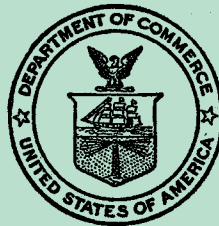


Printed Circuit Techniques

National Bureau of Standards Circular 468



United States Department of Commerce

National Bureau of Standards

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NATIONAL BUREAU OF STANDARDS • E. U. Condon, *Director*

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by Cleo Brunetti and Roger W. Curtis



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Preface

Printed circuits have emerged from purely laboratory experiments to become one of the most practical new ideas of mass production of electronic devices in several decades. Although many of the techniques employed in the practice were known and used long ago, printed circuits as we understand them today represent a comparatively recent accomplishment. Interest in printed circuits has increased steadily since February 1946, when the Army Ordnance Department approved the release of the development of the stencilled-screen process, which had played an important part in the design of the miniature radio proximity fuze for the trench mortar shell. Printed electronic subassemblies have been manufactured in large quantities, and coincident with going to press, it is learned that the first commercial electronic set to be manufactured by the printed process, a hearing aid, has now been placed on the market.

Over the past two years, the National Bureau of Standards has received an unprecedented demand for technical information on the subject from other Government agencies, from industry, and scientific institutions. This Circular outlines the practical details of the art and represents the first general treatise on the subject. To cover completely all the information on the various processes, applications, and other matters related to printed circuits is beyond the scope of the Circular. The main methods have been treated in detail, and others have simply been introduced to stimulate further experimentation by other laboratories and industry. A bibliography is included as an important supplement. The study was carried out in collaboration with scientific and industrial organizations, whose valuable contributions are acknowledged.

E. U. CONDON, *Director.*

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Abstract

A comprehensive treatment of the complete field of printed circuits is presented. Circuits are defined as being "printed" when they are produced on an insulated surface by any process. The methods of printing circuits fall in six main classifications: *Painting*—Conductor and resistor paints are applied separately by means of a brush or a stencil bearing the electronic pattern. After drying, tiny capacitors and subminiature tubes are added to complete the unit. *Spraying*—Molten metal or paint is sprayed on to form the circuit conductors. Resistance paints may also be sprayed. Included in this classification are an abrasive spraying process and a die-casting method. *Chemical deposition*—Chemical solutions are poured onto a surface originally covered with a stencil. A thin metallic film is precipitated on the surface in the form of the desired electronic circuit. For conductors the film is electroplated to increase its conductance. *Vacuum processes*—Metallic conductors and resistors are distilled onto the surface through a suitable stencil. *Die-stamping*—Conductors are punched out of metal foil by either hot or cold dies and attached to an insulated panel. Resistors may also be stamped out of a specially coated plastic film. *Dusting*—Conducting powders are dusted onto a surface through a stencil and fired. Powders are held on either with a binder or by an electrostatic method.

Methods employed up to the present have been painting, spraying, and die-stamping. Principal advantages of printed circuits are uniformity of production and the reduction of size, assembly and inspection time and cost, line rejects, and purchasing and stocking problems. Production details as well as precautions and limitations are discussed. Many applications and examples are presented including printed amplifiers, transmitters, receivers, hearing aid subassemblies, plug-in units, and electronic accessories.

I. Introduction

Printed electronic circuits are no longer in the experimental stage. Introduced into mass production early in 1945 in the tiny radio proximity fuze for mortar shells developed by the National Bureau of Standards, printed circuits are now the subject of intense interest of manufacturers and research laboratories in this country and abroad. From February to June 1947, the Bureau received over 100 inquiries from manufacturers seeking to apply printed circuits or printed circuit techniques to the production of electronic items. Proposed applications include radios, hearing aids, television sets, electronic measuring and control equipment, personal radiotelephones, radar, and countless other devices.

The first mass production of complete printed circuits as they are known today, was set up at the plant of Globe-Union, Incorporated, at Milwaukee, Wis., and a subsidiary plant at Lowell, Mass. Facilities were provided for daily production of over 5,000 printed electronic subassemblies for the mortar fuze shown in figure 1. The plate, on which a complex electronic circuit was printed was made of thin steatite 1¼ in. long and 1¼ in. wide. The circuit was produced by the stencilled-screen process [1] pioneered by the Centralab Division of Globe-Union. Figure 2 shows a two-stage amplifier printed on a thin, ceramic plate alongside a similar amplifier constructed according to present day standard production methods. The reverse sides of the units are seen in figure 3.

Other printing processes, such as spraying and stamping, have reached the production lines, and today we find many manufacturers in mass production of whole radio sets or subassemblies by one or other of the printed circuit techniques.

Manufacturers are producing thousands of special printed electronic circuits per day. Many of these are resistor-capacitor units such as filters and interstage coupling circuits. One unit is shown in figure 4. It is made by the stencilled-screen process and designed with various combinations of resistors and capacitors so as to provide coupling circuits useful in most applications. The portion of the circuit that has been printed is shown within the dotted rectangle of figure 4. This unit also serves as a single stage amplifier simply by wiring to a triode. This arrangement is shown at the left in figure 5. A London concern has designed and is now using an automatic equipment that starts with a molded plastic plate and turns out a completely wired (printed) radio panel in 20 seconds. Other manufacturers are employing spraying procedures using scotch-tape stencils and metal-spraying equipment. Another large producer of electronic items stamps the electronic circuit out of 0.005-in. sheet copper.

The principal physical effect of printing circuits is to reduce electronic circuit wiring essentially to two dimensions. The effect is enhanced where it is possible to employ subminiature tubes and compact associated components. A properly de-

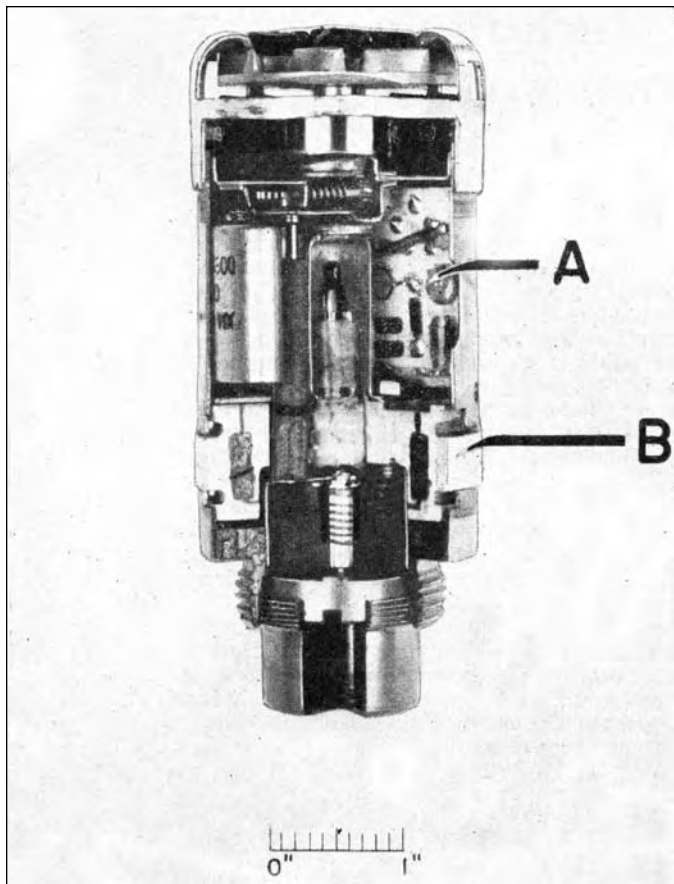


FIGURE 1. Cutaway model of a simulated radio proximity fuze for mortar shell showing an electronic control circuit on steatite block B, and the remainder of the circuit painted on steatite plate A.

signed printed circuit offers size reduction comparable to the best of standard miniature electronics practice and in certain cases affords a degree of miniaturization unobtainable by other means. Just how much space saving may be realized depends on the application. Standard electronic components are now available in such miniature size that complete amplifiers may be built into volumes of less than 1 in.³ using standard methods. This is exemplified in modern hearing aid designs. The greater part of the volume of a hearing aid, for example, is occupied by the microphone, transformers, batteries, earphones, etc. The actual wiring occupies a small fraction of the total volume, hence even if the wiring were eliminated completely, it would not represent a substantial further reduction in the total volume of the unit. In the printed electronic circuit, a large part of the volume is occupied by the base material. By providing thinner base materials,¹ or better by applying the wiring to an insulated outer or inner surface already present in the assembly such as, for example, the tubes themselves or part of the plastic cabinet, a significant reduction in volume occupied by the wiring may be

¹Ceramic plates 0.01 in. thick have been produced by mass production techniques.

had. The development of truly diminutive electronic devices now awaits only the availability of smaller microphones, transformers, speakers, batteries, etc.

Although size reduction is the factor that has attracted the most attention, there are other equal or more important advantages to be gained from the use of the techniques. Uniformity of production, reduction of assembly and inspection time and costs, and reduction of line rejects make the processes attractive, even in applications where size is not important. Purchasing and stocking of electronic components and accessories are reduced considerably as many items are eliminated and others such as the wide variety of resistors usually carried are replaced by a few types of parts. Obsolescence of components is also avoided in great part.

In present assembly-line practices, wiring represents one of the larger items of production cost. Wires must be cut to length, bent into shape, twisted together or around soldering lugs, and individually soldered or connected. As there are over 100 soldering operations in even the small radio sets, the cost of labor and materials for soldering alone represents an important item. In a television set the number of soldering operations is nearer 500. The new wiring processes eliminate as much as 60 percent of the soldering needed for conventional circuits. A single operator on a production line may turn out thousands of plates each day.

Certain types of electronic circuits adapt themselves better to the printing technique than others. Standard amplifier circuits are readily printed as are T-pads and similar attenuating circuits and in general, any electronic configuration that does not have included within it large transformers and similar unusually bulky items. Even in this case, the printed wiring may be arranged with useful eyelets or sockets to which the larger components are attached in the same manner as the tubes.

Because of the early experience on printed circuits acquired by the National Bureau of Standards during and subsequent to its wartime program of radio proximity fuze design and the demands of other Government agencies and industry for more information on the subject, a comprehensive study of printed circuit techniques was undertaken. This study revealed a large number of methods for condensing the size of electronic assemblies, for mechanization of chassis wiring and reducing electronic wiring essentially to two dimensions. Although it would be beyond the scope of any single paper to attempt to cover thoroughly all the possible methods and processes, an effort has been made to present a reasonably complete treatment of the more important ones. They fall in six main classifications: painting, spraying, chemical deposition, vacuum processes, die-stamping and dusting. Some of the processes are new,

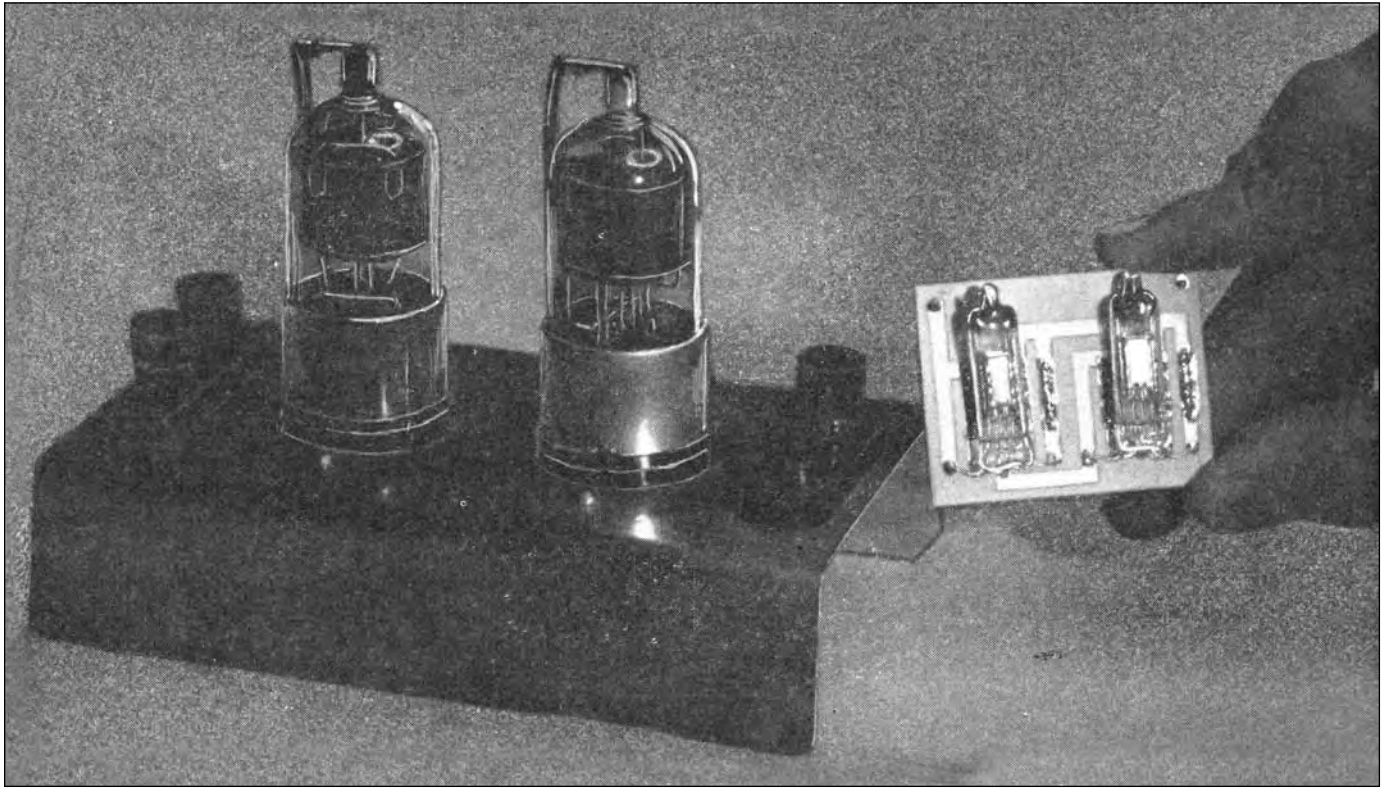


FIGURE 2. Comparison of two-stage voltage amplifier printed on ceramic plate (right) with equivalent amplifier constructed according to present day radio practice (left).

some have been used for years, others have not been applied to production of electronic circuits but are included because they point the way to new techniques.

All are methods of reproducing a circuit design upon a surface and as such fall under the general classification of printing² processes. Electronic circuits produced by any of these methods will be called printed electronic circuits. The processes differ mainly in the manner in which the conductors³ are produced. Resistors and capacitors are applied by methods that in general may be used interchangeably with any of the processes.

Painting. Metallic paints for conductors, inductors and shields are made by mixing a metal powder with a liquid binder to hold the particles together and a solvent to control the viscosity. Resistance paints are made in somewhat the same manner, using carbon or metallic powders. The circuit is painted on the surface by brush or stencil. It is fired at elevated temperatures. Tiny capacitors and subminiature tubes are added to complete the electronic unit.

