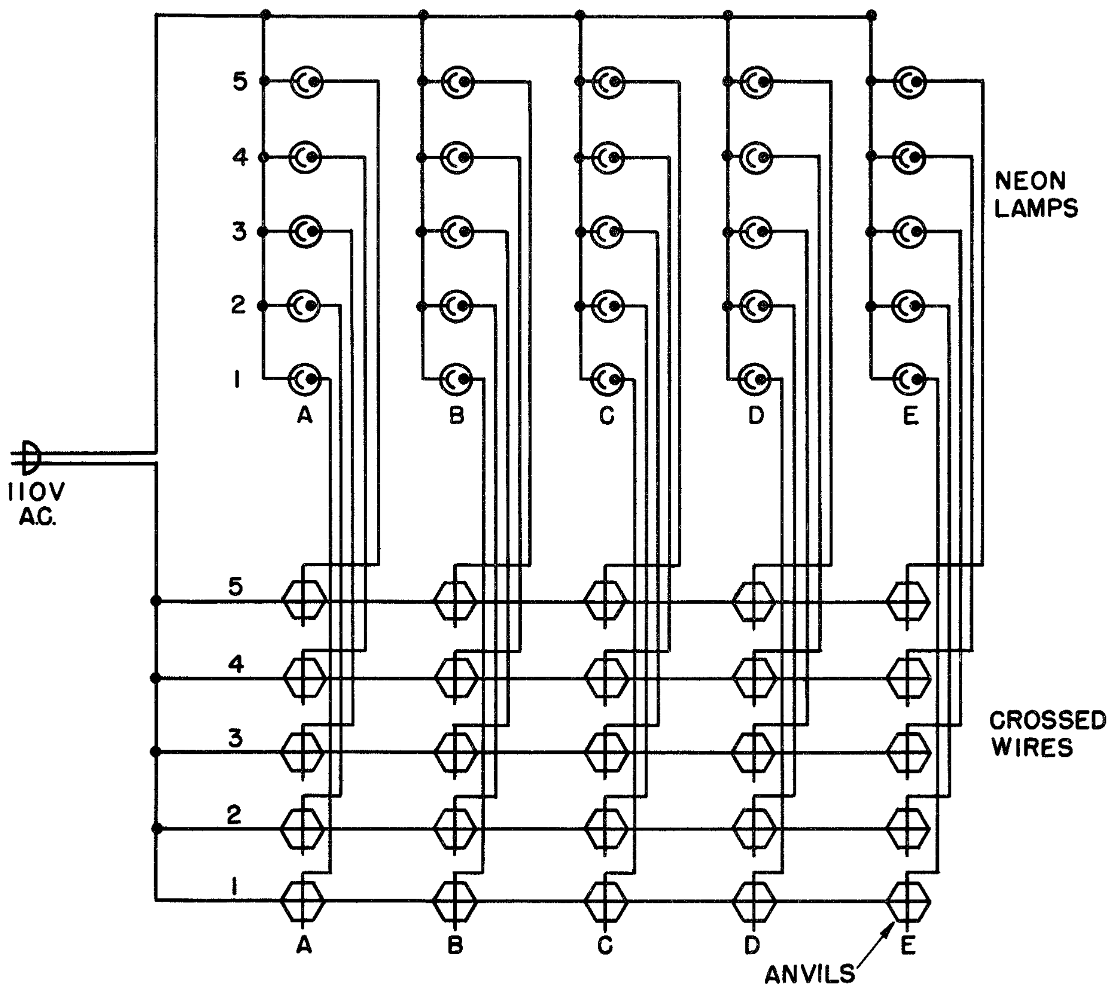


Fig. 6 Schematic diagram of cut-through tester circuit.

touch. A schematic diagram of the circuit is shown in Fig. 6.

To test a particular wire sample, the tester is loaded with wire, proper electrical contact being established through the binding posts which also position the wire. The push-rod guide, wedge, and weights are put in place and the oven turned on. It was necessary to leave the oven on for three hours, so that all the parts of the cut-through apparatus would be up to temperature before the wedge was pulled to lower the weights. Pulling the wedge lowered the push-rods gently on the crossed wires. Then the neon panel was observed visually to record the time of cut-through. In some instances, the approximate time of cut-though was recorded by a time-lapse movie camera, which photographed the neon panel and a clock at periodic intervals. In still other instances, no record of the time of cut-through was made, but after one week the neon panel was examined to determine which wires had cut through in that time.

