SILICONE RUBBER AS CABLE INSULATION

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The first shipments of silicone rubber to cable manufacturers were made in 1945. These early silicone rubbers were characterized by unusual thermal stability, fair electrical properties over a wide temperature range, and resistance to corona and weathering. Their usefulness as cable insulation was limited, however, by relatively poor physical strength and fabrication difficulties. During 1946 only a few hundred pounds per month of silicone rubber were used for wire and cable insulation.

In spite of their physical limitations, some uses and many potential applications were found for silicone rubber insulated cable. Interest stimulated by the inherent stability of these rubbery insulating materials resulted in progressive improvement in their physical and dielectric properties and in their handling characteristics. During the past seven years, radical improvements have been made in the polymerization, compounding, and vulcanization of silicone rubber. As a result, the consumption of silicone rubber as cable insulation has increased to tens of thousands of pounds a month.

Early in the development of silicone rubbers it was recognized that the polymer determined the inherent stability of the rubber, while fillers determined to a great extent the physical and electrical properties of the vulcanized and cured rubber. The properties of silicone rubbers can therefore vary over a wide range. Considerable research was necessary to obtain the best combination of properties. The properties of the silicone rubbers that are dependent primarily upon the silicone polymer are:

Low temperature flexibility

Thermal stability

Oil and solvent resistance

Corona, ozone and weather resistance

Non-adhesiveness to organic materials

These properties can be modified to a certain extent by changes in the polymer. Incorporation of a small amount of phenyl as a side group into the otherwise standard dimethyl polysiloxane polymer will extend the low temperature operating range of a silicone rubber from -55 to -90 C. Changes in the polymer size determine to a great extent the consistency of the silicone rubber stock. A silicone polymer with low molecular weight will make a paste suitable for knife coating onto fabric or for caulking voids in electrical equipment. Higher consistency rubber stocks can be made from higher molecular weight polymers. These rubber stocks are suitable for molding, extruding and calendering. Improvement in these polymers has resulted in stocks that can be handled by conventional wire covering techniques. Silicone rubber stocks are now easy to mill. They can be extruded uniformly and vulcanized in continuous vulcanizers. Adhesion or release from the wire can be controlled by treating the wire.

The properties that are dependent upon the type and amount of fillers compounded into the polymer are:

Color

Specific gravity

Elongation

Tensile strength

Durometer

Tear strength

Dielectric properties

Compression set

Expansion coefficient

Moisture resistance

Chemical resistance

Thermal conductivity

Many hundreds of fillers and combinations of fillers have been investigated. Only a few of these have proved useful and they have been incorporated in the commercial compounds. The filler used in the first commercial compounds was titanium dioxide. These rubbers had fair physical and electrical properties but their electrical properties were adversely affected by moisture.

Because they are less affected by water, silicon dioxide fillers were next to receive attention. Silicone rubbers compounded with silica in the form of diatomaceous earth have been used in large quantities. These rubbers are characterized by excellent handling properties, fair physical and good electrical properties. In general, they can be extruded in conventional rubber extruders at rates comparable to those obtained with organic rubbers. The electrical properties are satisfactory and they are less affected by moisture than the titanium dioxide filled stocks.

Several years ago, the first major improvement in the toughness and physical strength of silicone rubbers was achieved when stocks containing silicas of the aerogel type were developed. These stocks have good physical and electrical properties. However, fillers of this type contain inorganic salts, and stocks compounded with them have high water absorption. At elevated temperatures the effects of water are accelerated. Both the physical and electrical properties of these stocks deteriorate rapidly when the rubber is subjected to hot, moist conditions or immersed in water. A water absorption value of 20% after immersion in boiling water for 70 hours is not unusual for stocks of this type. This fact seriously limits the usefulness of these stocks for wire and cable insulation.

The physical and electrical properties of typical commercial silicone rubbers compounded with titanium dioxide and with silicon dioxide of the diatomaceous earth and aerogel types are given in Table I.

Table I

Typical Properties of Earlier Silicone Rubbers

	Silastic 167	Silastic 181	Silastic 250
Filler	Titanium Dioxide	Diatomaceous Earth	Aerogel
Tensile Strength[1], psi	550	755	675
Elongation, %	85	65	290
Durometer, Shore A	75	85	45
Tear Strength, lbs./in.	55	38	70
Compression Set @ 150 C.	50	70	60
Dielectric Strength[2], V/M	350	400	400
Dielectric Constant 100 cps.	9.6	3.6	3.4
Power Factor 100 cps.	0.007	0.018	0.004
Water Absorption, %			
7 days @ room temperature	1.3	1.1	6.5
70 hours @ 100 C.	--	--	20.0

[1] All measurements according to ASTM methods made on molded sheets cured 24 hours at 250 C.

[2] Rapid rise, 1/4" electrodes on 1/16" molded sheet.

The improvement in physical and electrical properties obtained with silica aerogel fillers stimulated further interest in fillers of this general type. It was also recognized that the dielectric loss of the silicone polymer approaches that of pure quartz. It is obvious then that if an extremely pure silica could be obtained the excellent dielectric properties of the silicone polymer would not be deteriorated by additions of such a filler. Furthermore, if the silica were pure, the physical and electrical properties would not be affected appreciably by water.

Recently, a silica meeting these requirements has been developed. This silica is called "fumed silica" or silica soot. Fumed silica is made by passing silicon tetrachloride through an oxygen and hydrogen flame. The reaction produces a finely divided, chemically pure silica. This silica is the basis for a series of new silicone rubbers that are of special interest to the cable industry. Electrical properties of silicone rubber are no longer limited by the filler since the fumed silica possesses dielectric properties essentially the same or better than those of the silicone polymer. Thus, these fumed silica filled silicone rubbers have the lowest dielectric losses obtainable with the present silicone polymers.

Because of the physical nature of the fumed silica, tough, tear resistant silicone rubbers are obtained. By varying the amount of silica in the formulation, rubbers with varying degrees of hardness can be made. In Figure 1, the tensile strength and elongation of commercial silicone rubbers compounded with the various fillers mentioned previously are compared with two typical commercial silicone rubbers compounded with fumed silica. A silicone rubber compounded with fumed silica especially for cable insulation and identified as Silastic 80, will be described in greater detail. The properties of this silicone rubber are given in Table II.