Spraying. Molten metal or paint is sprayed onto an insulating surface with a spray gun. In some processes, metals in the form of wire, powder or solutions are supplied to the gun and sprayed di-

rectly on the surfaces through stencils to form the conductors and to fasten in place resistors, capacitors, and other electronic components that have previously been placed in depressions on the surface. Resistance paints may also be sprayed. Chemical spraying is possible using a spray gun with two openings, one ejecting silvering material and the other a reducing liquid. In another method, a metallic film on an insulated surface is subjected to an abrasive blast through a stencil

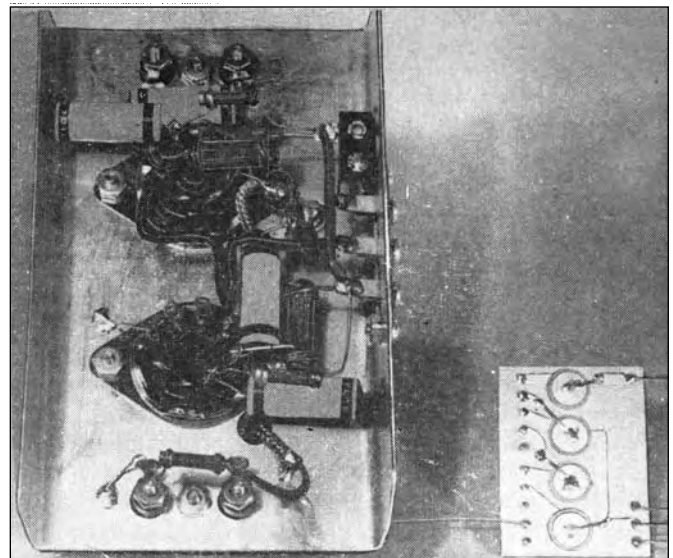


FIGURE 3. View of bottom sides of the printed and conventional units of figure 2.

² *Printing* is defined in the dictionary as "the act of reproducing a design upon a surface by any process."

³ The term "conductors" herein is used to denote the leads or that part of the circuit wiring which connects the electronic components such as the resistors, inductors, etc.

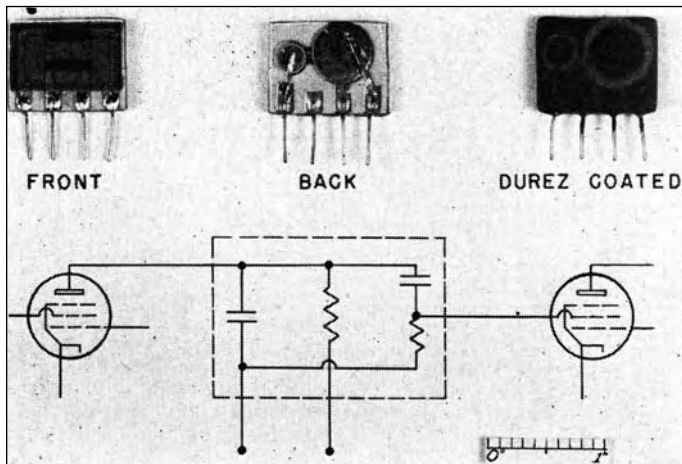


FIGURE 4. Printed interstage coupling unit, made by stencilled-screen process.

bearing the circuit pattern. Included in this classification is the die-casting method. A special low-melting point alloy is cast directly into grooves in the insulating surface. Expansion on cooling holds the metal in place.

Chemical deposition. A metallic solution, such as silver for example, is prepared by adding ammonium hydroxide to a solution of silver nitrate. A reducing agent is used to precipitate metallic silver on the insulating surface. A stencil is employed to define the circuit. Thin films are formed that may serve as resistors or conductors. Electroplating is used to increase the conductance of the part of the wiring serving as the conductors.

Vacuum processes. The coating metal is made up in the form of a cathode or placed in a container in an evacuated chamber opposite the plate on which the pattern is to appear. Raising the metal to proper temperature distills it onto the plate through a suitable stencil to define the circuit. Resistors as well as conductors are made this way.

Die-stamping. Circuit wiring is punched out of metal foil and attached to one or both sides of an insulating panel. A variation is to use a heated die with the circuit wiring pattern on its face. Pressing the die on a thin sheet of metal foil over a plastic surface prints the complete wiring in a single step. The heat causes the foil to adhere strongly to the surface. The process is applicable to production of inductors and resistors.

Dusting. Metallic powders with or without a binder are dusted onto a surface in a wiring pattern and fired. The powder may be held to the surface by coating the latter with an adhesive through a circuit defining stencil. The powder adheres to the surface in the desired circuit pattern and fuzes strongly to it on firing. An electrostatic method of holding the powder on prior to firing or flashing has been developed. The process is adaptable to making resistors and conductors. Electroplating may be used to increase the conductance where necessary.

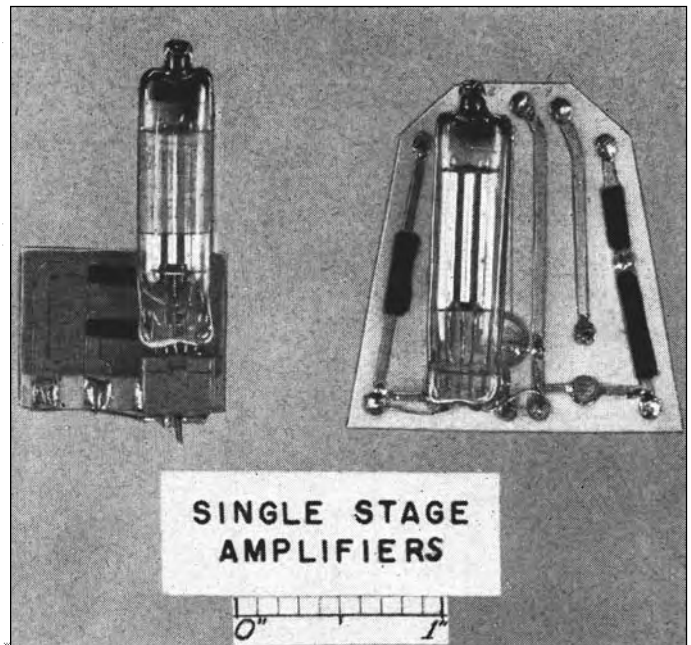


FIGURE 5. Single-stage amplifiers printed on steatite plates by stencilled-screen process.

In this country considerable interest is being displayed in the painting, spraying, and die-stamping methods. A good deal of experience has been accumulated and practical methods of operation adaptable to mass production worked out. Review of progress in foreign countries also reveals development and usage of some of the methods, particularly in England and Germany. The literature is replete with methods of depositing metals on nonmetallic materials. A large number have been patented long ago and the patents expired. Early methods consisted of applying finely divided graphite or metal powders to wax coatings on the surfaces. The chemical reduction methods were probably the first to be used for producing thin metallic films on nonconducting surfaces for decorative arts. Some have been used for over 100 years. The resulting films were usually very thin, and plating was used to increase the thickness.

Before entering on a detailed description of individual methods it will be of value to consider some general facts. Not all the components of an electronic circuit may be printed. The practice is adaptable to conductors, resistors, capacitors, inductors, shields, and antennas. By printing the circuit on a base plate of high dielectric constant one may print the capacitors, wiring, and inductors all in a single operation. The capacitors in this case may be made up by silvering equal areas on opposite sides of the plate. This practice is applicable to uses where high capacity between leads and components may be tolerated, such as in phase shift networks comprising only resistor

and capacitor elements. It is desirable that the circuits and components adhere strongly to the base plate. The wiring should be of low resistance and of sufficient size to carry large currents without appreciable heating. The resistors and other printed components should be stable under rated

electrical loads and should show a minimum aging effect. The complete printed circuit should withstand fairly severe temperature and humidity exposures, rough handling, and mechanical abuse.

The six main classifications of printed circuits will now be discussed in detail.

II. Painting

This process is now well adapted to the production of printed circuits. Paints for resistors may be made up as well as conductor paints. It has been the subject of considerable attention in the laboratories of the National Bureau of Standards and in industry. Suitable metallic paints have been developed for use on most types of surfaces from glass to plastics. In those applications in which the base material may be raised to elevated temperatures, the paint may be fired onto the surface with excellent adhesion. For materials such as plastics which cannot be raised to high temperatures, satisfactory results are obtained although the adhesion of the paints is considerably less than is obtained by firing. Printing the conductors is the easiest part of the operation. Printing resistors is a more difficult problem, especially where it is necessary to hold them within close tolerances.

The painting of conductors in general follows the practice used in pottery manufacture of burning metal oxides containing ceramic fluxes onto hard insulating surfaces. As is well known, pottery is decorated by mixing finely ground metal powders and fluxes with oil and turpentine and applying the mixture to the surface either by brush or through a stencil. It is then baked at temperatures of the order of 450° to 750° C sufficient to melt the flux and reduce the metal oxide. The metals are used because of the color they impart to the pottery. Chromium, iron, and cobalt, for example, result in green, brown, and blue colors, respectively. Unfortunately, the silicates or borates of the various metals except the noble metals are poor conductors.

Although it would appear to be a brief step from the pottery methods to those now used in painting electronic circuits, a considerable amount of research has gone into developing paints of sufficiently high conductance and adhesion that may be applied in a practicable way.

1. Paints

A. Constituents

Paints for printed circuits are made up of selected combinations of constituents, examples of which are included in table 1.

(a) Pigment

The pigment is the conducting material for the circuit wiring. For the leads, powdered silver, sil-

ver oxide, silver nitrate or organic combinations of silver are generally used. Silver has proven to be a most practicable metal for this purpose. Not only is it highly conductive, but silver films are easily produced. Copper or noble metal powders or salts may also be used effectively. Though salts of other metals might be employed, some form corrosion products that have such high resistance as to make them useless. The need for additional research in this direction is evident.

The cost of the silver is usually a small item, in fact the relatively small amount required makes the cost of the actual silver paint no more than that of copper required for ordinary wiring. One ounce of silver is sufficient to paint as many as 125 average two-stage amplifier sections. Sheet silver, such as that used in the production of Edison cells, properly ground is an excellent pigment for conductor paints. Flake silver in small particles works very well on most surfaces.

The pigment for resistors is usually carbon black, colloidal graphite, or a "flake" type of microcrystalline graphite. Carbon black and colloidal graphite appear better for screen painting and spraying. Flake graphite is used only for brush painting. Lampblack has been tried, but the more common types available apparently do not have the proper physical properties to produce reasonable values of resistances. One of the theories advanced is that the configuration of the pigment particles must be such that they overlap or bridge one another in the finished resistor. It is an empirical fact that the shape and size of the pigment particles do play an important part in the resultant electrical properties of the circuit.

(b) Binder

The binder is the constituent that holds the pigment together so that it may be painted on the surface, and also serves to bind the pigment to the plate. A resin is used that can be easily dissolved. Satisfactory synthetic resins are the phenolics dissolved in acetone or silicones dissolved in chlorinated hydrocarbons. Although essential oils such as lavender oil are recommended as suitable binders, they are more or less a carry-over from other metallizing techniques. The essential oils as a rule are aldehydes which tend to reduce the salt or oxide to metal. Vegetable oils like linseed, cottonseed, china, soybean, or even castor oil contain unsaturated acids, which in the process of oxi-

TABLE 1.—Composition of paints

Constituent	Function	Applications	
		Conductors	Resistors
Pigment	Conducting material	Powdered silver Silver oxide Silver nitrate Powdered copper Linseed oil Cottonseed oil Castor oil Resin Lacquer	Carbon black Colloidal graphite Flake graphite Phenol-aldehyde resins Melamine aldehyde Vinylite resins Silicone resins Styrene resins Methacrylate resins
Binder	Holds pigment together and binds it to plate.	For refractory base plates— Lead borate Lead silicate Ethyl silicate Chlorinated solvents	Chlorinated solvents Alcohols Aromatics Ketones Acetates
Solvent	Dissolves binder if in solid form and adjusts viscosity of mixture.	Alcohols Aromatics Ketones Acetates	Chlorinated solvents Alcohols Aromatics Ketones Acetates
Reducing agent	Converts metallic salt to pure metal at low temperature.	Formaldehyde Hydrazine sulfate Hydrazine hydrate	
Filler	Increases electrical resistance by separating pigment particles.		Powdered mica Mineralite Asbestos dust (iron free) Phenolic lacquers Silicone resins Vinylite lacquers Melamine formaldehyde lacquers
Protective coating	Protection against abrasion and atmospheric conditions.		

dation or drying have a tendency to absorb the oxygen from the metal oxide, thus converting it to metal. In those cases where the metallic oxide is not reduced, it is held to the surface entirely by the binder. The conductance and adhesion, therefore, are determined by the amount and type of binder employed. Where the paints are applied to surfaces that are not entirely rigid, the vinylite resins provide needed flexibility. For certain plastics, nitrocellulose or ethyl cellulose lacquers provide quick drying action at low temperatures. The phenolic resins are usually used to bond resistance paint. They yield excellent stability in respect to changes in temperature. Lead borate, lead silicate, sodium borosilicate and similar fluxes⁴ are recommended as binders for ceramics and glass. Although a stronger bond to the surface is had by firing, the use of ethyl silicate as a binder for silver oxide on glass and steatite without firing produced a satisfactory bond.

(c) Solvent

The solvent is used to dissolve the binder if it is in solid form and to adjust the viscosity of the pigment-binder mixture. Most of the common aromatic and aliphatic solvents may be used in paints for printed circuits. Typical examples are alcohol, acetone, ethyl acetate, butyl acetate, cellosolve acetate, carbitol acetate, amyl acetate, turpentine, and butyl cellosolve. One manufacturer recommends either high boiling solvents of the glycol-ether type or high boiling lacquer thinners of the ester-ketone type [2]. Lacquer thinners such as butyl acetate as well as glycol-

⁴ The term flux is used to designate a binder and not a cleansing agent.

ether solvents such as methyl cellosolve are also recommended. Solvents that mildly attack the surface of the base plate, such as toluene on a polystyrene base, usually improve the adhesion.

(d) Reducing Agent

A reducing agent is used to reduce the metallic compound to metal when the base material will not stand high firing temperatures, for example a plastic. Formaldehyde and hydrazine sulfate are used to convert silver oxide to pure silver. They are driven off at the relatively low temperature 70° C, considerably less than the temperature required to reduce silver oxide by the firing process.

(e) Filler

The filler is the material used to spread or separate the particles of pigment to increase the electrical resistance. Powdered mica, mineralite, diphenyl, and powdered chlorinated diphenyls are typical types of fillers employed.