B. Wire Tested

Polychlorotrifluoroethylene on aluminum wire was used in these test. This was the only thermoplastic insulated magnet wire obtainable with various coating thicknesses and wire diameters. Formex-covered wire could not be used, because the yield value of the insulation changes with time on heating in a temperature region where cut-through could be studied. One series of polychlorotrifluoroethylene-covered wire studied was made in a wire tire by J. W. Eustance and W. F. Gilliam. They coated 14-,32-, and 64- mil aluminum wire, previously cleaned with trisodium phosphate solution at 95° C. The coatings slurries contained a low-molecular-weight polymer of Kel-F, hexanol, and ethylene glycol, and were prepared by F. M. Precopio and R. W. Finholt.

A study of coating thicknesses and aluminum wire diameter was made on some of the wires. Short sections from the wires were embedded in Selectron resin, microtomed, polished, and measured with a calibrated microscope. The coating thickness was measured at the four points a, b, c, and d, as shown in Fig. 7. The diameter of the aluminum conductor d-b and a-c was also measured. The results are displayed in Fig. 8. The number of samples found to have a given coating thickness $\tau$ or wire diameter D is plotted as ordinate. The coating thickness or wire diameter is plotted along the abscissa (given as so many divisions on a calibrated microscope scale). The deviations given are plus or minus average deviations from the mean. Another series of wires were “hand-dipped” by J. f. McDevitt, Jr. He used slurries similar to those of Eustance and Gilliam to put various builds of polychlorotrifluoroethylene on 32-mil aluminum wire. The diameter and build of these wires were measure with a micrometer.

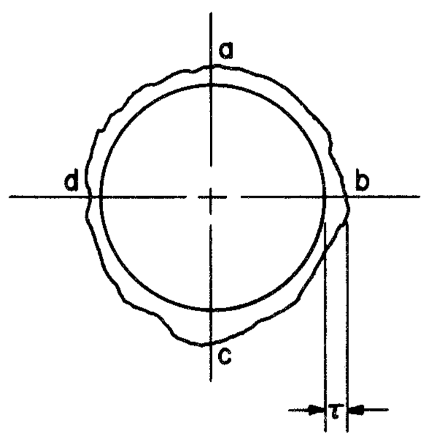


Fig. 7 Points at which coating thickness was measured.