Table II

Typical Properties of Silastic 80

Color	White
Specific Gravity	1.25
Durometer, Shore A	80
Tensile Strength, psi	800
Elongation, %	200
Compression Set at -40 C., %	46
150 C., %	30
200 C., %	70
Dielectric Strength, V/M 1/4" electrodes, rapid rise	
(a) Cond. D 24/25/50	500
(b) Immersed in 70 C water for 7 days	400
Dielectric Constant	
(a) Cond. D 24/25/50	
10^2 cps	2.92
10^6 cps	2.92
(b) Immersed in 70 C water for 7 days	
10^2 cps	3.48
10^6 cps	3.48
Power Factor	
(a) Cond. D 24/25/50	
10^2 cps	0.0006
10^6 cps	0.0006
(b) Immersed in 70 C water for 7 days	
10^2 cps	0.002
10^6 cps	0.0016
Volume Resistivity, Ohm-cm	
(a) Cond. D 24/25/50	$>10^{14}$
(b) Immersed in 70 C water for 7 days	10^{14}
(c) Measured at 200 C	10^{13}

Surface Resistivity, Ohm	
(a) Cond. 24/25/50	$>10^{13}$
(b) Immersed in 70 C water for 7 days	10^{12}
(c) Measured at 200 C	10^{13}
Thermal Conductivity, cal/cm^2/°C/cm/sec.	0.513×10^{-3}
Coefficient of Thermal Expansion	$\alpha = 7.2 \times 10^{-4}$ $\beta = 7.76 \times 10^{-8}$
Shrinkage, after curing 24 hours @ 250 C	5%
Brittle Point, °C	-62
Durometer Change at 250 C	0
Water Absorption, 7 days @ room temperature, %	0.8
70 hours @ 100 C, %	2
Chemical Resistance as Indicated by % Swell	
ASTM #1 Oil, 7 days @ 150 C	8
ASTM #3 Oil, 7 days @ 150 C	38
Chlorinated Transformer Oil, 70 hours @ 175 C	36
Acetone, 7 days at room temperature	13
Ethyl Alcohol, 7 days @ room temperature	2
Gasoline, Stoddard Solvent, Carbon Tetrachloride, Toluene, Methyl Chloride — 7 days @ room temperature	>150
Sulfur Dioxide, 7 days @ room temperature	2
Freon 12, 7 days @ room temperature	39
Freon 114, 7 days @ room temperature	39

Note: All measurements in accordance with ASTM methods. Tests made on molded sheets cured 24 hours at 250 C.

Two silicone rubbers may be blended to give certain specific properties. In general, when two silicone rubbers are blended, most of the properties vary in direct proportion to the amount of the two rubbers in the blend as indicated in Figure 2. These data show the physical properties resulting from the blending of a fumed silica filled silicone rubber with a diatomaceous earth filled stock. The properties at the right and left hand ordinates are typical of the two stocks before blending. As they are blended in various proportions, the properties are changed in a similar proportion.

This is also true of the electrical properties that are dependent upon the filler. For these particular stocks, power factor is dependent upon the filler, but the dielectric strength and dielectric constant remain essentially the same. For the blends shown in Figure 2, the dielectric constant and power factor at 100 cycles per second are given below:

Percent of Silastic 80	Percent of Silastic 172	Dielectric Constant	Power Factor
0	100	3.25	0.0064
20	80	3.20	0.0047
40	60	3.14	0.0034
60	40	3.09	0.0024
80	20	3.06	0.0017
100	0	3.04	0.0008

A similar change in the properties of a silicone rubber will be obtained when additional filler is added to a compounded stock. For example, the addition of titanium dioxide to a stock containing fumed silica will alter the properties as shown in Figure 3. The tensile strength and elongation are decreased as the percentage of titanium dioxide increases. Since titanium dioxide has a high dielectric constant, the dielectric constant of the compound will increase as more filler is added. In this example, the power factor remains the same.

An outstanding property of silicone rubbers filled with fumed silica is the stability of electrical properties over a wide temperature range. In Figure 4, the electrical properties of Silastic 80 are shown as a function of temperature. Dielectric strength, dielectric constant, and loss factor remain unchanged at temperatures as high as 250 C. Only the insulation resistance of extruded cable shows a decrease with increasing temperature. However, this decrease is not serious within the useful temperature range for the material. Properties at low temperatures have not been investigated completely, but indications are that no significant changes will occur at temperatures down to -50 C.

The low dielectric loss of this type of silicone rubber has been mentioned previously. The loss factor of Silastic 80 as a function of temperature is compared with several typical silicone rubbers in Figure 5. It is interesting to note that the loss factor of Silastic 80 is two orders of magnitude below that of a diatomaceous earth filled stock and it does not change with temperature.

The unusual stability of fumed silica filled silicone rubbers when immersed in water is shown in Figure 6. In this figure, the insulation resistance of 50-foot lengths of extruded cable immersed in hot water is plotted against immersion time. For comparison a silica aerogel filled silicone rubber was tested at the same time and failed in about 3½ months. After more than 11 months immersion in water at 70 C, the silastic 80 insulated cable shows only a small decrease in resistance and no failure in the near future is indicated. The dielectric strength of cable removed from the water periodically is not changed. The change in capacitance and dissipation factor of this cable is given in Table III. These measurements were made on the same length of cable described above.

Table III

Electrical Properties of Silastic 80 Cable
Immersed in Water at 70 C.

Time	Insulation Res. Meg/1000 ft.	Capacitance mf	Dissipation Factor %
0	10,000	0.0034	0.43
6 mo.	5,000	0.0041	0.30
11 mo.	5,000	0.0041	0.10

Further evidence of outstanding moisture resistance is the fact that the insulation resistance of a 50-foot length of extruded Silastic 80 cable with an insulation thickness of 0.030" is 2500 megohms per 1000 feet after more than 30 days in boiling water.

The dielectric constant and loss tangent of silicone rubbers filled with fumed silica do not change appreciably with frequency between 60 cycles per second and 1 megacycle per second. However, at higher frequencies, the loss tangent increases with frequency and peaks at a frequency greater than 10,000 megacycles per second. This increase in loss tangent at the higher frequencies is due to polarity of the silicone-oxygen linkage in the silicone rubber polymer. It is characteristic of all silicone rubbers. The dielectric constant and loss tangent at various frequencies for a sample of Silastic 80 are given in Table IV.

Table IV

Dielectric Constant and Loss Tangent for Silastic 80

Cycles Per Second	Dielectric Constant	Loss Tangent
10^2	2.96	0.00058
10^3	2.95	0.00052
10^4	2.95	0.0005
10^5	2.95	0.0006
10^6	2.95	0.0006
10^7	2.95	0.0010
10^8	2.95	0.002
10^9	2.93	0.0059
3×10^9	2.90	0.010
10^{10}	2.85	0.0167

Of the elastomeric insulating materials known today, silicone rubbers are the most resistant to the chemical and electrical effects of corona discharge. The results of a severe corona test are shown in Figures 7 and 8. In this test, samples of extruded cables were wrapped around an insulated mandrel having a diameter equal to that of the cable. A copper screen electrode was then wrapped around the coil of cable. A voltage stress of 400 volts per mil was applied between the cable conductor and the copper screen. Severe corona discharge occurred between the screen and cable surface and electric discharge streamers were observed from the ends of the screen to the cable surface. Organic rubber insulated cables reported to be compounded for corona resistance failed this test in 3 minutes. This sample is shown in Figure 7. The silicone rubber cable failed after 12,000 hours under continuous stress. This sample is shown in Figure 8. It will be noted that there is no sign of deterioration of the silicone rubber. Failure was due to voltage fatigue under the high electrical stress rather than to any effects of the corona.