B. Conductor Paints

Although paints for the conductors⁵ may be made up in the laboratory, there are commercially available excellent products that have been developed as the result of careful research. Not only are there a variety of preparations for special purposes, but the manufacturers have demonstrated unusual ability and cooperation in making up special paints for specific applications. The commercial paints require no additional attention

⁵ Conductor paints are used not only for conductors but for inductors, capacitor electrodes, shields and other low resistance elements.

prior to application.⁶ Whereas practically all paints may be used on highly refractory material such as glass and steatite, it is best in purchasing paint for use on plastics, cloth and paper to request formulations especially suited for that purpose. The intended manner of application should also be stated. There are paints suited for polystyrene or for Lucite and Plexiglas, others are especially prepared for the prime base materials such as glass and steatite. One can go so far as to specify the degree of scratch or abrasion resistance desired. Although paints are available for painting on paper and on cloth (such as Metaplast 17A) one must expect the conductance to be affected by use, especially by folding. The silver content is usually adjusted according to the manner in which the paint is to be applied. If it is to be brushed on, a paint of at least 50 percent of silver by weight is recommended. For spraying a silver content of 35 percent by weight is suitable while for application by use of a stencil screen, the silver content should be as much as 60 percent by weight [2]. The composition and viscosity are selected to suit the method of application. The unused paint should be checked often, perhaps once or twice a day in order to keep the composition of the paint from varying due to the evaporation of the solvent. About the only additional precaution that must be observed is that of thoroughly stirring the paint before using. For this purpose, it has been found convenient to place the container on its side on a set of mechanical rolls. This allows constant and uniform stirring with the container sealed, thus preventing loss of solvent that would occur should the stirring be carried out in an open vessel.

There are several ways of preparing conducting paints in the laboratory. In one the pigment is dispersed in the binder and applied to the surface. The unit is then elevated to the proper temperature required to drive out the solvent and to adhere the metal to the plate. To improve the bond, a flux may be added and a similar procedure followed. The units must now be raised to a temperature above that at which the flux melts and below the melting point of the metal. Although silver oxide may be reduced at approximately 400° C, on steatite a temperature of 700° to 800° C is usually employed.⁷ As the temperature is raised, in a typical example of paint, the solvent evaporates at 150° C, followed by the binder at 200° C. At 400° C, the flux melts and at 800° C, the silver forms into a smooth conducting film. The par-

⁶ American manufacturers include E. I. duPont de Nemours Co., Inc., and Metaplast Co., Inc. A paint consisting of silver suspended colloiddally in oil sold in Germany under the name of Mattsilber K, produced by W. C. Heraeuse GmbH, Platin-schmeize, Hanau, Germany [3]. A study of a British publication [4] on silvered ceramic capacitors and inductors indicates the availability of silver paints with suitable electrical properties on the British market.

⁷ Silver melts at 961° C.

ticles of silver are spread evenly over the surface and held tightly to the base plate by the flux. The firing temperature depends on both the flux used and the material of which the base plate is made. A minimum amount of flux should be used, just enough to bond the silver tightly to the plate. Excess flux reduces the conductance of the silver film. Care must be exercised in preventing the temperature from rising high enough to produce tiny metal globules that weaken the bond to the plate and interfere seriously with the conductance. A satisfactory formula for a flux type paint is five parts of metallic silver or silver oxide and one part of binder such as lead borate, ground together in a paint mill with enough vegetable oil to give the paint the proper consistency. The viscosity may be adjusted further if desired by adding a small amount of acetone.

Silver oxide paints using laboratory prepared lacquers as binders and containing vitreous materials such as lead silicate glass (softening point about 550° C) or lead borate (softening point about 500° C) in several percentages have been successfully prepared in the laboratory. The paints were applied to steatite plates and dried under infrared lamps for several minutes, then fired in a muffle furnace at 800° C to 850° C for 1 to 1½ hours. Metallic silver of low resistance was deposited attached firmly to the plate. Other sample formulas used in the laboratory are shown in table 2.

TABLE 2.—Conductor paint formulas

[All percentages are by weight]

Base plate material	Ceramics	Glass	Thermosetting type plastics	Thermoplastic type plastics
	* 450° to 800° C.	* 450° to 650° C.	* 25° to 175° C.	* 25° to 75° C.
Pigment...	Finely ground silver powder 65%.	Finely ground silver powder 65%.	Finely ground silver powder 70%.	Finely ground silver powder 70%.
Binder....	Cellulose resin, 13%+ Finely divided low softening point class, 12%.	Cellulose resin, 13%+ Finely divided low softening point class, 12%.	Cellulose resin, 13%+ Methacrylate resin Phenolic resins, 20%.	Methacrylate resin, Polystyrene resin, 20%.
Solvent...	Acetates or Cellosolve derivatives, 10%.	Acetates or Cellosolve derivatives, 10%.	Acetates, Ketones or Cellosolve derivatives, 10%.	Ketones, Benzene, Toluene or Ethylene-dichloride, 10%.

* Processing temperature.

C. Resistor Paints

The resistor paint consists of the conducting pigment (such as carbon black or powdered graphite in carbon resistors or a metallic salt in resistors of the metal film type), a binder (such as phenolic resin in solution), a filler (such as mineralite) and a solvent (such as alcohol). These ingredients are varied in proportion to produce resistances varying in value from a few ohms to hundreds of megohms. They usually are printed in widths

TABLE 3.—Resistor paint formulas

[All percentages are by weight]

Approximate resistance	Approximate thickness ^a	Pigment	Binder	Solvent	Processing temperature
1,000 <i>Ohms</i>	0.003 <i>In.</i>	38% Graphite	62% Silicone resin		° C.
2,000	.003	3% Carbon black	70% Silicone resin		275
		27% Graphite			
5,000	.003	4% Carbon black	77% Silicone resin		275
		19% Graphite			
25,000	.003	12% Carbon black	17% Phenolic resin	33% Phenolic resin thinner	175
		38% Graphite			
25,000 to 50,000	.0015 to 0.003	7% Carbon black	72% Silicone resin	21% Benzene	275
25,000 to 50,000	.0015 to 0.003	4% Carbon black	74% Silicone resin	22% Benzene	275
45,000—10 megohms	.001 to 0.004	12% Carbon black	20% Crystallite	12% Toluene	50
		27% Graphite			
50,000—10 megohms	.001 to 0.004	11% Carbon black	66% Ethyl cellulose lacquer	29% Ethylene dichloride	50
		23% Graphite			

^a All Resistors were approximately 0.10 in. wide and 0.40 in. long.

from $\frac{3}{64}$ in. to $\frac{3}{32}$ in. and in lengths from $\frac{1}{8}$ in. to $\frac{3}{8}$ in.

The choice and ratio of ingredients govern the degree of adhesion to the base plate and determine other physical and electrical characteristics. In present practice the paints are mixed by the user who determines experimentally the proper formulation to obtain the desired resistance in the specified area.⁸ As an example, good results in the 1- to 10-megohm range on a steatite base were achieved at the Bureau using 7 percent of colloidal graphite, 46.5 percent of Dow resin 993 and 46.5 percent of benzene. A second useful formula was 15 percent of colloidal graphite, 9 percent of lampblack, 29 percent of bakelite BL-68 and 47 percent of bakelite thinner BS-68. Two coats were applied. The first was dried at 75° C for 15 minutes, after which the second was applied and the whole unit baked at 150° C for 1 hour. On temperature cycling over the range +50° C to -50° C, the average resistance change was approximately ± 10 percent as shown by curve A in figure 19.

In the present state of the art it is not feasible to present a set of resistor paint formulations that one may use without special attention in the laboratory. Resistors may be painted readily only after careful practice. A paint formula that is successful to one experimenter may not work well for another because of the manner in which the ingredients are mixed, the quality of the ingredients, the amount of evaporation of solvent prior to application or any number of other small but important factors. However, the data of table 3

⁸ Resistor paints for printed circuits unlike conductor paints, are not readily available commercially. There are many suppliers of carbon black, graphite and other paint constituents. High resistance graphite paints that can be applied by the silk screen process are "Dispersion No. 22 or No. 154," manufactured by Acheson Colloids Corp., Port Huron, Mich. They are dispersions of colloidal graphite in organic solvents. Highly pure electrical-furnace nonfusible graphite is used. Concentrated dispersions of colloidal graphite in distilled water may be applied direct to glass, ceramics and other materials to form electrically conductive (resistance) films that are chemically inactive and nonfusible. Although this practice is satisfactory to form a base for electroplating or for electrostatic shields, it is not readily adaptable to printing resistors.

are presented as a compilation of formulas used to print resistors of the values indicated.

There is need for additional experimental work in developing improved methods of printing resistors and in clarifying the theory of resistor composition and performance. This is especially true with carbon resistors. At the present time, the best resistor mixes are considered to be those in which the conducting element is predominately or entirely carbon black⁹ dispersed in a suitable resin. However, carbon black is high in resistivity so that it has been necessary to add acetylene black or graphite to bring the average value within practical limits. There are many types of carbon black each characterized by particle size, particle arrangement, the type of gas used in its manufacture and its impurities, particularly surface impurities.

Current knowledge points to the use of carbon blacks of relatively small size for resistor paints, those of particle diameter in the range 20 to 50 mμ. The carbon black should have its surface impurities, principally oxygen, removed by calcining. This is done by heating to a temperature of approximately 1,050° C for 4 hours preferably in a nitrogen atmosphere. The oxygen concentration is reduced to a limit of about one-half of 1 percent.

After calcining the carbon black, it is best to disperse it in the binder by ball milling, using for example, flint balls. The size and density of the balls and the speed of the mill are all important factors in this operation. The dispersion may be checked by measuring the resistance that decreases asymptotically with time as the milling proceeds. When the resistance has reached a minimum, the milling should be stopped. A good ball milling technique applied for 72 hours usually assures adequate dispersion of the carbon in the resin. The resin plays an important part in the dispersion

⁹ Carbon black here is interpreted to mean carbon produced by impinging the flame of hydrocarbon gas on a metal surface such as a plate or channel. Also known as channel black, gas black or impingement black.

and considerable practice has been necessary to determine the best type of resin to use. It must have good solvent release.

Much also remains to be learned about the factors contributing to noise in resistors. Noise appears to be a function of particle size, the finer the carbon, usually, the less the noise. This is perhaps due partly to the fact that smaller particles present more contacts. A good deal of experimentation, including X-ray and electron microscope studies, is now underway seeking to clarify the relationship of carbon particle size and shape, particle arrangement in solution and other factors to resistor performance.

2. Surface Preparation

The insulating surface on which the circuits are to be printed may first have to be treated to improve the adhesion. The methods described herein are adaptable to all of the printing processes. Adhesion to methyl methacrylate (Lucite, Plexiglas, etc.) may be increased by roughening the surface as by sand blasting. Roughening produces a minute granular surface to which better mechanical bonding may be had. When this is done, however, the surface becomes porous and the internal strength of the plastic may be reduced, causing the plate to buckle. In such instances, precautions should be taken to coat the surface after printing the circuit. Glass surfaces may be prepared by etching with hydrofluoric acid fumes or sand blasting. Etching may also be used, if necessary, on glazed ceramic materials. Glass may be sand blasted or sprayed with other abrasive materials. Usually, suitable protective stencils or coatings are used to confine the roughening to that portion of the surface occupied by the circuit.

The next step is to make sure that the surface is absolutely clean, for the bonding or adhesion may be weakened considerably by the presence of impurities. The impurities prevent direct contact between metal and surface, and are a poor or useless base on which to form the circuit. The problem of cleaning is not difficult, and customary procedure may be followed using standard cleaning materials [5, 6, 7]. In selecting the chemicals, it is important to consider the type of surface being cleaned. A material suitable for glass, for example, might produce undesirable effects if tried on plastics.

On hard surfaced material such as glass and ceramics, after washing the surface with water followed by a rinsing with a suitable detergent, the surface may be swabbed with a dilute solution of nitric acid. If soap is used as the detergent, it should be rinsed off well with distilled water. Detergents such as aerosol are preferred because they form water soluble compounds with magnesium

and calcium solids commonly found in tap water.¹⁰ If the cleansing is carried out thoroughly, one operation should be sufficient. If desired, one may follow with a second operation by treating the surface with a dilute solution of potassium hydroxide [6, 7]. The second operation, commonly followed in silvering mirrors, may not be necessary in printing electronic circuits. Glazed surfaces may be cleansed of paraffin and carbonized organic materials by using a mixture of chromic and sulfuric acid. In stubborn cases, the material may be placed in the solution and heated slightly.

Thermoplastics such as Lucite or Plexiglas may be cleansed with a dilute solution of tri-sodium phosphate, then rinsed in water and dried to remove any oil. For certain types of plastics, such as the phenolics, the surface may be cleansed with ordinary carbon tetrachloride followed by swabbing with a very dilute solution of potassium hydroxide or warm chromic acid. In one practice, this is followed with a quick dip in a strong caustic soda solution or nitric acid.

3. Application of Conductor Paints

A. Circuit Design

In many applications the arrangement of the circuit can be chosen in any convenient manner. The circuit may be painted in the same way it would be drawn on paper. Eyelets would be placed where the tube elements are later to be attached. It will generally be found more convenient and economical, however, to lay out the printed circuit in such a way as to keep the length of leads to a minimum and to avoid cross-overs. Cross-overs are handled by going through the base plate and continuing on the opposite side, by going around the edge, or by cementing or spraying a thin layer of insulating material over the lead crossed.

It is important to emphasize that observation of good electronic wiring practice is as essential to the successful design of printed circuits as it is in standard circuits. In printed circuits the parts are usually placed closer to each other so that caution must be exercised to see that the components do not affect each other adversely while the circuit is in operation. In one experience poor performance of a printed oscillator in the 150-megacycle range was traced to excessive grid-ground capacity resulting from excess silver in a groove of the base plate. The heavy silver deposit in the groove being at ground potential and also near the grid terminal of the oscillator tube by-passed the RF

¹⁰ Dr. Carl Bosch (of Heidelberg, Germany) has described a procedure for cleaning glass, which is very good. He washes the glass with a potassium nitrate and sulfuric-acid solution. In this way, any chemical action taking place results principally in gaseous products which evaporate. Then follows a hot-water dip after which a blast of steam is played on the surface. The surface is dried while still hot in a water-vapor atmosphere. It dries instantaneously, without forming minute water droplets, which on drying might leave nonuniform traces of materials dissolved in the water.

current from the tank inductor. Reducing the width and depth of the silver line restored the electrical performance to normal.

Proper attention to circuit layout may produce many desirable advantages such as the electrostatic shielding of leads from one another. A ground lead painted between two other leads acts as an electrostatic shield in a manner similar to the screen in a screen grid tube. This effect has been used to good advantage in providing hum reduction by shielding grid leads from the filament leads [8].

B. Brushing

The paint may be applied to the surface in any one of a number of ways depending upon the type of apparatus available and the electrical tolerances required. When close electrical tolerances are not needed, the paint may be simply brushed on.

For brushing, an ordinary soft camel hair brush may be used. After the paint is stirred and the viscosity adjusted, it is applied in smooth, even strokes, care being taken to avoid air bubbles or films between the plate and the paint, or other imperfections that ultimately might result in blisters or cracks in the paint.

If the conductors are to be held to close dimensional tolerances, more care is necessary in applying the paint so as to maintain the necessary degree of uniformity between assemblies. There are, however, a large number of radio and electronic applications where, except for a few components, close tolerances in current-carrying capacity are not needed nor is exact electrical duplication of subsequent assemblies important.

C. Stencilling

(a) Stencil Material

The simplest stencil is one in which the pattern is cut from a thin sheet of metal, plastic, paper, or cloth and the paint applied in a manner similar to that in which commercial packages are labeled. Uses of this type of stencil are limited. Electronic assemblies for hearing aids, radios, etc., are produced uniformly at high rates of speed by using a thin screened stencil made of cloth or metal. The higher the quality of the screen and the finer the weave, the greater the uniformity in production. By employing a finer mesh, the edges are more sharply defined and the variation from assembly to assembly will be reduced.