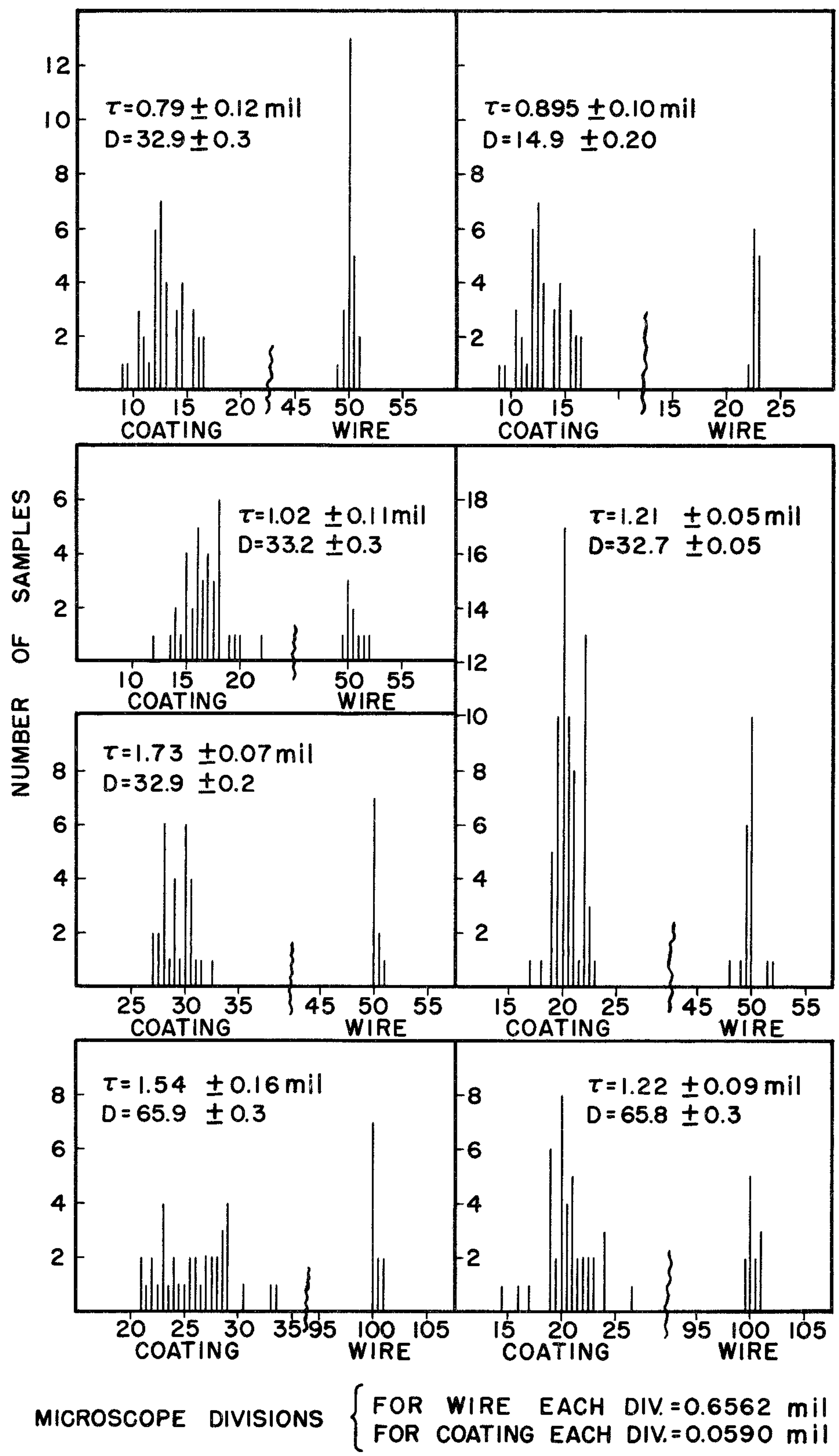


Fig. 8 Number of samples found to have a coating thickness $\tau$ or wire diameter D.

DATA

Early tests indicated that a load threshold existed; i.e., a given wire test at fixed temperature would cut through above a certain load but would not cut through below a certain load even if the load was maintained for periods up to three weeks. Most of the wires that were going to cut through would do so in the first 24 hours of test. In the tests that follow, the load was maintained on the wires for one week. If the insulation did not cut through in that time, it was assumed that it would never cut through. Above the threshold load, the time-load relationship seems to be adequately described by an empirical equation formulated by Nutting,[2] who first used it to describe the complex deformation of certain materials. Nutting's equation is:

$$d = \psi W^{\beta} t^{k}, \quad (2)$$

where d is the deformation (in our case, for a given wire size and coating thickness, the total deformation at cut-through is constant); W is the load (on the crossed wires); t is the time (for cut-through to occur); and $\psi$, $\beta$, and k are constants characteristic of the material. Equation (2) indicates that a lot of log time vs. log W is linear. This is shown in Fig. 9 for 32-mil aluminum wire with a 3.9-mil coating thickness of polychlorotrifluoroethylene. The three lines correspond to three different temperatures. At 175° C, the two lowest weights did not cause cut-through in one week's time. Each point on the graph is the average of five determinations.

Figure 10 shows the fraction cut through after one week as a function of load for 14.9-mil aluminum wire with builds of 1.00, 1.80, and 3.00 mils. The fraction cut through was determined by placing the same load on at least five pairs of crossed wires. In each case, all the wires will show cut-through when the load is over a certain amount. Then there is a "fuzzy" region is which some of the wires cut through and some do not. If enough samples are taken, the "fuzzy" region is generally quite regular, the larger loads causing cut-through in a greater fraction of the samples than the smaller loads. Below a certain load, none of the samples show cut-through. The number beside the experimental points indicates the number of pairs of crossed wires tested from which the fraction cut through was determined. The temperature in these experiments was 175° ± 1.5° C. Figures 11, 12, and 13 show fraction cut through vs. load for other wire sizes and coating thicknesses.

Examination of the data in Figs. 10 through 13 indicates that the largest weight that does not cause cut-through of any of the samples [W of Eq. (1)] does not obey Eq. (1). The weight is more dependent on wire diameter than coating thicknesses.

An empirical relationship,

$$W_{\text{none cut}} = CYD^{a} \tau^{b}, \quad (3)$$

was assumed. The slopes in a plot of log $W_{\text{none cut}}$ vs. log $\tau$ give $b \cong 1/3$ (see Fig. 14). The intercepts in the same plot (log W at $\tau = 0$), when plotted vs. log D, give from the slope of the line A = 2 and from the intercept CY = 0.022 (see Fig. 15). The yield value of quenched polychlorotrifluoroethylene at 175° C is 208 lb/in$^2$; therefore:

$$W_{\text{none cut}} = 1.06 \times 10^{-3}\, YD^{2} \tau^{1/3}, \quad (4)$$

where W is expressed in grams, Y in lb/in2, and D and $\tau$ in mils (0.001 inch). Equation (4) can be rearranged to give:

$$W_{\text{none cut}}/D_t^{7/3} = 0.175\, [1 - (B/D_t)]^2 (B/D_t)^{1/3}, \quad (5)$$

where $D_t = D + B$ = bare wire diameter + build, where build = $2\tau$. $(W_{\text{none cut}})/D_t^{7/3}$ as a function of $B/D_t$ is given in Fig. 16. The graph shows that, for a fixed total wire diameter $D_t$, the best wire design for resistance to cut-through is obtained when the build equals 1/7 the total wire diameter. However, 90 percent of the maximum load can be supported by a wire where $B = 0.06\, D_t$. Where $B/D_t < 0.06$, the load

[2] P. G. Nutting, J. Frankl. Inst., **191**, 679 (1921).