The high thermal conductivity of many silicone rubbers is another property of special interest in power cable applications. In Figure 9 the copper temperature rise of silicone rubber insulated cable is compared with that of conventional thermoplastic insulated cable at various load currents. In this test four cables were placed in a conduit and then loaded from a variable voltage source. The temperature of the copper was determined from its change in resistance. The copper temperature rise of the plastic insulated cable was about 40% higher than the silicone rubber cable at a load current of 10 amperes and 33% higher at 30 amperes. Not only can the silicone rubber cable operate at much higher temperatures than the plastic covered wire, but the silicone rubber cable will be significantly cooler at the same load.

The thermal stability of silicone rubber insulated cable is difficult to define since its life at high temperature will depend greatly upon the application. One test of thermal stability is to age lengths of cable at various temperatures and periodically measure the dielectric strength of the cable insulation. A test of this type shows that the dielectric strength of a Silastic 80 insulated cable remains unchanged after 6 months aging at 250 C.

Tests at lower temperatures give increased life. Evaluations of this kind and several years' field experience indicate that silicone rubber insulated cables can be operated continuously at temperatures in the range 150 C to 200 C with a life expectancy equal to that of organic insulated cables at their respective operating temperatures.

As the temperature is increased above 150 C, however, some decrease in flexibility of the cable will occur. If flexing is a requirement of the application at these higher temperatures, some decrease in life must be expected. However, unlike most organic insulating materials, silicone rubbers do not lose their insulating qualities after aging at high temperatures. When silicone rubbers are completely decomposed by burning, the remaining ash retains its insulating properties. This fact is used to advantage in military control cables that must remain operative after several hours in an open flame.

A special silicone rubber coated glass cloth is also being used for electrical insulation. Recent work has produced silicone rubber pastes that can be applied in one-pass to glass cloth to form a uniform coating of high dielectric strength. This material in the form of completely cured tapes can be wrapped in conventional equipment to produce electrically insulated cables.

For some cable construction a wrapped or taped insulation may be desirable. A semi-vulcanized silicone rubber tape is ideal for such applications. One commercially available tape consists of an impregnated Fiberglas backing with a layer of silicone rubber calendered on one side. The layer of rubber is given a partial vulcanization to facilitate handling. A typical construction consists of several layers of this tape applied on a conventional taping machine followed by a wrap of Fiberglas or cotton stripping tape. The cable is then placed in an oven for a few hours to complete the vulcanization and cure of the silicone rubber tape. The tape will bond to itself to form a solid, tough jacket with high dielectric strength. Cables insulated in the laboratory with 6 layers of 0.010" semi-vulcanized silicone rubber tape can be flexed around a mandrel having a diameter twice the cable diameter without damage to the insulation or decrease in dielectric strength.

Silicone rubbers can be colored by adding small amounts of inorganic pigments. A wide range of colors are possible. The physical and electrical properties of the stock are not changed appreciably when very low percentages of pigment are added. Colored silicone rubbers are usually required in multiconductor cables for identification purposes.

Special Silicone Rubbers

Fully cured silicone rubbers have higher shrinkage values than organic rubbers. The shrinkage of silicone rubber just after vulcanization is equivalent to that of organic rubbers. The high temperature oven cure generally required in fabricating silicone rubber results in additional shrinkage. Where the shrinkage of silicone rubber after vulcanization may be only 2%, the fully cured silicone rubber part may show total shrinkage as high as 6%. In the fabrication of parts to close tolerances, this presents problems. It means that molds and dies designed for use with organic rubber produce undersized or distorted parts. In the past, molds and dies have been cut especially for silicone rubber. Recent work done on new silicone rubber stocks, however, has reduced over-all shrinkage to 2½ to 3%. This makes it possible in many cases to use these new stocks in molds and dies designed for organic rubber. These stocks are useful for molded cable connector inserts and similar cable terminal and sealing parts.

In the past it has been necessary to vulcanize silicone rubber stocks by heating them at 120 to 150 C. Recent work has produced silicone rubber stocks that will vulcanize at room temperatures. This is accomplished by incorporating special vulcanizing agents in the silicone rubber stocks. Two component formulations are made and mixed just before use. Working time is several hours and vulcanizing time is about 24 hours. The mix sets up without porosity. Pastes suitable for caulking and coating, and stocks for calendering and solution coating are available. These room temperature vulcanizing formulations show promise where heat cannot be applied to vulcanize the silicone rubber. Sealing electrical equipment and field repair and splicing of silicone rubber insulated cables are suggested uses.

Fabrication of Silicone Rubber

In general, silicone rubbers designed for extrusion can be handled on conventional rubber or plastic extrusion machines. Extrusion rates comparable to those used for organic rubber compounds can be maintained.

The type of feed screw in the extruder is an important factor in determining the extrusion rate and quality of the extruded cable. A single thread diminishing pitch screw is recommended for extruding most silicone rubber. This type of screw is similar to those generally used for extruding plastic covered cable. In a particular test using such a screw with a compression ratio of 2.76 to 1, silicone rubber insulated cable with a wall thickness of 0.060" was extruded at a rate of 400 feet per minute with a screw speed of 35 rpm. Increasing the screw speed to 65 rpm increased the extrusion rate to 700 feet per minute. These extrusions were smooth, uniform and free from porosity.

Most silicone rubber will stiffen in storage and must be broken down on a mill prior to extruding. Recent developments in compounding have improved the aging characteristics of silicone rubbers making it much easier to prepare a stock for extrusion.