Screens made of silk have found wide use in printed circuits work. Metal screens have also worked out satisfactorily and in many cases have proven more practical than silk screens. They are prepared by the same process as silk screens. Either stainless steel, copper, phosphor-bronze or similar materials may be used. It should be possible to use screens made of glass mesh. The mesh

size usually used varies from around 74 to 200 mesh.¹¹ Stainless steel screens of 300 mesh have been used to print silver leads. With screens of 120 mesh, it is practicable to print resistors of ± 20 percent tolerance or better.

Stencilled screens for printed circuits may be purchased commercially. Separate stencils are used for the conductors and resistors. Stencils are often used for preparing the plate, that is for cleaning and roughening, and for applying protective resin coatings to resistors and inductors.

(b). Preparation of Stencils

The screen is prepared by stretching it tightly over a wooden¹² frame. A photographic method is used to impart the circuit design to it. The screen is coated with a thin film of material such as gelatin or polyvinyl alcohol and photosensitized with potassium dichromate.¹³ When subjected to strong ultraviolet light, the film becomes insoluble in water. To impart the stencil pattern to the film, a photographic positive of the pattern desired is held tightly against the sensitized screen and exposed to light as in figure 6, A. Those parts of the film which are not exposed to the light are water soluble and wash out in cold water, leaving the design of the pattern to be printed.

Figure 6, B, shows a typical screen prepared in this manner. Polyvinyl alcohol yields a highly satisfactory blocking material for the screen. Although gelatin has not proven as good, it usually gives acceptable performance. It is important that the blocking material be selected such that it will not be attacked by solvents in the paint.

Silk screens once stencilled may not be restencilled satisfactorily. To use the metal screens for new designs, the backlog material may be removed by soaking them in a hot hydrogen peroxide solution, containing 3 percent of H_2O_2 , for 30 minutes to an hour. Scrub with hot water, dry, and remove any remaining traces of organic material in an open flame.

(c). Stencilling Procedure

This practice is basically the same as any stencilling procedure, although certain precautions must be observed. For example, extreme care must be exercised to see that the screen is level and

¹¹ Mesh classifications are: 6xx, 74 mesh; 8xx, 86 mesh; 10xx, 109 mesh; 12xx, 125 mesh; 14xx, 139 mesh; 16xx, 157 mesh.

¹² Metal, plastic or other types of frames may be employed.

¹³ A formula recommended by duPont [9] is polyvinyl alcohol 11.5 percent by weight, potassium dichromate (saturated solution) 5 percent by weight, water 83.5 percent by weight (color with dark blue pigment dye). The alcohol is dissolved in cold water, then heated and filtered (polyvinyl alcohol is supplied as a water soluble powder). The solution may be poured into a shallow tray and the screen dipped into it sufficiently to coat the entire outside surface. The screen with coated side up is whirled in a suitable device to distribute the solution uniformly over the entire surface. After drying in a dark room, it may be exposed through the photographic positive to a 1,500 candle power arc lamp, 3 ft away, for about 5 minutes. It is developed by a light spray of cold water on the underside of the screen. The meshes may be blown open with light blasts of air to insure good detail. The screen is then dried and ready for use.

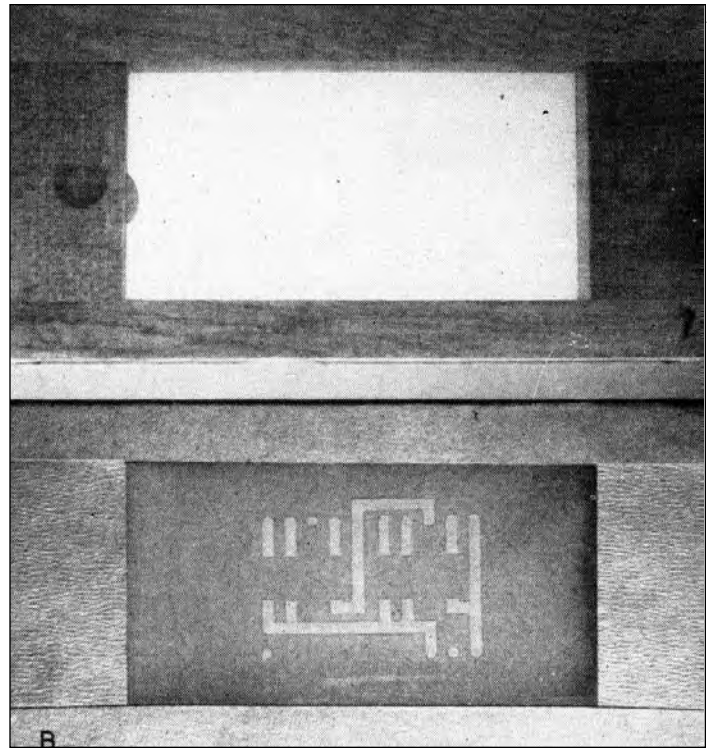
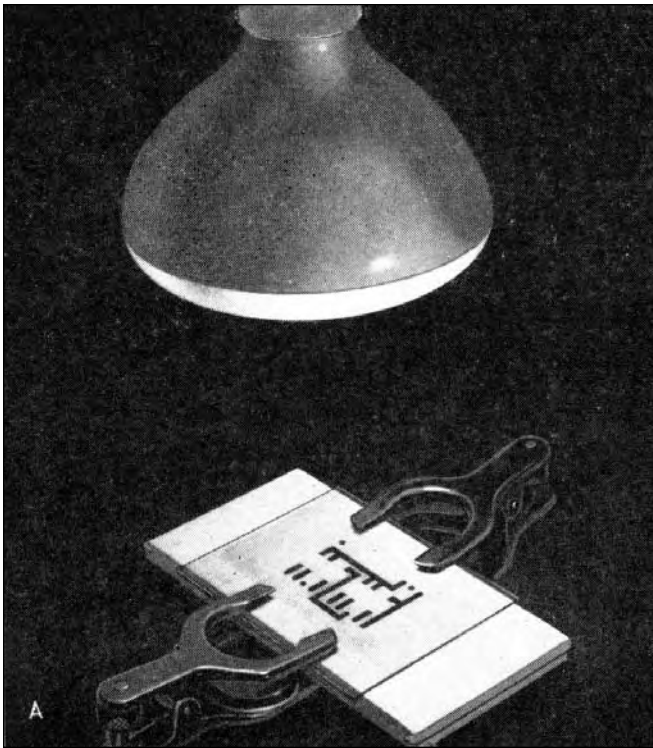


FIGURE 6. Preparation of stencilled-screen.

A, Screen coated with photosensitive material is exposed to strong light through a photographic positive of circuit pattern; B, stencil screen before and after pattern is applied photographically.

contacts all parts of the work evenly. This may be accomplished without difficulty by using a well designed holder for the screen, which positions it

properly over the work plate and allows intimate contact with the latter without forcing the screen. A retractable stencil holder is shown in figure 7A.

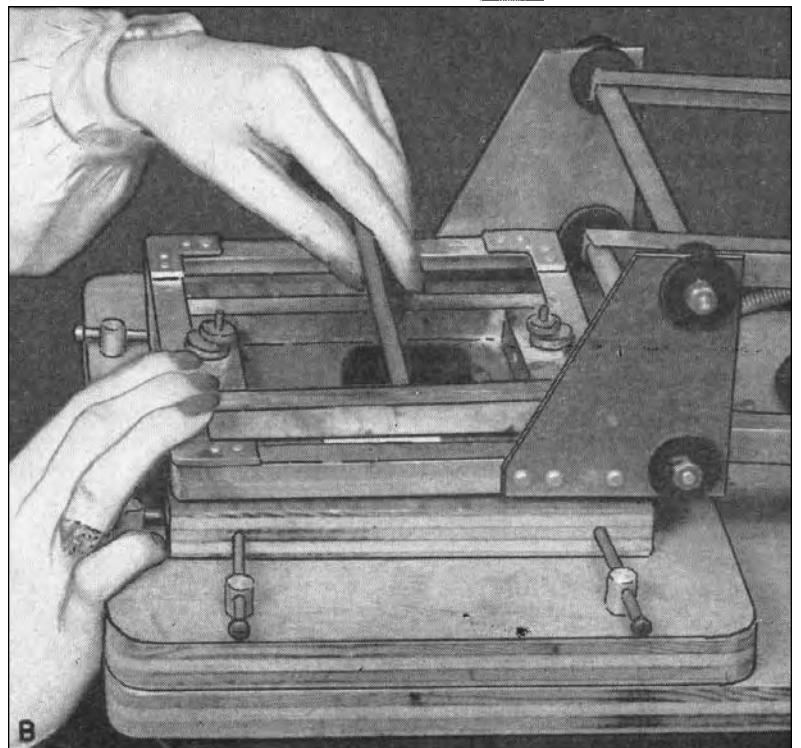
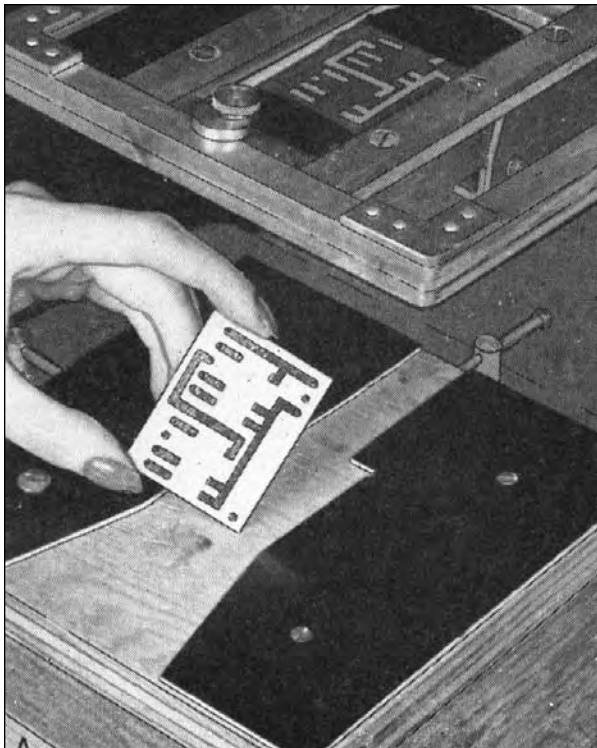


FIGURE 7. Stencilling operations.

A, Retractable stencil holder for applying paint to insulated plate. Holder moves forward and down over plate held in platen. Plate shown has just been removed from platen; B, application of paint through stencilled-screen. A single smooth stroke of the squeegee is required.

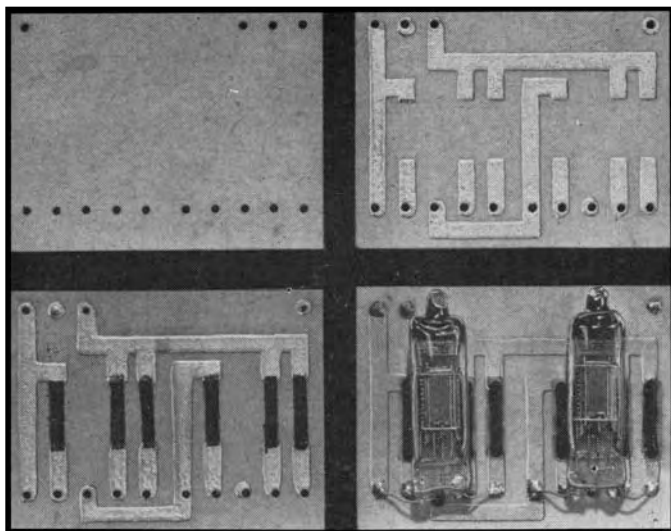


FIGURE 8. *Four stages in printing an electronic circuit by the stencilled-screen process; top left, blank steatite plate; top right, conductor pattern of silver paint applied through silk screen; lower left, six resistors added with carbon paint using second stencil; lower right, subminiature tubes soldered in place.*

The mechanical assembly is designed to swing the screen clear of the plate after the printing operation.

The next step is to place the paint on one end of the top surface of the screen and bring the plate on which the wiring is desired into contact with the bottom surface. A neoprene bar or "squeegee" is moved across the top surface, forcing the silver paint ahead and through the open mesh of the screen pattern as illustrated in figure 7B. A uniform film thickness is obtained and very little paint is wasted. When the screen is removed, the plate bears a design which conforms identically to that of the stencil pattern. Figure 8 shows a steatite plate before and after stencilling operations.

Neoprene makes an effective squeegee as it has the right degree of pliability. However, it may be attacked by ingredients in the paint. If this happens, a squeegee constructed of Buna-N rubber or other comparatively inert material should be used.

Mesh marks will be left by the screen if the paint is allowed to get too thick or if too much pressure is exerted on the squeegee. It is not out of order to emphasize the need for checking the viscosity to see that the paint composition is maintained within close limits if uniform electrical performance is to be obtained. Other simple precautions are necessary, such as maintaining the underside of the screen free of paint during printing and to see that paint does not remain in the open meshes of the screen at the end of the day's operation. If the impression appears smeared, it will be best to clean the screen by going through the painting operation a few times over a spare

base plate rather than to attempt to wipe the screen. Silk screens may be cleaned by using special commercially prepared solvents applied very carefully with a soft cloth so as not to rub off the blocking portion.

D. Other Methods of Applying Paint

Other methods of applying the paint are apparently limited only by the ingenuity of the user. Some which appear to have good possibilities include the use of decalcomanias, the application of ordinary printing, engraving and lithographing techniques, intaglio process and the special pencils, fountain pens and fountain type brushes. Printing electronic circuits by the decalcomania process is feasible and useful in applying the circuits to cylindrical and irregularly shaped objects, including vacuum tubes. The procedure is to print the circuit on a thin film which may be transferred to the final surface. After transfer, the film is removed by firing. The firing operation may also serve to drive out residual solvents and binder from the paint and to fuse the metal to the final surface. The wiring may be applied to the decalcomania film by many of the methods described above, including stamping.

Attention has been directed toward developing and using methods of printing electronic circuits involving the standard processes of printing. Here also precedents have been set since, for example, metal designs are printed directly on china using rubber stamps. Exactly the same practice is applied to printing circuits by using a rubber stamp bearing the circuit wiring pattern on its face. The stamp is first pressed onto a pad saturated with conducting ink, then onto the surface to be printed. If air drying ink is used and the base material, for example, is plastic, the ink may be allowed to dry in air. Plating will increase the conductance if needed. If the base material is glass or ceramic, the paint may be fired after the impression and essentially the same steps followed as in the silk screen method. Although this practice is well suited to printing conductors, it may not work out well with resistors if close tolerances are necessary.

It is now an easy step to the letter press or offset printing processes used to print literature [10]. Figure 9 shows a printing press arranged to print an electronic circuit on an insulated plate D. The soft rollers A first pass over the ink plate B, which is coated with conducting ink. On the return motion, they sweep over block C, which carries the metal pattern of the circuit to be printed, and coat it with a layer of ink. In the final step, carrier E presses the plate firmly against C, printing the desired pattern on plate D. Units of this type may print a layer of silver paint 2 or 3 mils thick.