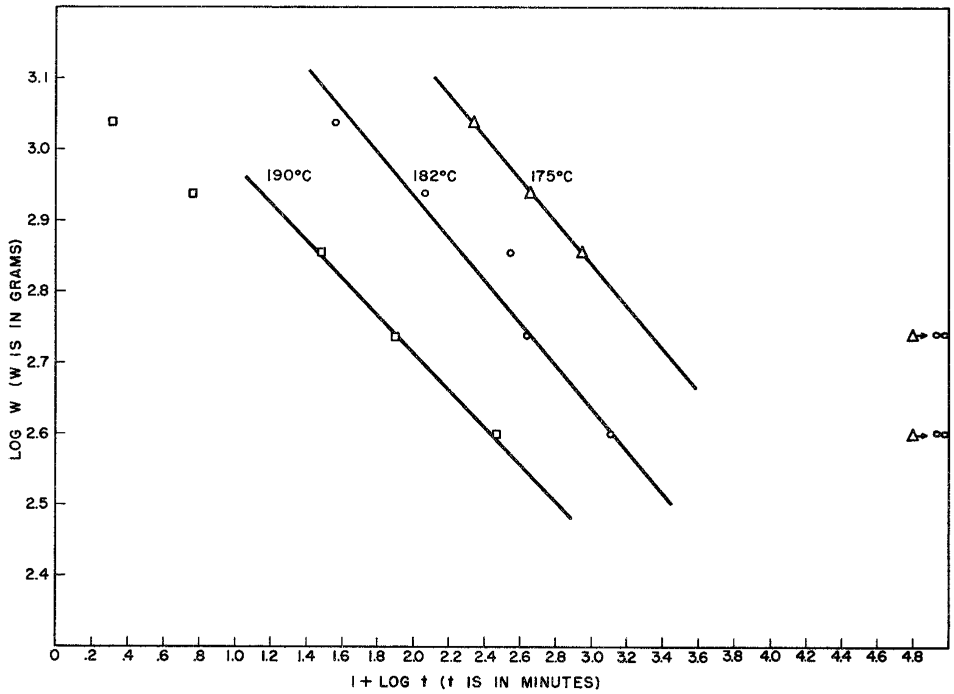


Fig. 9 Time of cut-through as a function of load for 32-mil aluminum wire with 3.9-mil coating thickness of polychlorotrifluoroethylene.

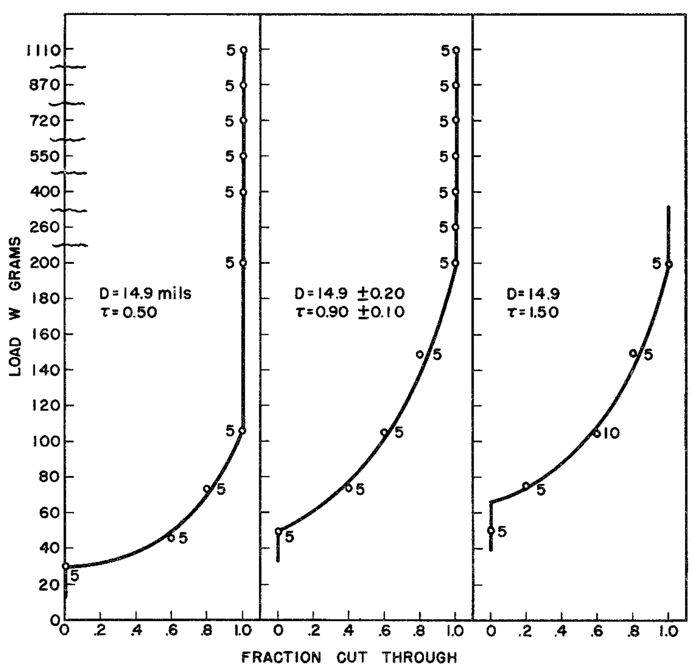


Fig. 10 Fraction cut-through as a function of load for 14.9-mil aluminum wire with 1.00-, 1.80-, and 3.00-mil coating thicknesses.