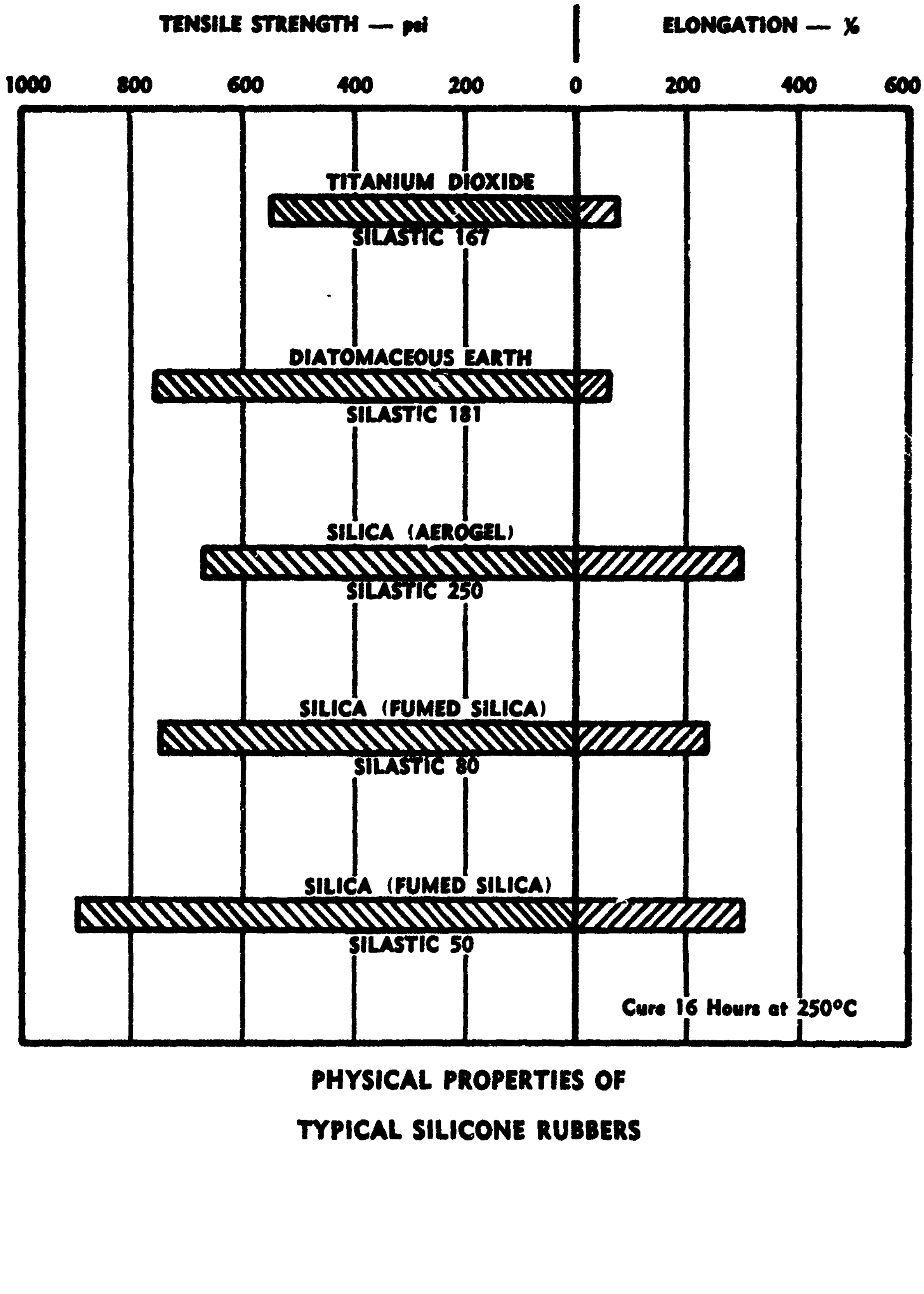
A recent development of interest to cable manufacturers is a method for hot air vulcanizing of extruded silicone rubber. In this process the extruded rubber is passed directly through a tube in which the temperature can be controlled over a range of 300 to 500 C. The proper temperature for a particular extrusion is determined by the length of the tube, the thickness of the extruded part and the extrusion speed. For example, a cable with a wall thickness of 0.030" can be vulcanized in 25 seconds at 350 C. Sections of silicone rubber 7/8" in diameter can be vulcanized in 125 seconds at 350 C. This method is applicable, however, only to certain silicone rubbers. Other silicone rubbers will sponge and blister when placed directly in the very high temperatures required by this process. But, where it can be used, this method of vulcanization eliminates the problems and the high investment associated with continuous steam vulcanizing equipment.

It is recommended that after vulcanization silicone rubber be cured for several hours at high temperatures in an air circulating oven. Optimum physical and electrical properties can be obtained only after such oven curing. Figure 10 shows the increase in insulation resistance of silicone rubber insulated cable with various cures following the initial vulcanization. The insulation resistance of the cable increases to more than 50,000 megohms per 1000 feet after curing for 8 hours at 200 C. Comparable insulation resistance can be obtained by curing for 30 minutes at 300 C. This suggests the possibility of curing extruded cable continuously by passing it through a high temperature curing tower.

Summary

Several typical silicone rubbers have been reviewed briefly showing the improvements made in their properties during the past few years. A new type of silicone rubber using an improved fumed silica as a filler has been reviewed in detail. These fumed silica filled silicone rubber stocks are believed to have the best electrical properties and the widest utility of any silicone rubber available today for general application as cable insulation. The electrical properties are stable over a wide temperature range and are not affected adversely by moisture, corona, weathering, or aging at high temperature. These stocks can be fabricated using conventional methods or a hot air method not requiring steam as a vulcanizing medium.