To increase the conductance the printing may be repeated. A variation of this process is to interpose an additional roller between C and E to transfer the print C to D. In this manner, plate D is retained in a fixed position during the printing [11].

The printing press process has been used to print spiral loop antennas on the internal surface of radio cabinets. It is adaptable to any type of base plate. After the paint has been applied, the plate is subjected to the usual drying or firing procedure. A paint that has proven successful for use in the printing press consists of a colloidal suspension of metallic silver but with silver oxide and other inorganic materials kept to an absolute minimum. Up to 70 percent of silver may be used. The binder and solvent are volatile below 300° C. This paint produces an even coating, which adheres strongly to the base plate after firing at 300° C. Coatings of fair conductance [11] are obtained even after firing at 110° C.

The technique of printing metal decorations on paper from steel and copper plates offers a possible field for exploration in printed circuits. Other variations suggested are the direct application of paint to the insulating surface by means of a rubber, metal or plastic block with the circuit design prepared as a cavity or deep etch to hold an appreciable quantity of paint. The primitive and seldom-used method of employing an ordinary lead pencil to draw a high resistance line on a sheet of paper should not be overlooked. The principal objection is the low conductivity and wide variation in resistance of the line. It is conceivable that pencils may be developed that contain better conducting "leads" so that not only resistors but conductors may be drawn. Such a pencil might find use in such applications as in laboratory work where it is desired to arrive at a rapid estimate as to how various circuit configurations perform electrically.

To date, no satisfactory method of applying the paint by dipping the work into it has been found. The principal drawback to this method is the inability to control the thickness of the paint. Tear drops are formed and an uneven distribution of paint usually results. With plastics, dipping allows more of a chance for the solvent to attack the base material. It is possible that a satisfactory means of employing it might be worked out, using glass, steatite and other hard base materials. Tear drops and fat edges may be eliminated by means of a recently described electrostatic method [12] which removes the excess paint, leaving a smoothly coated surface. Although this technique has not been tried in connection with printed circuits, it appears to have possibilities for printing circuits both by dip and flow coating.

A process has been developed for applying the printed circuit technique to thermosetting plastics in such a manner that the circuit can be formed

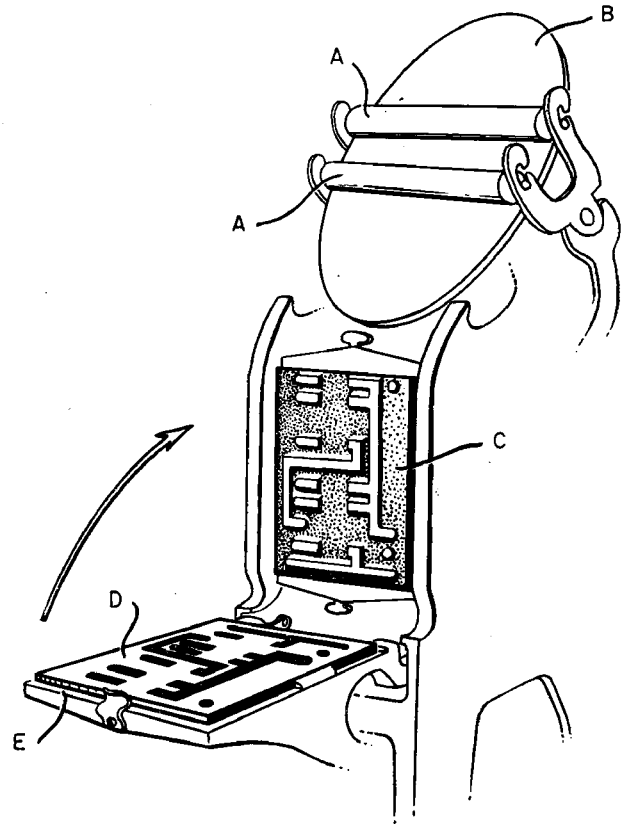


FIGURE 9. Printing press for printing electronic circuits.

into cup shaped or irregularly shaped forms.¹⁴ It consists of applying the paint to an organic insulating supporting structure (paper impregnated with phenolic lacquer) and curing both the paint and plastic simultaneously. Although it has been tried only with thermosetting base materials, it appears feasible for application to thermoplastic materials as well. Any desired thickness of metallic conductor may be applied as well as resistors and other component parts. A measure of the flexibility of this process is afforded by the fact that external connections to the circuit may be made through eyelets on the base material. The eyelets may be applied after printing without danger of cracking the base. An antenna printed by this process is shown in figure 10. Note the eyelets to which external leads are readily soldered.

E. Drying

After applying silver wiring to ceramic plates, they are heated to remove the binder and solvents and to bond the silver to the plate. Properly fired silver has the typical dull metallic silver appearance and will adhere to the ceramic surface with a tensile strength of approximately 3,000 lb./in.²,

¹⁴ Developed by Herlec Corporation.

when the paint is made of finely divided metallic silver or silver oxide uniformly dispersed in a suitable binder. The degree of bonding or adherence of the fired silver depends on the surface condition of the ceramic before the paint is applied. To obtain the strength quoted, the surface must be absolutely free of dust, dirt, grease or other contaminants.

As with most techniques, the successful painting of electronic circuits depends upon the careful observation of small points. The manner in which the coating is dried is important and may be determined experimentally for the type of paint used. Instructions may be obtained from the paint manufacturer. For example, one manufacturer specifies a 3-hour drying at 50° C for silver paint which it manufactures for use on thermoplastics applied by means of a screen. Other paint and spray preparations dry satisfactorily in 1 hour at 40° C or overnight at room temperature [2]. Longer drying is to be preferred if time allows. If the basic material is thermosetting instead of thermoplastic, the temperature may be raised 10° or 20° C and the time reduced. Infrared lamps are often used for drying printed circuits.

Dielectric heating may be employed to heat the paint after application to the surface. By designing a suitable set of electrodes under which the work is slowly passed on a conveyor belt, it is possible to drive the binder and solvents out of the paint by treating them as the dielectric in a high frequency dielectric heating system. It is suggested that binder and solvent materials be selected which, if possible, have high loss factors, i. e., a high product of dielectric constant and power factor. Thus, acetone is preferred over alcohol. This method may be useful in working with base materials such as thermoplastics which will not stand

high baking temperatures. In dielectric heating, the heat can be centered in the material it is desired to evaporate from the paint.

4. Application of Resistor Paints

A. Carbon-Film Resistors

Resistors may be painted by brushing or stenciling the resistance material onto the wiring surface. In brushing, the same technique is followed as for the conductors. In the stenciling method, stencils are employed with openings at positions corresponding to blanks in the conductor wiring stencil. The position of the openings in one example may be seen by referring to figure 8 in which are shown plates before and after resistors have been applied.

Excellent results have been obtained using a simple squeegee as is done in painting conductors. The stencilled-screen is prepared in the same way. Resistors of better quality are produced with two applications of paint through an 80 mesh silk or 120 mesh copper screen, using a pressure-controlled squeegee. As might be expected, the pressure and speed of the squeegee bar moving across the screen play an important part in the uniformity of the resistance produced. Using similar paints, stencils and base plates, the pressure-controlled squeegee yields a considerably larger percentage of resistors within fixed tolerance ranges than the hand wiping method. Uniformity suffers in the hand wiping method because of the difficulty of exerting the same pressure each time the bar is moved across the screen. Any paint remaining in the screen after one operation will affect the value of the resistors painted in the subsequent operation.

A pressure-controlled squeegee used by one manufacturer is illustrated in figure 11. The work is moved accurately into position against the

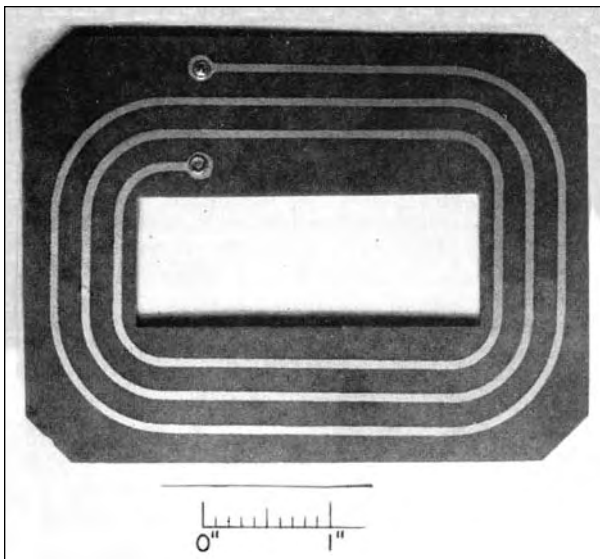


FIGURE 10. Loop antenna printed on plastic sheet.

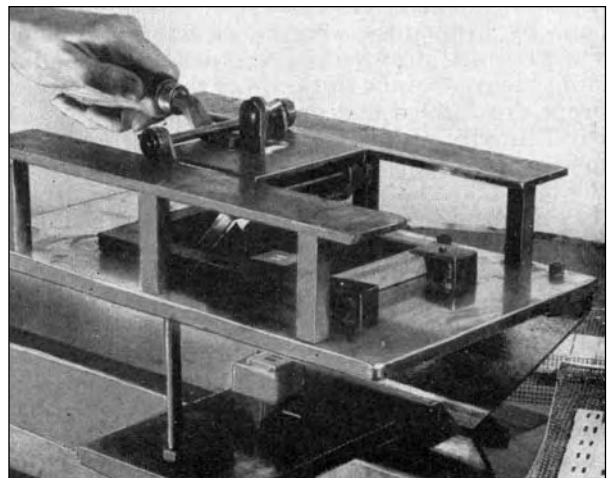


FIGURE 11. Pressure-controlled painted resistor applicator.

Circulars of the National Bureau of Standards

screen by a pedal operated elevator. The screen is held securely in place while the squeegee, which rides on a carriage, sweeps over it. The squeegee may be adjusted for angular position and securely locked in place. The carriage is constrained to move only in a horizontal direction within close vertical tolerances. In this manner, pressure over the screen is maintained uniform as the device sweeps back and forth. Although designed to produce uniform resistors, the device is applicable to silver painting as well as to applying a lacquer coating to the resistors.

As powdered carbon has more of a tendency to adhere to the screen than silver, clogging may occur. The difficulty is relieved by proper selection of the other paint ingredients. A screen with larger mesh openings may also be used. Typical silk screen mesh sizes vary from 74 to 200 mesh. The latter is useful only for painting high values of resistance for which carbon of very small particle size is used.

Not only the paint formulation but the width, length, and number of coats of resistor material may be varied to increase the range of resistor values possible. Practice has shown that closer uniformity may be had using several coats to build up the resistor. The paint should be allowed to dry between coats. The drying cycle between coats is determined by practice and may vary from exposure to air for 5 minutes at room temperature to a 10-minute exposure at 75° C. Filing or grinding may be employed to increase the resistance after the resistor has dried. A small dental grinder serves well for this purpose. To decrease the resistance, additional paint is brushed on. In this manner individual resistors may be adjusted to very close tolerances.

The type of stencil and the accuracy with which it is made are important factors influencing the reproducibility of painted resistors. The stencil must adhere closely to the base plate. Paper masks have been used to position the resistors and determine their size but although they adhere closely to the surface, they tend to leave ridges at the sides of the resistor. Adoption of the silk or metal screen has eliminated the ridges and given remarkable improvement in uniformity. It should be possible to obtain better than 80 percent yield of resistors within ± 15 percent tolerance with production line methods. Those few that ordinarily require closer tolerances may be adjusted as described above. The distribution of a limited number of resistors of values ranging from 5.9 ohms to 8.4 megohms produced by the silk-screen method on a small pilot line is shown in table 4. From 79 to 98 percent were within ± 10 percent of their average value. Greatest spread was observed with the smallest (5.9 ohm) resistors. Those of 1,500 ohms and above were held within limits much closer than is required in usual electronic sets man-

ufacture. On an amplifier chassis, one manufacturer successfully uses four resistance paint formulations and makes a total of from 8 to 16 application of resistance paint to the two sides of the base plate. In this manner resistors of close tolerance are produced. The operation, although seemingly complex, is readily adaptable to the assembly line as the applications and subsequent drying adapt themselves either to manual or automatic operation using either the conveyor belt or pass-along system. After the resistors have been air dried, the paint is finally cured in an oven. Curing is affected at the proper temperature to convert the heat polymerizable resin into an infusible state. For carbon paint in a bakelite resin binder, the curing temperature is approximately 150° C. One practice is to oven dry the first side of the plate for 20 minutes at 150° C, then paint the second side and oven dry the assembly for 2 hours at the same temperature.

TABLE 4.—Variation in pilot production of printed resistors

Number of resistors tested	Minimum resistance	Average resistance	Maximum resistance	Mean deviation from average	Outside $\pm 10\%$ tolerance	Outside $\pm 20\%$ tolerance
	<i>Ohms</i>	<i>Ohms</i>	<i>Ohms</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>
38	4.5	5.9	10.6	± 11.7	21.0	13.0
61	1,500	1,600	1,800	± 3.1	9.8	0
61	48,000	54,000	59,000	± 3.0	1.6	0
61	81,000	93,000	110,000	± 5.0	8.2	0
376	800,000	1,800,000	2,100,000	± 4.5	9.5	1.6
91	3,200,000	3,600,000	4,200,000	± 2.8	2.2	0
35	7,200,000	8,400,000	9,500,000	± 4.5	11.5	0

It would be highly desirable to be able to print the complete useful resistor range with a single paint formulation. Although this is theoretically possible, it may require printing some resistors in unreasonable sizes or placing unattainable tolerances on the physical dimensions of other resistors. A practical compromise is to cover the range from 3 ohms to 200 megohms with from three to six resistor mixes using one or more applications of the paint. Figure 12 shows a coverage of the range 1,000 ohms to 10 megohms using four mixes and two applications of paint.