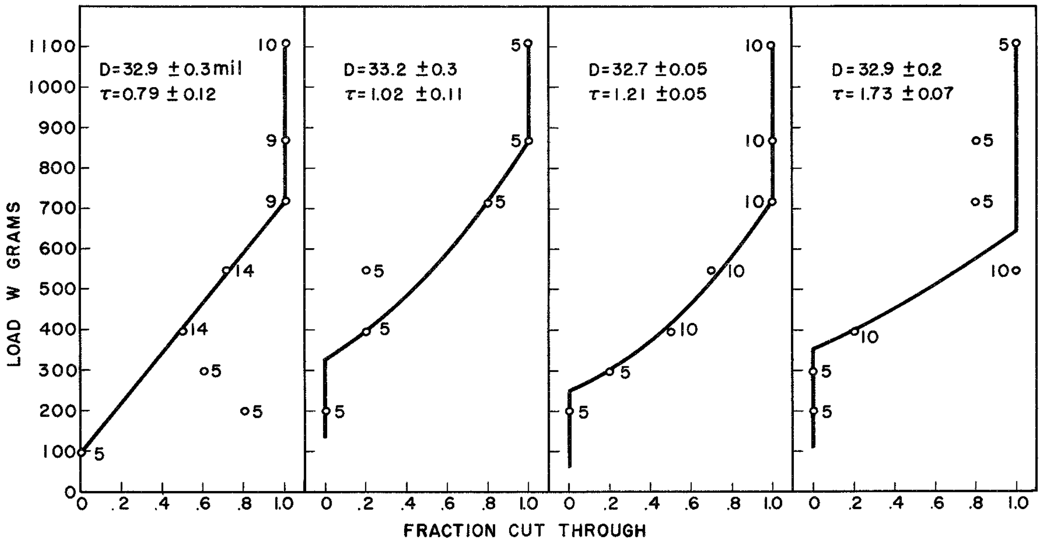


Fig. 11 Fraction cut-through as a function of load for 33-mil aluminum wire with 0.80-, 1.02-, 1.21-, and 1.73-mil coating thicknesses.

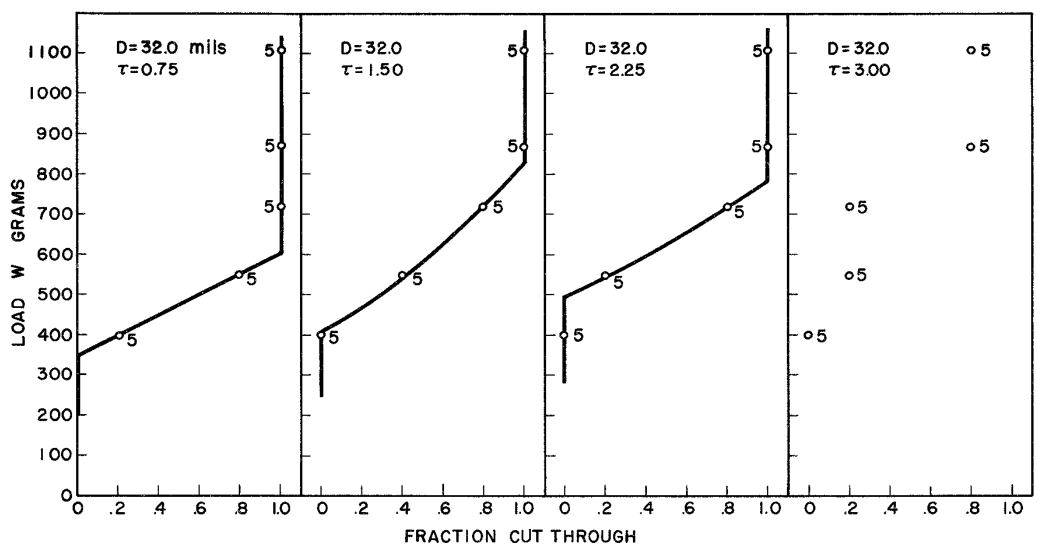


Fig. 12 Fraction cut-through as a function of load for 32-mil aluminum wire with 0.75-, 1.50-, 2.25-, and 3.00-mil coating thicknesses.