FIG. 1



PHYSICAL PROPERTIES OF

TYPICAL SILICONE RUBBERS

FIG. 2

PROPERTIES OF SILICONE
RUBBER BLENDS

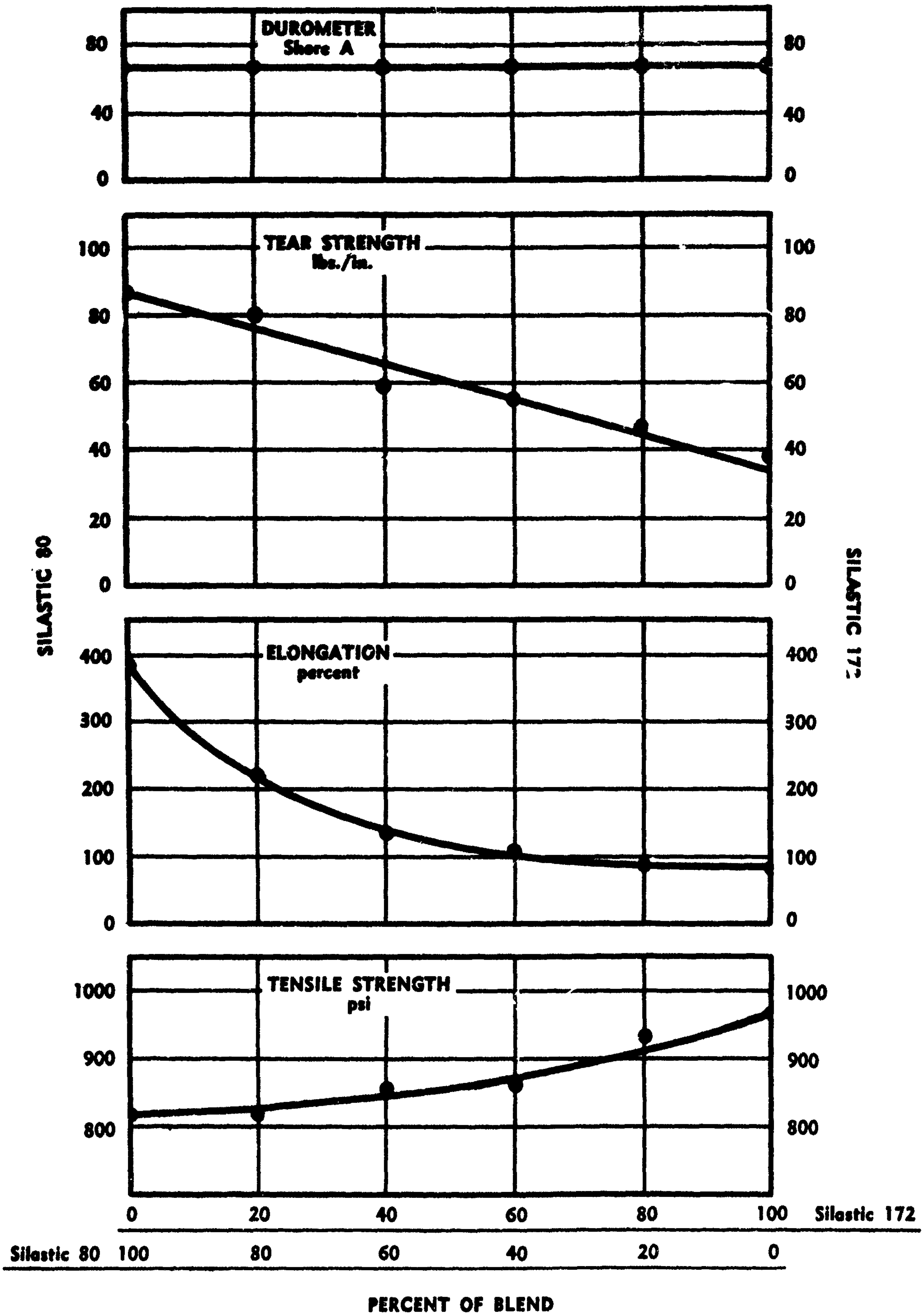


FIG. 3

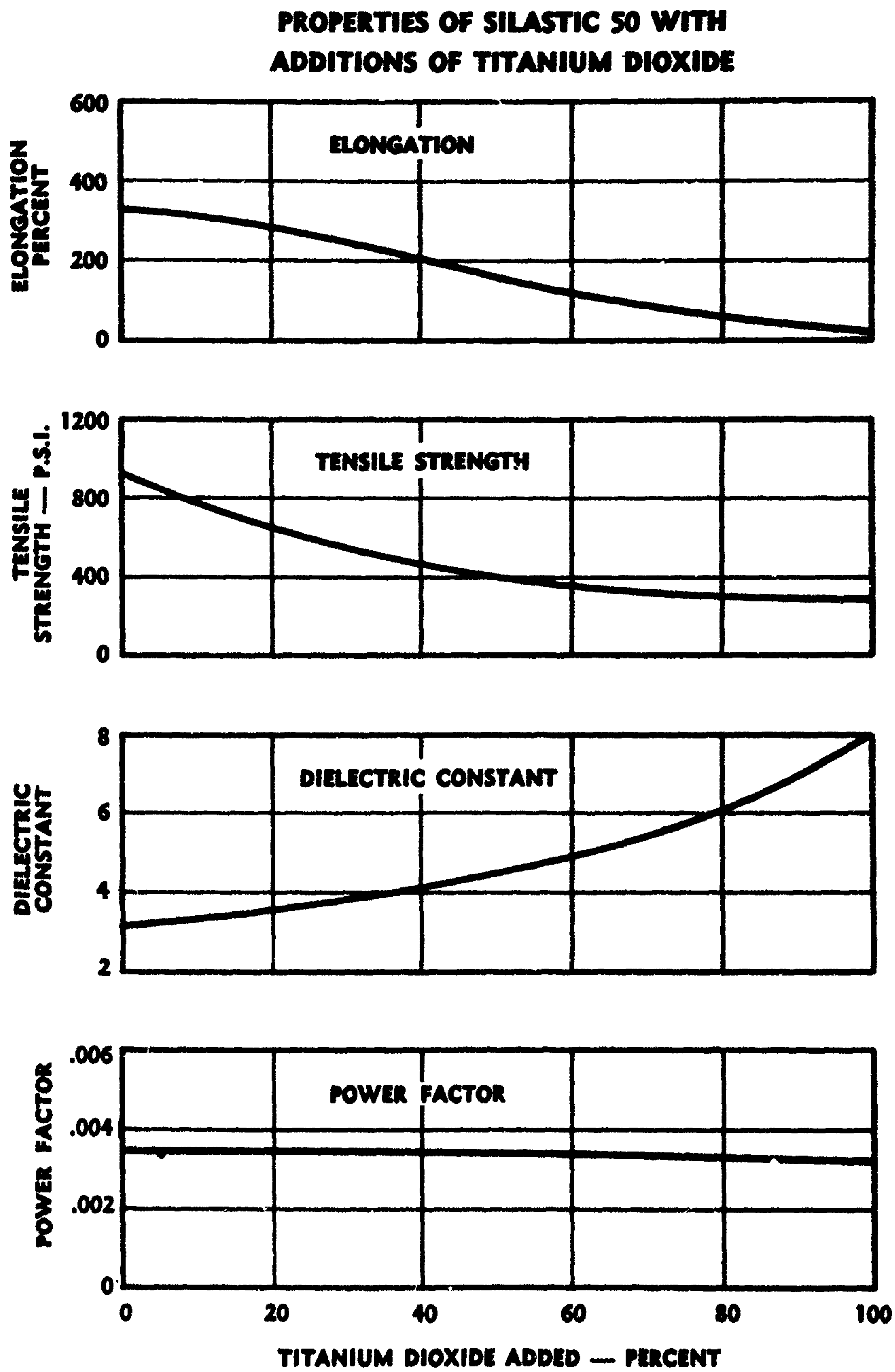

PROPERTIES OF SILASTIC 50 WITH
ADDITIONS OF TITANIUM DIOXIDE
ELONGATION
ELONGATION PERCENT
600
400
200
0
TENSILE STRENGTH
TENSILE STRENGTH — P.S.I.
1200
800
400
0
DIELECTRIC CONSTANT
DIELECTRIC CONSTANT
8
6
4
2
POWER FACTOR
POWER FACTOR
.006
.004
.002
0
0
20
40
60
80
100
TITANIUM DIOXIDE ADDED — PERCENT