If the design permits, some advantage may be gained by placing the low values of resistance on one side of the plate and the higher values on the other. This reduces the number of repetitions per face required to produce the requisite number and range of resistors. High values of resistance may be painted in a small space by zig-zagging the lines in any of the several variations used to denote resistors in conventional wiring diagrams. If resistors of large power capacity are needed, they may be painted on the inside of the cabinet housing the set. The resistance may also be divided in two or more parts, each placed on a sep-

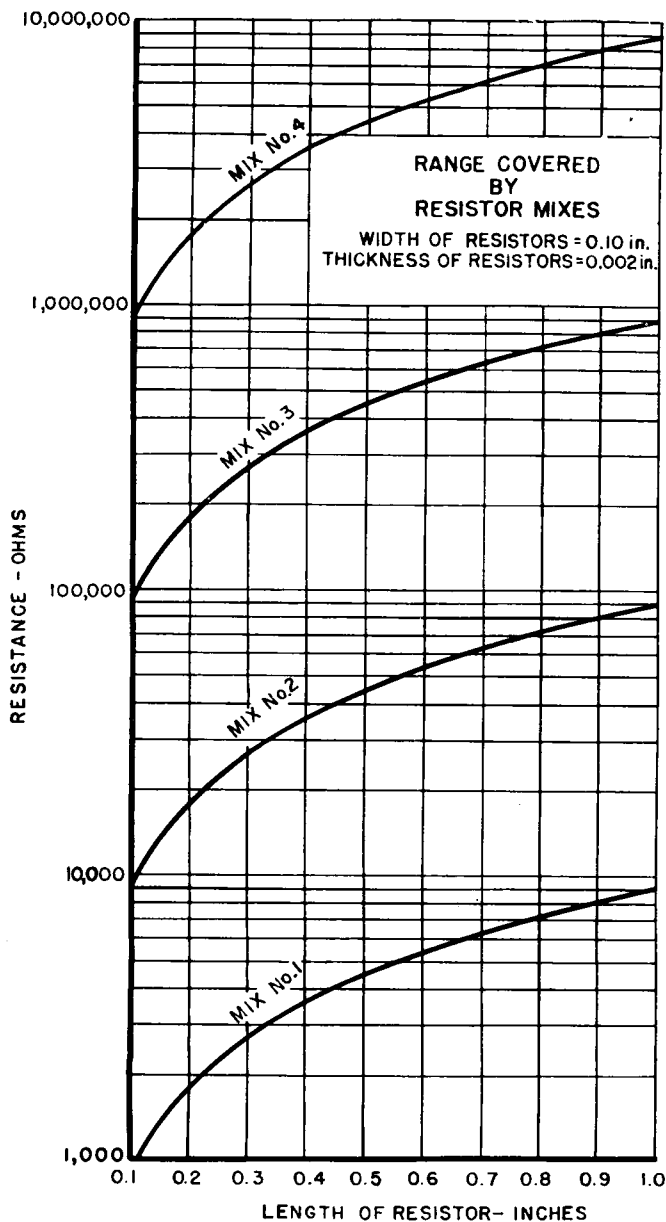


FIGURE 12. Typical range covered by carbon resistor mixes.

arate wall to dissipate the heat better and further increase the power rating.

Reports show that during the past war, German plants produced carbon film resistors in fairly large quantities. At one plant, [13] a colloidal suspension of carbon in lacquer was used, followed by firing in an oven at 250° C. Only single resistors or cylindrical ceramic sticks were manufactured.¹⁵ The 0.25 watt size was 0.16 in. in diameter and 0.6 in. long. Tolerances of $\pm 10\%$ were met by production methods. The carbon film type of resistors were claimed to yield superior performance over the molded type and particularly to have a lower noise level.

¹⁵ No record is available of the printing of complete electronic circuits in Germany although metallized electronic components such as capacitors and inductors on ceramic forms were developed.

B. Metal-Film Resistors

Metal-film resistors are produced by depositing a thin film of metal on a suitable base. In one method [14] this is done by painting a dilute solution (as low as 1 percent) of palladium resinate in ketone on a ceramic base material, drying in air for 30 minutes and heating to 750° C for an hour to an hour and a half. Under the high temperature, an extremely thin layer of palladium is deposited on the ceramic surface and the residue burned off. The noble metals are used in this process because they remain substantially stable and nonoxidizable at the high temperature. The palladium is deposited chemically as the temperature passes the range 200° to 400° C. The temperature is kept in this range for 15 to 30 minutes, after which it is raised to 750° C for an hour to completely oxidize the ash or residue and insure thorough precipitation of palladium.

Resistors up to 1 megohm may be produced in this way. Higher values are difficult to produce by the painting method principally because of the problem of depositing a uniformly thin or narrow strip. However, the resistors have better characteristics than wire-wound resistors, i. e., low positive temperature coefficient, good stability, low-noise level, very good frequency characteristics and good heat dissipation. The adherence to the ceramic base is particularly strong.

5. Capacitors

It was stated that capacitor components of printed circuits may be printed by using a base material of high dielectric constant and painting silver disks of the correct area on opposite sides of the plates. The capacitance is effectively that formed by the two silvered areas and the dielectric between them. This practice is now used in applications where the high dielectric constant base material does not affect the electrical performance adversely or where it may be advantageously used in designing the circuit.

Where it is necessary to use base plate materials of low dielectric constant, one accepted practice is to solder capacitors directly to a single silvered area on the base plate. The miniature thin-disk type of high dielectric constant capacitors having ceramic dielectrics have proven very satisfactory for this use [15, 16]. Titanium compounds and other dielectric materials have been developed that exhibit a wide range of dielectric constants. The principal problem has been the control of dielectric losses and performance with temperature. The capacitance for printed circuit use is controlled not only by the chemical formula of the dielectric but the thickness of the disk and the area of silvering on the faces. Dielectric constants ranging from 40 to 10,000 have been used for capacitors from 6.5 to 10,000 $\mu\mu\text{f}$.

They are from 0.020 to 0.040 in. thick and 0.125 to 0.5 in. in diameter. Higher dielectric constant materials are available, but their electrical losses and extreme variation with temperature in certain temperature ranges limit their use. Properties of barium-strontium titanate dielectrics have been measured and reported by the National Bureau of Standards [16]. Examination of this work will show that it is possible to select mixtures to meet a wide variety of applications.

The capacitors are soldered to the plate with a low temperature solder, such as 20 percent tin, 40 percent bismuth, and 40 percent lead. This solder has a melting point of 110° C. Soldering is accomplished by laying the capacitors over a silvered area of the plate, after tinning the surface, and simply pressing down on top with a soldering iron. Preheating and the low temperature solder prevent the dielectric from fracturing during the soldering operation. High dielectric constant ceramic capacitors used at the Bureau have not exhibited appreciable hysteresis with temperature. Upon cooling, they return to their original value. In special cases the thermal shock received on soldering may cause a small permanent change.

Any type of capacitor may be soldered to a printed circuit assembly but those described above have the greatest economy of space and adapt themselves very well to the printed circuit technique.

Capacitors may be built on the base plate by spraying alternate layers of a conductor, such as silver paint, and a high dielectric constant lacquer. The base plate may have a high dielectric constant material molded into it as a filler so that silvered areas on opposite sides of the base material will form a capacitor. By molding the space for the dielectric thinner than the rest of the plate, it is possible to obtain larger capacitors without weakening the base plate.

Another capacitor particularly adaptable to printed circuit techniques is the vitreous enamel dielectric type [17]. It consists of alternate layers of dielectric and conductive materials built up by spraying and fired together, producing a capacitor which appears to be a solid plate of vitreous material. This capacitor may itself be used as a base for printed circuits and may be built up to any reasonable size and in such a way that the base plate contains any reasonable number of capacitors. Thus the circuit can be printed over the capacitors, making a very compact assembly. These units may be made with any capacitance value if enough volume is provided. The usual volume allowance is 0.02 $\mu\text{f}/\text{in.}^3$ for a working voltage of 500 v direct current. The power factor is low enough so that Q's of 3,500 may be had above 250 $\mu\mu\text{f}$ and 1,000 for 10 $\mu\mu\text{f}$. Temperature coefficient is approximately +100 ppm/°C up to 125° C.

They are stable and in general are equivalent to mica capacitors. They can be produced to tolerances of ± 1 percent if desired. Average production batches show over 50 percent under 5 percent tolerance. One of the important features of this type of construction is that it is entirely mechanized so that it should be possible to turn out printed circuit assemblies including capacitors, wiring and resistors in an entirely automatic process. This should make possible inexpensive mass-produced electronic sets.

6. Inductors

The printed circuit technique may be used at high as well as low frequencies. The lowest frequency for which inductors may be printed is limited by the printing area available. For a given area, however, the inductance may be increased by printing the inductor in multiple layers. Circular or rectangular spiral inductor [18] may be printed flat on the base plate in the same manner as the wiring leads using silver paint. To increase the inductance, a layer of insulation is painted over the inductor after which a second inductor is printed. Any number of layers may thus be built up to form inductors of high inductance. The usefulness of this method is limited principally by the distributed capacity and the Q required of the inductor. Multiple layer inductors may also be printed on cylindrical tubing.

The multiple layer idea need not be restricted to inductors. Several circuits may be printed on the same plate, one above the other, by interposing a layer of insulation between them either by painting, spraying, etc. The proximity of the circuits to each other must be taken into account in laying out the design so that undesirable couplings are avoided.

It is possible to print reasonably high Q inductors by first applying silver paint and then silver plating. Spiral inductors in the two meter band have been printed on a circle 0.625 in. in diameter. A Q of 125 is obtained by silver plating to a thickness of approximately 0.002 in. Inductors painted on glass and steatite tubes have performed very satisfactorily in oscillator circuits.

Inductors of silver fired onto cylindrical ceramic forms have been manufactured for some time [19]. Better adhesion of the silver to the ceramic is had when the metal is fired onto the surface using a suitable flux than when some other method such as chemical reduction of the metal is used.

The inductance of printed inductors on an insulating surface is low not only because of the limited space employed for them but because they operate in a medium of low permeability. One side is principally exposed to air while the other side has the insulating base material, also of low per-

meability, in its field. A method of increasing the inductance is to eliminate some of the center turns and fill the area with a magnetic paint made as a colloidal suspension of powdered magnetic material. A modification is to print intertwined spirals of silver and magnetic material or, if the magnetic paint is made nonconducting, the whole inductor may be sprayed or painted with it.

To increase the inductance, the base plate may be molded with a cylindrical indentation so that a small cylindrical magnetic slug may be dropped into it and cemented into place. The base plate itself may be molded with a magnetic filler added to the plastic or ceramic. Another method is to paint or place a magnetic disk in the insulating plate below the painted inductor, followed by a second magnetic disk above the inductor. The combination may be painted on by first painting the magnetic disk. When this dries, a glaze or similar insulating surface is applied over it, followed by painting the flat spiral inductor, then another layer of insulating material and finally, a second magnetic disk. The disk tends to shield the inductor, thus eliminating undesirable magnetic couplings to other parts of the circuit. Obviously, extension of the practice may be made to printing inductors on cylindrical or other non-planar surfaces such as vacuum tubes. Inductors may also be printed on two pieces of base material that can be moved relative to each other to make a variable tuning unit [20].

The important characteristics of the spiral inductors used in printed circuitry are the inductance, the distributed capacitance, and the loss. Since the inductor is in intimate contact with the base plate, which is a dielectric, the characteristics of the dielectric are important. The distributed capacitance is increased by a material having a high dielectric constant, and the loss is increased (Q decreased) by material having a large dielectric loss. The inductance may usually be calculated, but the distributed capacitance and the loss have to be determined empirically.

The inductance of a thin flat spiral in a medium whose permeability is unity may be computed by the formula (in microhenrys) : [21]

$$L = 0.0319 \, a n^2 \left[2.3 \left(\frac{\log_{10} 8a}{c} \right) \left(\frac{1 + c^2}{96a^2} \right) + \frac{3c^2}{80a^2} - \frac{1}{2} \right]$$

Where a = average radius of the inductor in inches

n = number of turns

c = radial thickness of the inductor in inches

When the inductor starts at the center, $c = 2a$ and the formula simplifies to:

$$\begin{aligned} L &= 0.776 \, a n^2 \, \mu, \\ \text{or } L &= 0.0194 \, d n^2 \, \mu, \end{aligned}$$

where d is the outside diameter of the inductor (i. e., $d = 4a$).

An inductor having 20 turns with a 2-in. outside diameter would have an inductance of 16μ .

As the total self-inductance of two coils in series is $L = L_1 + L_2 \pm 2M$ and the mutual inductance for unity coupling is $M = \sqrt{L_1 L_2}$, it should be possible to obtain nearly four times the inductance of a single inductor by painting a similar inductor on the reverse side of a thin ceramic plate and connecting the two in series aiding. This will decrease the Q of the inductive circuit, however, as more flux is included in the dielectric material.

The mutual inductance of two inductors may be utilized in other ways, such as making antenna coupling inductors, grid to plate coupling inductors, band-pass filters, etc. These can either be printed side by side, one inside the other, or on opposite sides of the base plate. A compact band-pass filter may be made by printing inductors and the plates of the shunt capacitors on directly opposite sides of a sheet of thin dielectric material. Variable inductive or capacitive coupling between the two sections of the filter may be obtained by arranging so that either one of the inductors or capacitor plates may be shifted relative to its mate.

The maximum inductance available in the usual size of a plane spiral inductor without magnetic core material is of the order of 60μ , usually limiting their use to frequencies above 0.5 megacycle. The upper frequency limit will be set by the distributed capacity of the inductor in addition to the inter-electrode capacitance of the tube. Printed inductors for frequencies in excess of 500 megacycles may be simply a pair of parallel lines.

Unfortunately, the values of inductance obtainable from flat spiral printed inductors of any reasonable size are not large enough to allow radio frequency chokes to be used, hence where possible, chokes should be avoided in printed circuit design. If chokes must be used, they may be soldered directly to the printed wiring. It is good practice to design the circuit so as to require small capacitors and inductors and to use printed resistors in place of chokes. This is illustrated in figure 33B in which a 2,200-ohm resistor has the same function as a B+ choke.

Printed solenoidal inductors are important in such applications as the printing of circuits on the envelope of a vacuum tube. Samples of this practice are shown in figure 35. The formula for the inductance in this case is:

$$L = \frac{r^2 n^2}{9r + 10L} \, \mu h.$$

Where r is the radius and L the length, in inches, n is the number of turns.

7. Electron Tubes

A large variety of subminiature tube types are available that are applicable to the design of practically every type of low power electronic circuit. These include many types of triodes for amplifiers, oscillators, (including UHF types), electrometers, gas filled thyratrons, phototubes and diodes, tetrodes (also a twin tetrode), diode-pentodes, converters and a large number of different kinds of pentodes. The subminiature tubes have very low drain (10 to 200 ma at 1.5 to 6.0 v) and work well as voltage amplifiers. Their power output varies from a few milliwatts to almost 1 watt. Triodes of general purpose and UHF types are available milliwatts of output. RF pentodes have mutual conductances of 5,500 to 6,500 micromhos. At 500 megacycles, some of them deliver as much as 700 milliwatts of output. RF pentodes have mutual conductances up to 5,000 micromhos and plate resistances from 0.1 to 3.0 megohms.

The accomplishment of complete two-dimensional electronic circuits by incorporating the tube within the ceramic base plate is brought into the realm of practical possibility by certain recent developments [22, 23]. Vacuum tubes have been produced with part ceramic and part metal envelopes. The tube elements are held in ceramic forms metallized at the edges and sealed to metal end pieces. In one development the ceramic is metallized by applying a molybdenum-iron paint [22] and firing at 1,330° C for 30 minutes. To improve soldering to the edge, it is brushed with a paint consisting of nickel powder stirred in 10 percent collodion. The solvent on evaporation leaves a nickel film that wets hard solder well. The tube elements and leads are also soldered to the ceramic in this way. The molybdenum-iron layer provides a vacuum-tight junction between the ceramic and metal at all temperatures. Utilizing this practice, the internal structure of a sub-miniature tube may be mounted in a slot in the ceramic plate and the space sealed off by a thin ceramic wafer soldered to the plate. Tube leads may be brought out by several convenient methods. Ceramics such as steatite not only have excellent electrical characteristics but their mechanical properties are superior to those of the usual type of glass employed in vacuum tubes.