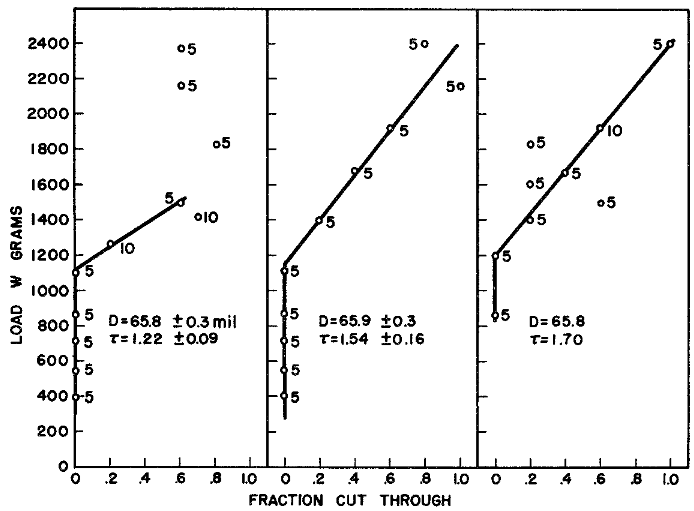


Fig. 13 Fraction cut-through as a function of load for 66-mil aluminum wire with 1.22-, 1.54-, and 1.70-mil coating thicknesses.

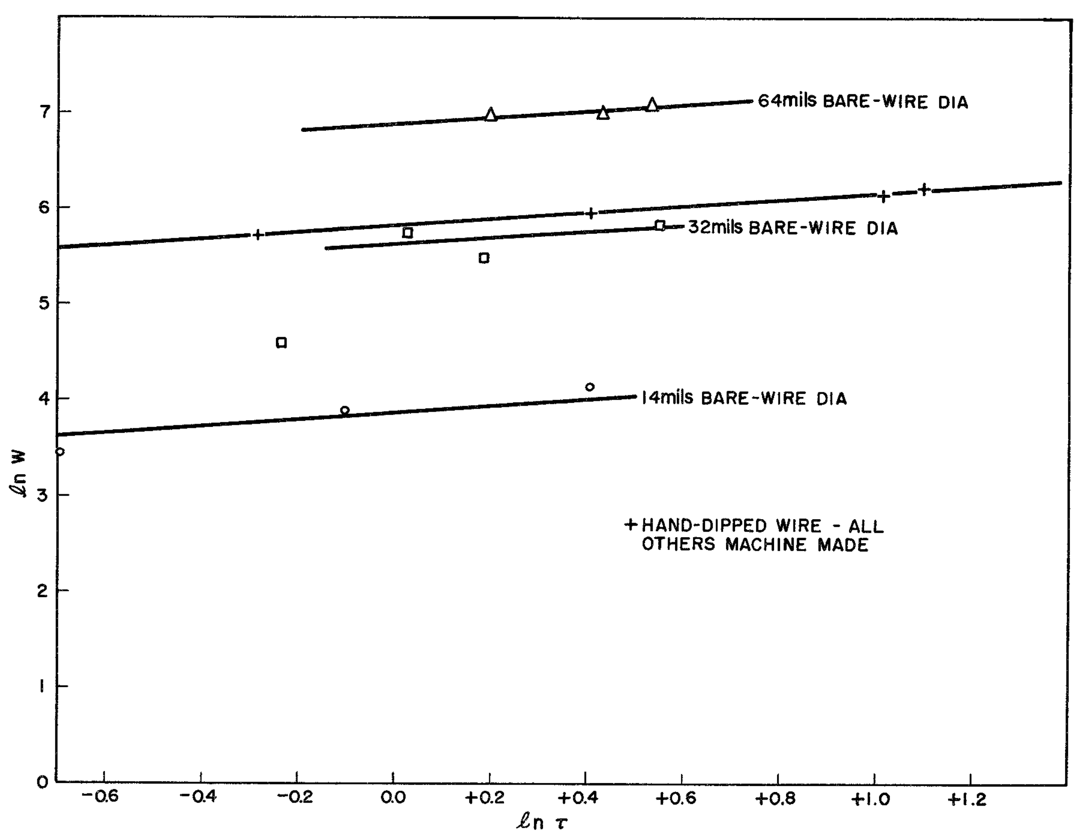


Fig. 14 Plot of log of threshold cut-through weight vs coating thickness.

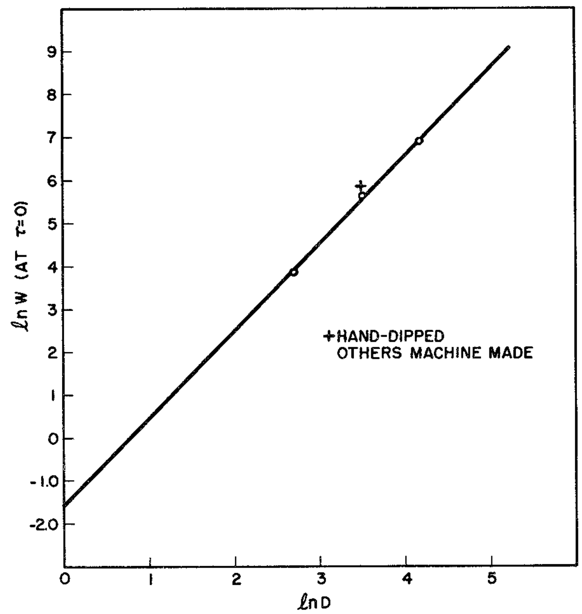


Fig. 15 Intercepts of Fig. 14 (log $W_{at\, \tau=0}$) plotted vs log bare wire diameter D.