FIG. 4

DIELECTRIC PROPERTIES OF SILASTIC 80
AS A FUNCTION OF TEMPERATURE

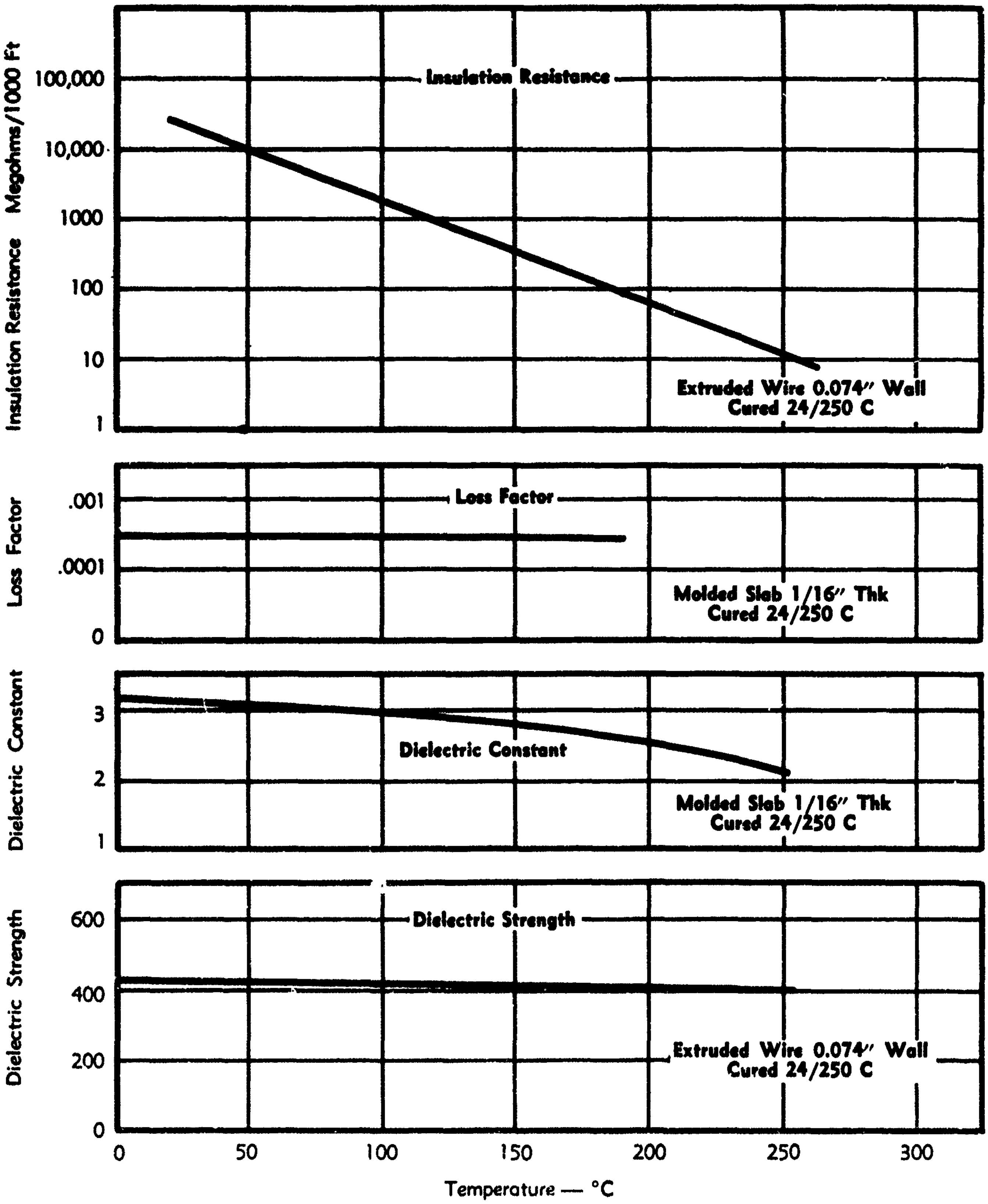


FIG. 5

LOSS FACTOR OF SILICONE RUBBERS
AS A FUNCTION OF TEMPERATURE