8. Protective Coatings

Protection against abrasion, humidity and other effects is obtained by applying special resin coatings over the resistors. Baking the coating produces a scratch-proof as well as humidity-proof envelope. It also renders the resistors more stable against the effects of temperature cycling. If desired, the coatings may be applied to the

printed conductors and inductors as well. Suitable protective coatings include: (a) Silicone resin in toluene; (b) polyvinyl acetate chloride lacquer; (c) polystyrene lacquer; (d) phenol-aldehyde lacquers.

The type of coating selected depends in part on the type of binder used as an ingredient in the resistor paint. If a phenolic binder is used, a corresponding phenolic lacquer coating that cures at approximately the same temperature as the paints should be used. If the coating requires higher curing temperature than the resistor paint, there is danger of carbonization of the paint when the coating is fired. If a phenolic base material is used, it is good practice to specify a phenolic binder in the paint as well as a phenolic lacquer for the coating.

The coating may be applied through a screen stencil in the same manner as the paint. A coarse screen, 74 to 86 mesh, is usually employed. As with the resistors, improved results are obtained by applying a double coat of resin with a 5 to 10 minute drying at elevated temperature (75° C) between coats. Infrared lamps work well for this purpose. If followed with a 1-hour baking at 150° C, the resulting coating will strongly resist abrasion, cracking and the tendency to chip. Where the electronic set is to be used under severe tropical conditions, an additional tropicalization treatment may be necessary.

If the protective coating is applied properly, the resistance stability with time, under load or under extreme humidity conditions, will be very good. When a set of resistors painted on steatite was exposed for 100 hours in 95 percent relative humidity at 43° C, the average resistance change was -10 percent for values in the range 5 ohms to 10 megohms. This was not a permanent change, for on drying the resistors returned to their original values.

The protective coating may cause a change in the value of the resistor under certain conditions. One manufacturer who had developed a good resistance paint to be used with the hand painting or spraying process experienced disturbing results on applying the same paint through a stencilled screen. After painting the resistors, a protective coat of resin was applied. Excellent results were attained when the resistors were hand painted or sprayed. Resistors produced with the same paint applied through a screen showed as much as 600 percent increase in value as the result of application and baking of the protective coating. An investigation revealed a porous condition in the stencilled resistor. A rearrangement of percentages of binder and filler in the paint corrected the condition so that application of the protective coating caused no changes in the value of the resistance.

9. Plating

The most practical way to increase the conductance of printed elements is to electroplate over the initial printing. A good rule is to print a thin layer of the order of 0.0005 in. or less and to electroplate on top of this. Copper plating on silver is very practical for increasing the conductance, using the usual acid-copper sulfate bath [24]. Best results are obtained if the initial layer is plated at low current density, i. e., a deposition rate of 0.0005 in. per hour [2] for the first 10 minutes. Copper plating baths are inexpensive, easy to prepare and require little maintenance, hence adapt themselves well to electroplating circuits printed in silver. A procedure followed in increasing the thickness of the coating is first to plate the initial silver layer with copper and then add a final silver coating over the copper. This facilitates soft soldering direct to the leads.

Other metals may be plated directly on the silver if desired. Good results are obtained by dipping the printed plate into a dilute sulfuric acid bath and rinsing with water, then plating. It is clear that the materials in the plating bath should be selected so as not to attack either the base material or any of the paint constituents.

10. External Connections

External leads and tubes may be soldered directly to the silver or to eyelets on which the silver wiring terminates, providing a solder having about 2 percent of silver to saturate against further absorption of silver is used.

A solder dipping technique may be used for soldering tubes and external leads to the printed circuits. The tube leads are placed in holes or eyelets at which the printed wiring terminates. The assembly is heated in air at approximately 230° C and then dipped into a solder bath at 200° C for about 20 seconds. When withdrawn, the terminal and tube leads are neatly soldered in place and, in fact, a thin layer of solder coats all of the printed silver leads. At low frequencies, this extra coating on the leads has the same effect as plating, i. e., increased current carrying capacity as well as conductance. If the assembly has painted resistors, the protective lacquer covering usually applied to them after painting keeps them from becoming coated with solder. When the wiring contains high-frequency inductors, the solder coating has been found to increase the losses in the inductors, i. e., decrease the Q of the inductors. This may be due to a combination of increased capacitance between turns as well as decreased average conductance of the leads at high frequencies. If the frequencies are such that the current flows en-

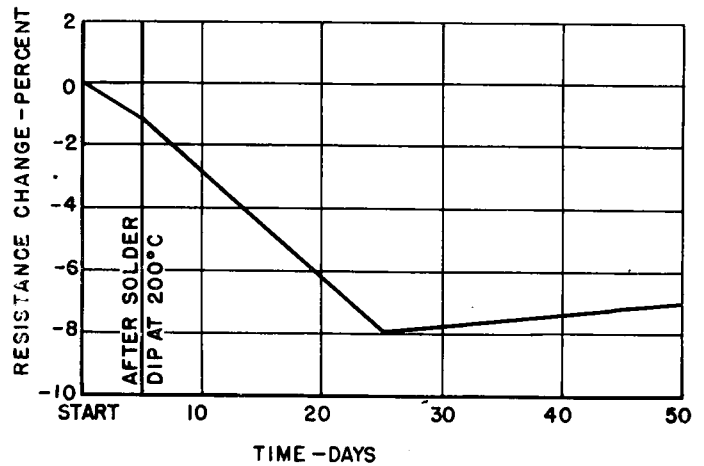


FIGURE 13. Change of resistance of printed resistor with time

Typical result obtained on test of 100, 1-megohm resistors.

tirely in the skin of the conductor, the tinned coating on top of the silver forces the currents to flow partially in the silver layer and partially in the higher resistance skin of the solder. To avoid this loss of Q , a protective coating of lacquer is put over the inductors that prevents tinning during the solder dip.

The solder bath is prepared as follows. The solder¹⁶ is first made molten by heating to 200° C. A layer of opal wax is then formed over the solder, after which polypale rosin is melted in the liquid. In this manner, three layers are formed. As the unit is dipped into the bath, the rosin cleans the parts to be soldered; the second layer, the opal wax, forms a protective film to prevent the solder from adhering to the prelacquered resistors and inductors; the third layer, the solder, attaches the units to their position. Upon removal from the solder bath, the unit is shaken to remove excess solder, then dipped in solvents to remove the excess rosin and wax.

The technique of soldering by dipping subjects the resistors to a thermal shock of 200° C. A result typical of 100 1-megohm resistors is shown in figure 13, in which the resistance decreased 8 percent during a 20-day period after dipping and thereafter increased about 1 percent in 25 days.

In some cases it may be advisable to use induction heating for soldering operations. High-frequency induction heating adapts itself well to soldering the thin capacitors usually employed with printed circuits, also for soldering other leads to the base plate. By using high frequency, heat will be generated in the thin silver layers as well as in the solder and leads in the junction, thus producing a more ideal bond.

¹⁶ 63 percent lead, 37 percent tin.

III. Spraying

1. Metal and Paint Spraying

A. Techniques and Apparatus

Spraying of conducting films on insulating surfaces, like the spraying of ordinary lacquers and paints, not only has popular appeal but is fairly easy to adapt to production line practice.¹⁷ The practice of spraying metallic and carbon paint onto insulating surfaces through stencils has been used with success. The same paints are used as for the stencilled-screen process. Special equipment is unnecessary, the ordinary lacquer spraying equipment being completely satisfactory. By using a spray gun with a properly controlled spray pattern and with the work attached to a moving conveyor belt (20 to 30 ft. per min) a good degree of uniformity may be obtained in the spraying assembly. Spray guns which automatically stir the paint in the container, such as those employing suction feed with the container adjacent to the gun are recommended. In spraying resistors, the electrical values may be controlled by means of the conveyor belt speed as well as regulating the flow of the material from the gun. In addition to paints, molten streams of metal may be sprayed directly through circuit locating stencils. The metal may be supplied to the spray gun in either wire, powder, or liquid form. Precautions must be taken to prevent the films from being coarse, thick, and nonhomogeneous and to adhere strongly to the surface. The latter is accomplished by roughening such as by spraying with an abrasive material or by treating the surface with special lacquers. [25]

Spraying apparatus must be provided that will raise the metal to molten form. Suitable guns are available commercially. The wire gun is very convenient as it allows spraying almost any type of metal that can be supplied in the form of wire. The metal is heated in the gun by means of a hydrogen acetylene or other flame. Compressed air is usually employed to atomize the melted metal and drive it over to the work. If metal powder is used, a special injector is required to feed the powder to the flame. The molten metal gun contains a heated chamber that maintains the metal

at the proper temperature prior to injection into the compressed air stream.

Molten metal may be sprayed on wood, bakelite, plastic, and even ceramic surfaces. Manufacturers of high voltage insulators have long employed the techniques to coat the insulators in order to distribute the electric field properly over the surface. Experience gained in this practice is directly applicable to printing circuits. Adherence of the sprayed metal to the surface is entirely mechanical, and hence, not as strong as when the metal is fused on. The adhesion on ceramics may be improved by glazing [4] the surface prior to roughening it. Further increase in adhesion may be had by using a glaze containing metallic particles. The adhesive strength of sprayed silver on ceramics is greater than sprayed copper. In order to take advantage of this and the greater economy of copper, it is frequent practice to spray a thin layer of silver followed by a thicker layer of copper to obtain the desired conductance.

Helical resistors for electric heating are made by setting up a metal spray gun on the carriage of a lathe and spraying a helix on a ceramic tube, using the thread cutting mechanism of the lathe [29]. No stencil is required, but the spray gun beam must be defined by a suitable aperture.

In a German plant [30], resistors were made by spraying a mixture of graphite and ceramic flux on a porcelain body and firing at 900° C for 2 minutes. A colloidal graphite known as Hydrokollag was used, dissolved in water. The ceramic flux was composed of:

Red lead.....	30%
Sodium silico fluoride.....	23%
Zinc oxide.....	10%
Feldspar (Swedish).....	10%
Kaolin.....	2%
Sodium titanium silicate.....	20%
Other.....	5%

These materials were first fused to molten glass, then quenched in water and ground to a very fine powder. For resistances from 40 to 1,000 ohms, a ratio of ten parts of flux, one part of Hydrokollag and one part (by weight) of water was used. Higher values, up to 10,000 megohms, were made by adding a filler such as lampblack in proper proportion and by slight variations in the above ratio constituents. A graphite layer of approximately 0.002 in. was sprayed on for the lower resistor values. Several coats were used. After firing, the resistors were coated with lacquer and baked at 150° C for 4 hours.

A conducting pattern having good adhesion may be applied to hard or smooth surfaces by a method analogous to that used in the manufacture of printer's letter press plates [25]. The desired pattern is printed on the surface using a muffle lacquer, i. e., one having either an urea-aldehyde

¹⁷ Another method of circuit wiring in two dimensions that accomplishes the same results as spraying is a die-casting process wherein the system of conductors is die-cast [26, 27, 28] instead of sprayed into the desired pattern on an insulated base. The base plate may be of any suitable material that will stand the temperature, such as certain plastics, phenolics, or ceramics. Recesses for the conductors are molded into the base plate and an alloy chosen for the conductors which expands on cooling, so that the finished product is a compact solid unit. In one method, a low melting point alloy (less than 500° C) is forced into recesses in the base plate under pressure. The metal is at a temperature near its melting point and is either in a liquid or plastic state. Soldering lugs, tube sockets, switches or other inserts may be installed and the metal cast around them. If the lugs are tinned and if the die-casting material alloys with the tin, a soldered joint is made which provides good electrical contact and mechanical strength.

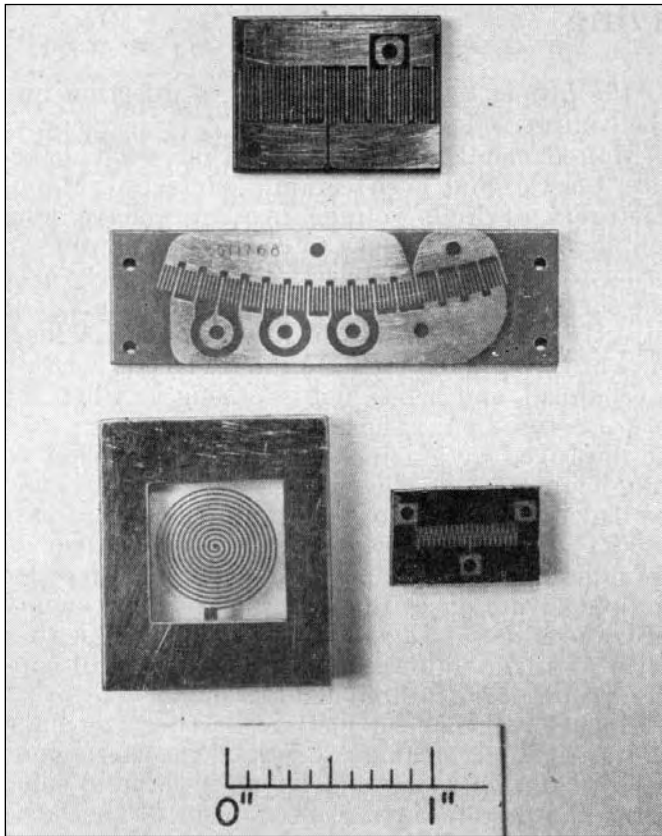


FIGURE 14. *Electronic items made by abrasive spray process.*

Top and center, radio sonde commutators; lower left, VHF inductor; lower right, center-tapped resistor.

resin or phenolic aldehyde resin base, modified by china wood oil and colophony. After printing, but while the lacquer is still sticky, a layer of metal powder is dusted on. The lacquer is hardened by heating to 170° C for 1 hour. A layer of the same metal is then sprayed over the hardened metallized lacquer. The adhesion of this metal layer is said to be three to seven times as great as that obtained by sand blasting the surface and directly spraying metal on without the lacquer. The pattern may be built up by plating or spraying other metals to any required thickness. In variations of the process, the sprayed metal may be applied prior to hardening the lacquer. After hardening the unit may be dipped into an alloy of lead, tin and cadmium at 120° C to deposit the conducting layer.

B. Abrasive Spraying Methods

In one of the simpler methods of spraying molten metal, a plastic base plate is used [31, 32, 33]. Shallow grooves are cut into the chassis by sand blasting, using a mask with lines cut out where connections are to be made. Following this, all component parts are placed either on the chassis or within the surface with their leads and terminals set in the grooves. The second mask is

then placed over the chassis and molten silver or copper sprayed into the grooves. On hardening, the metal provides the connections between parts. A layer of 0.002 in. to 0.005 in. thick is built up.

The process combines the complete wiring and cold-chambering of all components of the electronic chassis. Standard capacitors and inductors are used, although spiral inductors, especially in the high frequency range, may be sprayed on in this manner. This method, treated in patents issued over 17 years ago, has been adopted by some radio and television manufacturers.