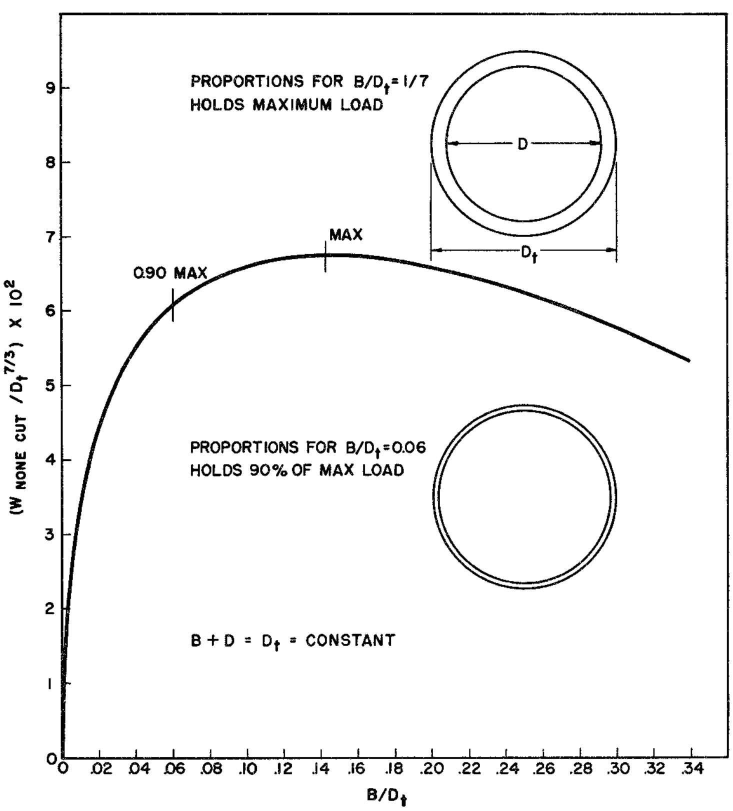


Fig. 16 Figure showing best design proportions for maximum resistance to cut-through.