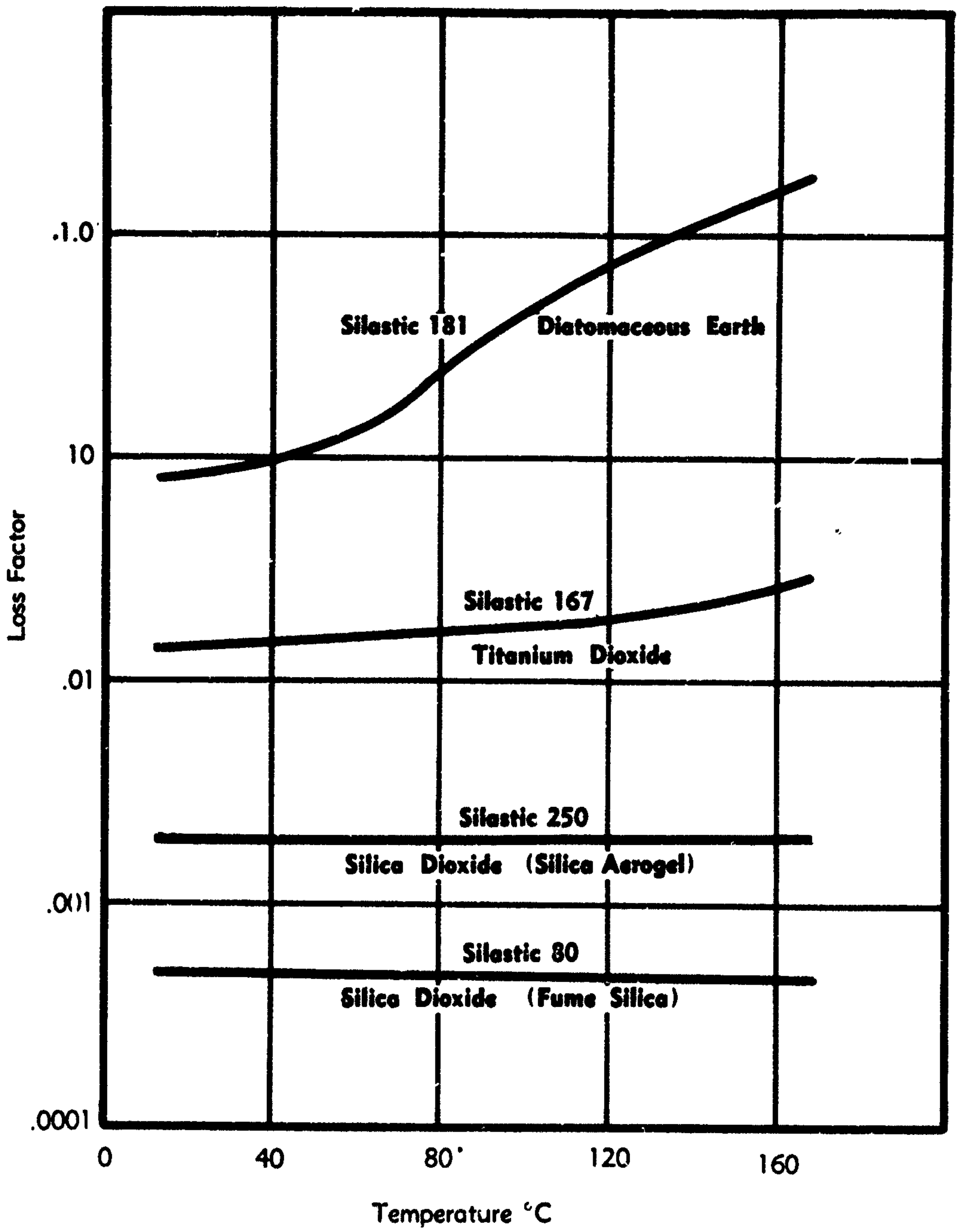


FIG. 6

INSULATION RESISTANCE AFTER 70 C WATER IMMERSION

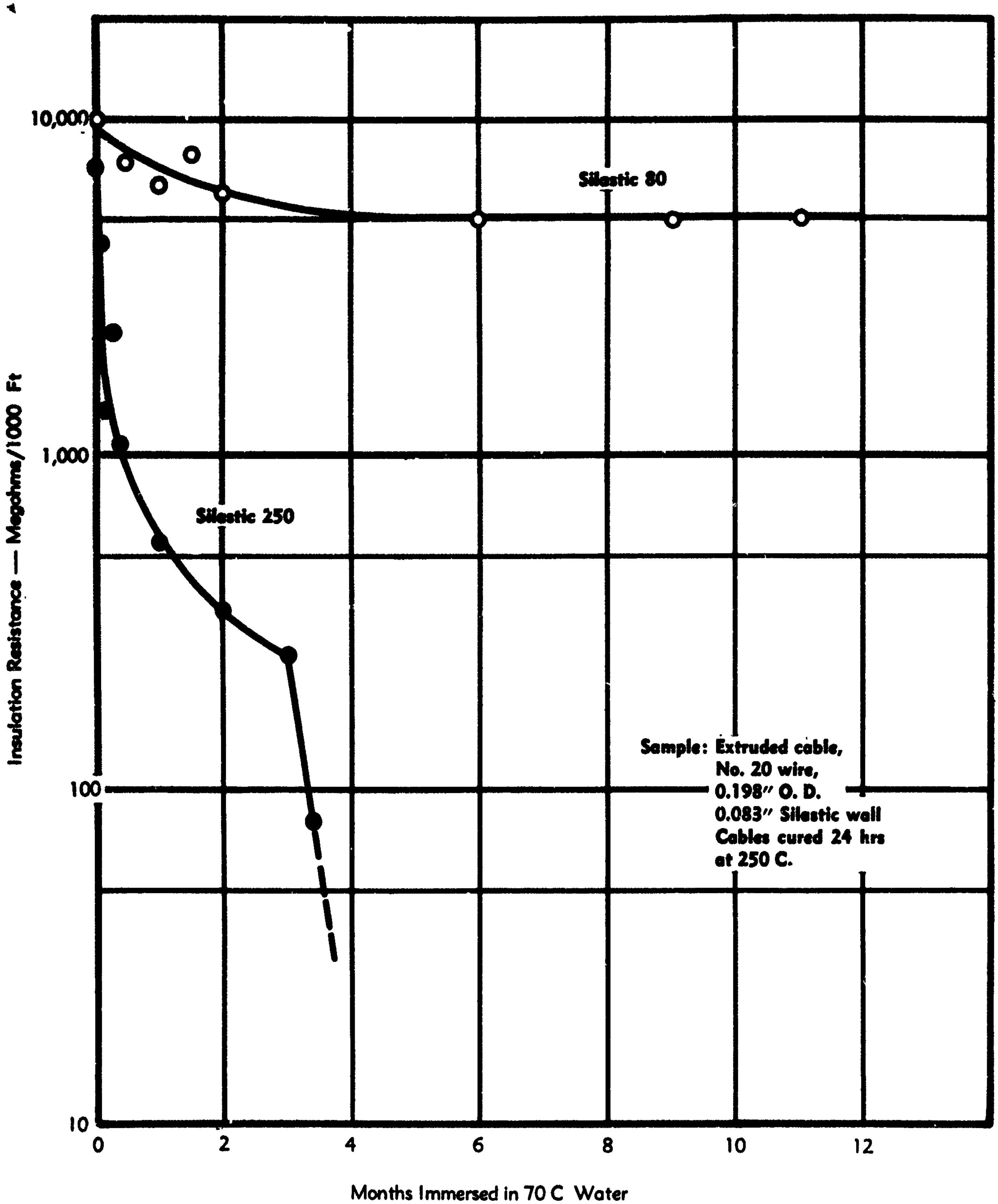
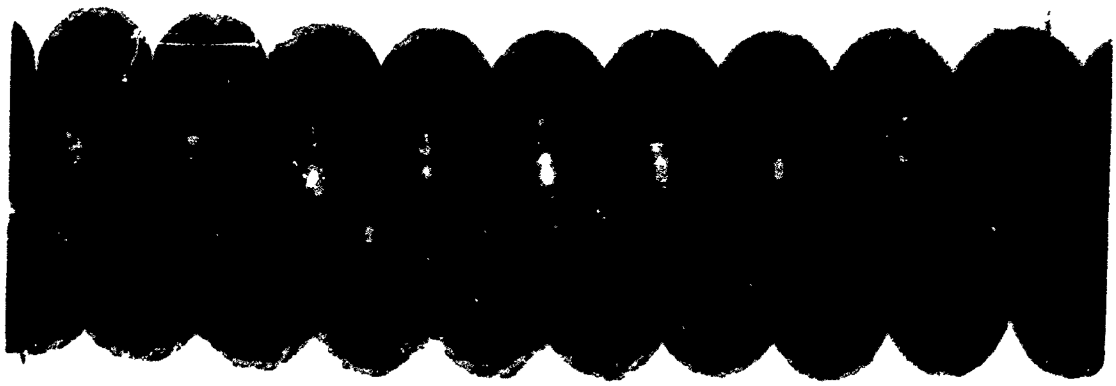