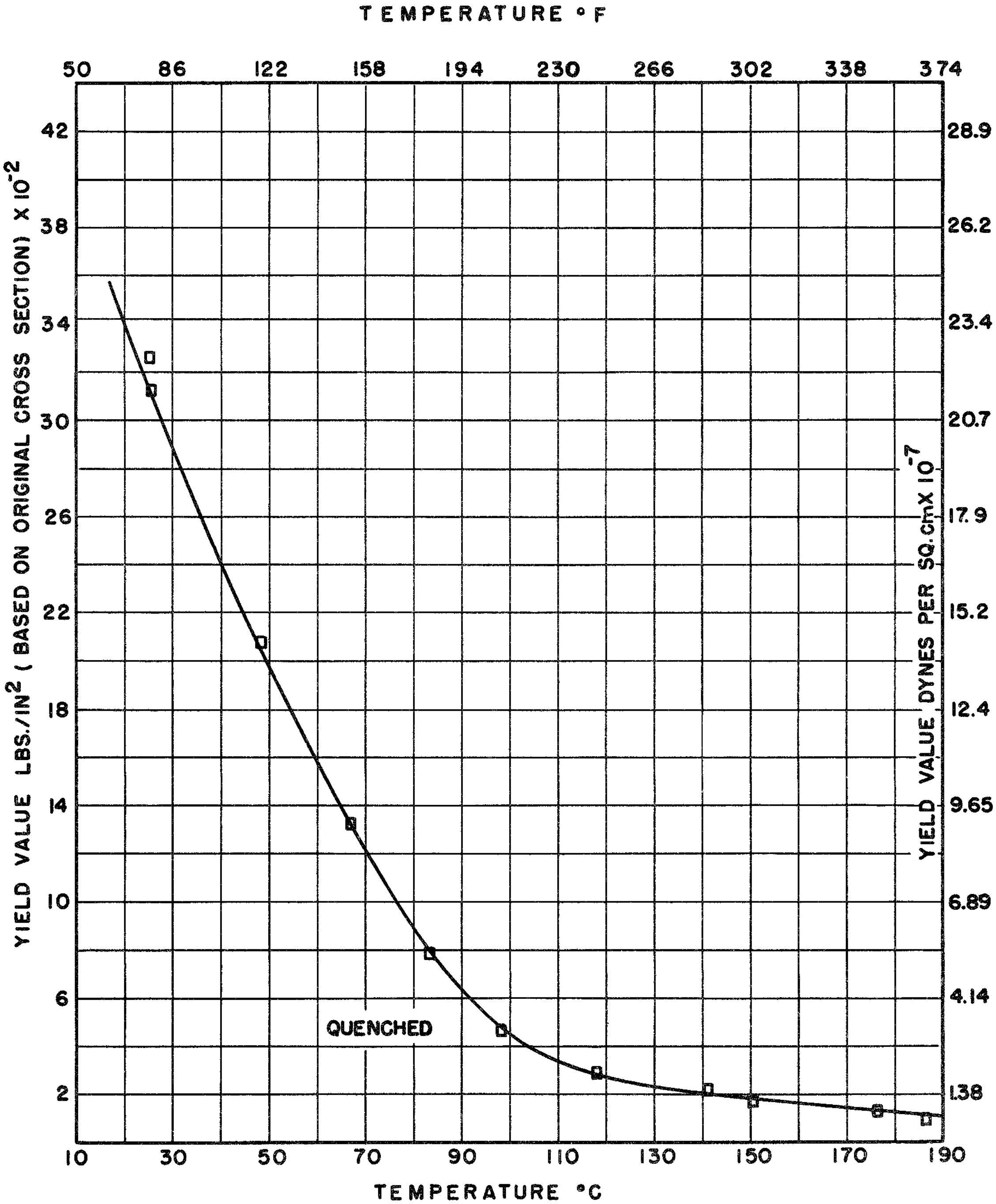


Fig. 17 Yield value vs temperature for quenched polychlorotrifluoroethylene.

that can be supported without the occurrence of cut-through falls rapidly. It would seem wise to stay on the high side of this point in deciding the best proportions for wire and thermoplastic insulation from a cut-through standpoint.

The results obtained above would be expected to apply to any thermoplastic insulation. If the yield value of the insulation is known at the temperature in question, Eq. (4) will give the maximum load the crossed wires will support at given bare wire diameter and coating thickness.

## CONCLUSIONS

(1) The most important result obtained in the above work is that there is a threshold cut-through load. This is shown conclusively in Figs. 10 through 13.

(2) For thermoplastic insulation, maximum resistance to cut-through is obtained when the ratio of "build" to total wire diameter is 1:7. However, a ratio of 1:10 is almost as good and provides a good margin of safety for variations in "build."

(3) Considering a thermoplastic insulation from a cut-through point of view, the higher the yield value of the thermoplastic, the greater the resistance to cut-through.

(4) The following equation, relating the threshold weight W (in grams), at which cut-through of crossed wires will not occur, to the yield value Y (in $lb/in^2$), the bare wire diameter D (in mils, i.e., 0.001 inch), and the coating thickness $\tau$ (in mils), has been obtained:

$$W = 1.06 \times 10^{-3}\ YD^2\ \tau^{1/3}.$$

This equation would be expected to hold for any thermoplastic insulation. Figure 17 (taken from Reference 3) gives Y as a function of temperature for polychlorotrifluoroethylene. This curve can be used with the equation above to obtain the threshold cut-through load at any desired temperature where the insulation has thermoplastic properties.

(5) J. W. Eustance and W. F. Gilliam of this laboratory have found, in a limited number of JAN-type tests with polytrichlorofluoroethylene on aluminum, that the cut-through obtained is not affected by bare wire diameter or coating thickness (within their experimental error). This means that the JAN test is measuring, in an arbitrary fashion, some complex property of the insulation. This is useful for comparative purposes. For instance, the JAN cut-through temperature can be correlated with the amount of cure in silicone-type insulations. However, it is impossible to relate the JAN cut-through temperature to any of the variables appearing in Eq. (4). In order for the JAN test to yield information that could be related to wire diameter, insulation thickness, etc., it would be necessary to raise the temperature much more slowly. This would make the total time required to complete a test so long that a more fundamental type of test, such as the one used here, might best be used—that is, a test to find the threshold weight necessary to cause cut-through at the temperature of interest, on the size wire available. Then Eq. (4) may be used to determine the threshold cut-through weight for wire of other sizes with various coating thicknesses. If the yield value vs. temperature curve for the insulation is known, then this may be used with Eq. (4) to determine the threshold cut-through weight at other temperatures. The drawback to the type of test performed here is the week's time required to complete a test. However, there seems to be no way to avoid using this much time if basic cut-through information is desired.

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