FIG. 7

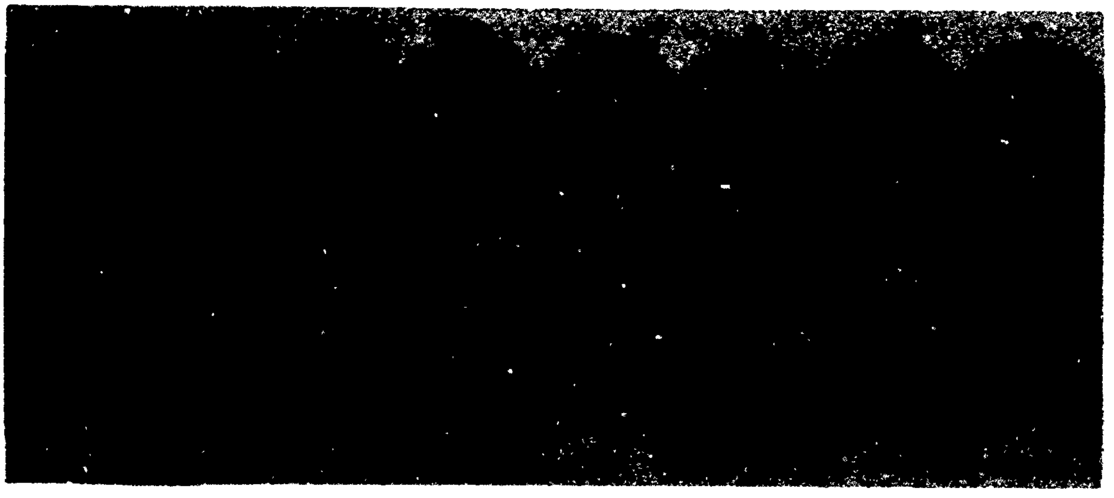
CORONA RESISTANCE



ORGANIC RUBBER
AFTER 30 MINUTES
TESTED AT 200
VOLTS PER MIL STRESS

FIG. 8

CORONA
RESISTANCE



SILASTIC
AFTER 12,000 HOURS
TESTED AT 200
VOLTS PER MIL STRESS

FIG. 9

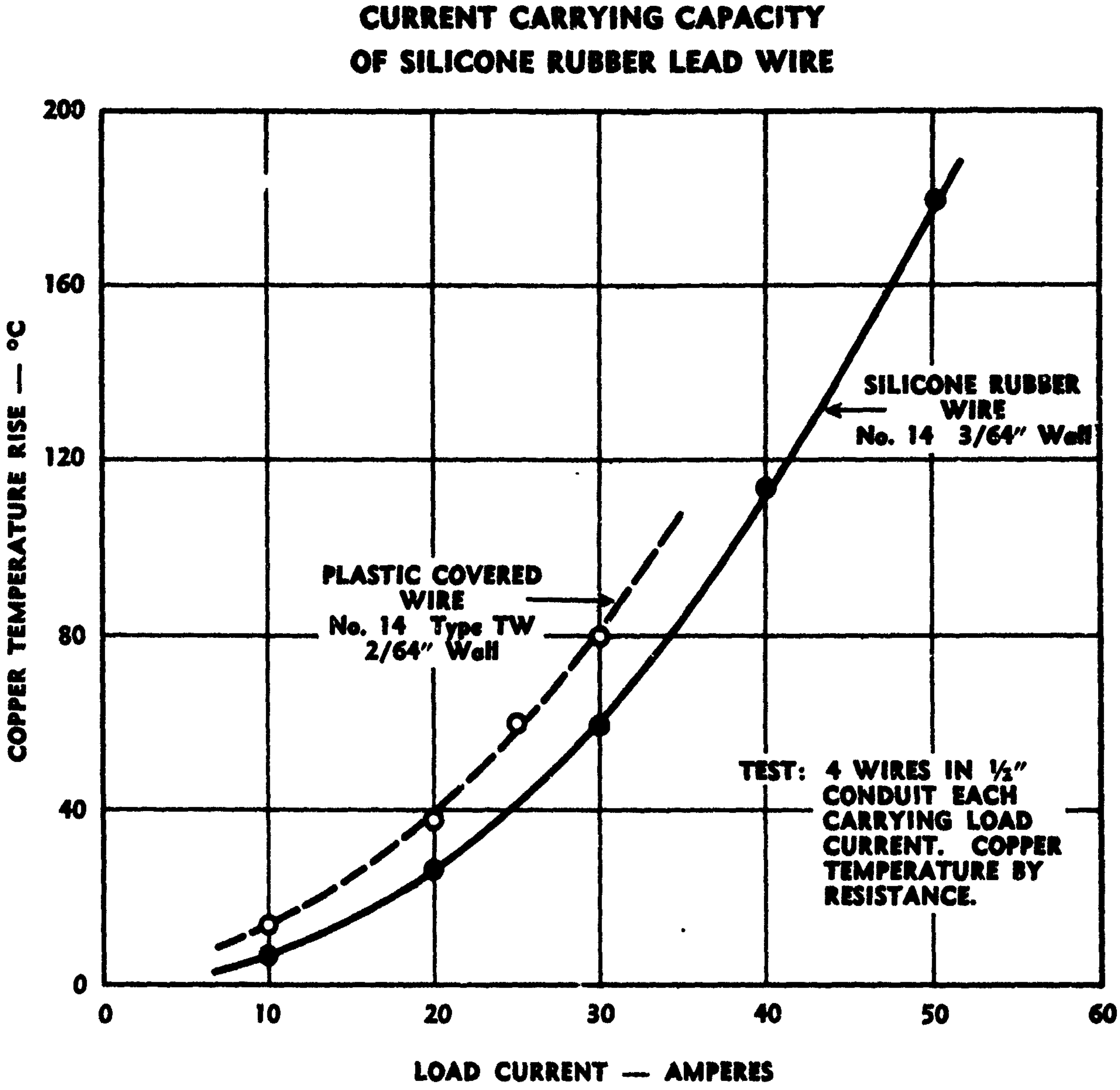

CURRENT CARRYING CAPACITY
OF SILICONE RUBBER LEAD WIRE
200
160
120
80
40
0
COPPER TEMPERATURE RISE — °C
0
10
20
30
40
50
60
LOAD CURRENT — AMPERES
SILICONE RUBBER WIRE No. 14 3/64" Wall
PLASTIC COVERED WIRE No. 14 Type TW 2/64" Wall
TEST: 4 WIRES IN ½" CONDUIT EACH CARRYING LOAD CURRENT. COPPER TEMPERATURE BY RESISTANCE.

FIG. 10

INSULATION RESISTANCE OF SILASTIC 80 CABLE AS A FUNCTION OF CURE