Another example of this practice [34] is to spray the circuit wiring onto an insulating surface through a stencil and to connect ordinary components such as inductors and capacitors thereto by soldering or by attaching to terminals. This practice has been used in making small filter panels in large quantities. Manufacturers employing the popular spraying methods have introduced many variations such as using a protective stencil made of masking tape [33]. This tape has an adhesive on one side and is easily applied to the surface. It is strong enough to protect the face of the insulating surface from the effects of sand blasting and metallizing. Stencils are produced rapidly by die-cutting in continuous strips. The extra components such as sockets, resistors, inductors, capacitors, and special terminals may be assembled on one side of a panel prior to sand blasting. The contacts of these components are lead through the panel and appear in grooves formed by the sand blasting procedure. These contacts or terminals are roughened during the sand blasting, thus contributing to a better bond with the sprayed conductor. No soldering is required. The procedure is applicable to both sides of the insulating plate. Conductors on opposite sides of the plate may be connected by metal eyelets or similar means inserted prior to sand blasting.

Another novel method adaptable to electronic wiring involves "spraying-off" the metal from a metal-plated plastic to leave the desired circuit wiring.¹⁸ A plastic or other insulator having on its surface a thin evaporated coating of metal such as silver or copper is coated with a photosensitive material. The material is then exposed to light through a shield or photographic negative bearing the pattern of the circuit desired. The photosensitive material is developed in such a fashion that the areas exposed to light are removed. The remaining portions of the fixed photographic material act as a protective resist so that when the surface is exposed to a spray of abrasive material, the metal is removed from all parts not covered by the resist. Using this method, circuit wiring may be printed with a dimensional tolerance of ± 0.0002 in.

¹⁸ Kenyon Instrument Co., Inc.

The process is applicable for circuit wiring including inductors. It may also be used to trace out contacting segments and other related components of electric systems such as radio sonde elements. Figure 14 shows four items produced in this manner. The two at the top are radio sonde commutators on a phenolic base. The lower left is a spiral inductor on plastic; the component at the right is an 1800-ohm resistor on bakelite.

2. Spraying-Milling Technique

A significant step in the application of printed circuit techniques to the production of radio sets has been made by the development in England of a completely automatic apparatus for wiring panels [8]. Known as the Electronic Circuit Making Equipment, it is a spraying-milling technic designed for automatic manufacture of panels for a small alternating current-direct current line-operated broadcast-receiver set. A plastic plate is utilized into which has been molded indentations to provide capacitors, inductors, and mountings for other components. The plate is fed into an automatic machine which sand-blasts both sides, sprays the surfaces with zinc, mills the surfaces to remove the surplus layer of metal, tests the resulting circuit, sprays on graphite resistors through stencils, inserts tube sockets and miscellaneous small hardware, tests the unit again and applies a protective coating over the panel, all at the rate of a 7-in. panel each 20 seconds. Tubes, electrolytic capacitors, loudspeakers, etc., are attached in the standard manner. Sockets, switches and variable capacitors are eyeletted in place.

The circuit wiring and inductors are determined by grooves molded in the original plastic plate. Inductors, for example, are spiral grooves that are filled with metal during the spraying process. Capacitors are formed by leaving thin webs in the mold when making up the original plate and spraying metal on both sides of the web in the regular spraying operation. For large capacitors, the whole base plate is molded using a high dielectric constant plastic filler. Inductors, capacitors, and wiring are all formed by the same spraying operation. After the sprayed metal has dried, the top layer is milled off leaving the circuit properly defined. Resistors are then added by spraying on a dispersed graphite solution through a stencil fol-

lowed by burnishing and aging. Resistors up to 1 watt capacity are printed.

Eighty hand-soldered connections are avoided by this method in the small set manufactured. The need for hand assembly of thirty components is eliminated. A special feature of the apparatus is that each operation is controlled separately by electronic circuits and operated only on the arrival of a panel. Should two successive panels be rejected in the automatic test at any point along the line, all previous operations are held up until a personal inspection is made. All panels beyond that point are continued on to completion.

3. Electrostatic Spraying

A novel method of electrostatic spraying may find application in electronic circuit work [12]. In this method, the work is carried on a conveyor belt between electrodes charged to high potential, of the order of 100,000 v direct current. The work is at ground potential. Paint is sprayed into the area between the electrodes. The finely atomized particles of paint become charged with the same polarity as the electrodes. Electrostatic force then pulls them strongly toward the work, which is at ground potential and located within the spraying zone. Smooth and uniform deposition of paint over the entire surface is possible with proper design. Very little paint is wasted as paint particles which would normally miss the work change their course and return to it because of the electric charge on them. In the printed circuit application, the plates on which the paint is to be sprayed would be nonconductors. In order to attract the ionized paint particles to the work the plates to be painted would be laid upon an electrically grounded metal mesh belt.

4. Chemical Spraying

Spraying of silvering solutions is accomplished by using a dual orifice spray gun. One orifice ejects the silvering solution and the second sprays the reducing solution. The solutions leave the nozzles so that they are thoroughly mixed before reaching the insulating surface. More complex solutions may be handled by multiple-nozzle spray guns [35], or a single-nozzled unit may be used in which the solutions are mixed just prior to entering the nozzle.

IV. Chemical Deposition

The methods in this classification involve the deposition of metallic films on an insulating surface by the reduction of metallic salts in solution. Although much of the material described under section II might properly be grouped under the heading of chemical methods, for practical rea-

sons a separate classification is preferred. The chemical methods described in this section, in general, are not as simple to apply as the paints. The silvering solutions must be handled properly by experienced personnel. They have had wide application to silvering mirrors and various types of

glass vessels and in preparing nonmetallic materials for electroplating.

One of the principal methods [5] of chemical deposition is that in which a silvering solution is made up by adding ammonia to a solution of silver nitrate.¹⁹ This silvering solution is then mixed with a reducing solution prepared, for example, by dissolving cane sugar in water and adding nitric acid.²⁰ The mixture is poured over the insulating surface, the latter bearing a stencil with the circuit pattern in it. As the silver precipitates from the mixture, it deposits uniformly over the surface.²¹ Removal of the stencil leaves the wiring pattern desired. The stencil should not be affected adversely by the mixture, should be designed so that it will adhere closely to the surface, and so that it may be removed by peeling off or by evaporation at low temperature.

The films formed are very thin and cannot be soldered to directly. They may be built up by repeating the silvering process as often as desired. For high conductance the circuit may be plated. The bond between the deposited film and surface is entirely mechanical, there being no chemical combination with the surface, consequently the adherence is less than is obtained by the firing processes.

Additional details on the silvering processes, including many variations of the chemicals employed, as well as the processes, may be found scattered profusely throughout the literature [5, 6, 7, 36, 37]. Not only silver films but those of copper, nickel, gold, iron and other metals and those of alloys such as silver-copper may be deposited on nonmetallic surfaces by chemical methods. An interesting variation is offered by the possibility of selecting the metallic salts so that metal films of different colors are deposited, thus allowing the printing of colored electronic circuits. Circuits of different colors may be used for identifying different sections in a multisection unit, for classifying as to frequency and volume

¹⁹ Silver nitrate is dissolved in water and precipitated in hydroxide form, using an alkaline hydroxide such as sodium or ammonium hydroxide. The precipitate is automatically redissolved in the solution by using an excess of the alkaline hydroxide.

²⁰ Nitric acid inverts the sugar to dextrose and levulose. Formaldehyde, rochelle salts, sodium or potassium tartrate or tartaric, citric or tannic acid also serve satisfactorily as reducing agents.

²¹ The alkaline silver solutions should not be allowed to evaporate and form dry residues, as there is danger of explosion. They should be mixed only as needed. Unused solutions should be treated by adding hydrochloric acid, which precipitates the silver and removes the danger [5].

ranges and other uses. Usually, however, such metallic salts produce high resistance films, and as such may be used to produce resistors of limited wattage.

Lead-sulfide infrared photoelectric cells [3] are made by chemically precipitating lead sulfide onto the supporting glass between parallel metal electrodes. The electrodes, which are of interest here, consist of a large number of alternate layers of gold and platinum. They are deposited by applying chloride solutions of the metal believed to be made by dissolving the chlorides in natural oil of lavender and alcohol and adding some pitch for stickiness. On heating, the chlorides are reduced to metal. The procedure is repeated with the opposite metal to obtain alternate layers.

As in the other methods, best results are obtained if the surface is first cleaned properly. General procedures for cleaning are described elsewhere in this paper. Strong, uniform adherence to glass surfaces has been obtained by first tinning the glass, that is by lightly swabbing it with a 10 percent solution of tin-chloride [6, 38]. Lead acetate, thorium nitrate, or other salts of metal that are strongly adsorbed by the glass may be used [38]. This practice should be useful in applying electronic circuits to the glass envelopes of vacuum tubes.

Special treatment is necessary in order to apply the chemical reduction methods to plastics. For good adherence, the surface should be roughened either chemically as by etching, or mechanically by a careful abrasive treatment. A method that has proven successful for preparing methyl methacrylates (Lucite, Plexiglas, etc.) for silvering consists in treating the surface with sodium hydroxide for 12 to 48 hours. This renders the surface receptive to silver [35] so that when the silvering mixture is poured over it, a firmly adhering metal film results. Several variations of this method also have been described [6].

The chemical deposition methods, although used extensively in the manufacturing of mirrors and other products, may currently be classified in the realm of laboratory methods not fully developed for mass production of printed electronic circuits. Their position, however, is similar to that of some of the vacuum processes described herein, which only a short time ago were considered strictly small-scale methods but today are used to produce electrical components by the millions.

V. Vacuum Processes

Another set of techniques employed to produce metallic layers on nonmetallic surfaces that may be adapted to electronic wiring are those of cathode sputtering and evaporation [7]. The methods are

fairly similar. In the sputtering process, the metal to be volatilized is made the cathode and the material to be coated the anode. A high voltage is applied between them after evacuation. Metal

emitted from the cathode is attracted to the plate by maintaining the plate at positive potential. In the evaporation process, the metal is heated in a vacuum to a temperature at which it evaporates onto the work located nearby.

1. Cathode Sputtering

Cathode sputtering is probably the oldest of the methods for depositing metals on a surface in a vacuum. The necessity for working with a vacuum appears to pose a major obstacle to mass production. A closer study will show, however, that the difficulties are not substantially greater than those attending processes requiring heating of the work to fusing or firing temperatures. Vacuum methods of silvering mirrors are now employed on a mass production scale.

In both the sputtering and evaporation processes, the work is covered with a suitable circuit-defining stencil and placed in the chamber opposite the cathode. For sputtering, the chamber is evacuated to a pressure of the order of 0.001 mm of mercury. Higher pressures may be used in certain cases. These pressures may be obtained with a good mechanical pump. The shape of the cathode that is made of the metal to be sputtered may take on any convenient form. It may be in the form of a straight wire, a wire grid or a thin sheet. If the work occupies a large area, more than one cathode may be necessary. To obtain a uniform deposition of metal on the work, the cathode and work should be placed as nearly parallel to each other as possible. Optimum spacing is determined experimentally and may be of the order of $\frac{1}{2}$ to 6 in.

A practical arrangement would be to have the cathode located over the work that lies on a horizontal metal anode. The latter is charged to a potential varying from 500 to 20,000 v, depending on the space and the pressure. Direct current is preferred with the plate at positive potential, although pulsating direct current or alternating current may be used. The high voltage may be obtained from a neon lighting transformer as the currents required are very small.

Any of a large number of metals may be used for sputtering, including silver, copper, platinum, gold, etc. A vapor of metal is formed that completely coats the work, including its protective stencil. In both sputtering and evaporation, the practice is confined to producing very thin films that may later be plated to achieve the desired conductance. Electrically conducting films as thin as $0.1 + 10^{-6}$ in. may be deposited satisfactorily although for electronic circuits it is desirable to make the film thicker so that satisfactory electroplating may be achieved without difficulty.

As the thickness of the layer deposited depends on the spacing between the cathode and article, irregular shaped objects will be covered with vari-

able thicknesses of metal. For conductor wiring, this is not a serious matter as in general the conductance is sufficient so that variations in it produce negligible effects on circuit performance. Both sputtering and evaporation will adapt themselves well to coating circuit wiring on inside surfaces of housings to which a protective mask or stencil may be applied.

2. Evaporation

The lesser complexity of the evaporation process and the possibility of evaporating uniform films of metal on nonmetallic surfaces has led to its general adoption by industry. One of the principal applications at present is to the production of paper capacitors. Thin aluminum or zinc films evaporated onto impregnated paper now yield capacitors not only of miniature size but having other valuable properties such as the self-healing; i. e., the ability to remove short-circuits automatically. These capacitors are made on a large scale using mass production techniques.

No high voltage source is needed for the evaporation. The metal is simply heated in a vacuum until it vaporizes onto the work. The properties of the metal layers deposited do not differ practically from those applied by the sputtering method. Adhesion is about the same, although not as strong as that obtained by the fusing methods. Pressures of the order of 0.001 to 0.00001 mm are usually employed. For best results the pressure must be reduced until the molecular mean free path equals or exceeds the maximum internal dimension of the chamber.

The arrangement of the apparatus is similar to that for cathode sputtering. Tungsten filaments may be used. The metal is placed directly on the filaments in the form of small hairpins or wire. The tungsten filaments are heated by electric current until the metal hairpins or wires are vaporized and the molecules transported to the target plate. Other shapes of filaments may be employed, such as flat plates shaped in the form of a trough or carrying dents to hold the metal to be evaporated [7]. For evaporating aluminum, filaments have been used with the aluminum pre-fused to the tungsten. Another variation is to use twisted strands of filament wire with the metal to be evaporated appearing as one or more of the twisted strands in parallel with the real filament. A variation that might be classified as a combination of sputtering and evaporation is to replace the filament with an arc formed between rods of the metal to be evaporated. On forming the arc, the metal is vaporized. The practice is similar to that of the carbon-arc lamp, except that the operation is carried out in vacuum. Although not necessary, application of a high potential to the work, as is done in cathode sputtering, may improve results with this method.

Practically all metals may be evaporated, the principal requirement being that their vaporizing point fall below the melting point of the filament. The practice has been used successfully to evaporate films of copper, silver, iron, platinum, lead, aluminum, gold, and tin. Table 5 shows evaporation temperatures of the metals [7].

TABLE 5.—Evaporation temperature of metals

Metal	Evaporation Temperature *	Metal	Evaporation Temperature *
	°C.		°C.
Mercury.....	47	Lead.....	727
Cesium.....	160	Tin.....	875
Rubidium.....	177	Chromium.....	917
Potassium.....	207	Silver.....	1,046
Cadmium.....	268	Gold.....	1,172
Sodium.....	292	Aluminum.....	1,188
Zinc.....	350	Copper.....	1,269
Magnesium.....	439	Iron.....	1,421
Strontium.....	538	Nickel.....	1,444
Lithium.....	548	Platinum.....	2,059
Calcium.....	605	Molybdenum.....	2,482
Barium.....	632	(Carbon).....	2,522
Bismuth.....	640	Tungsten.....	3,232
Antimony.....	700		

* Temperature at which vapor pressure equals 10⁻² mm of mercury.

Although the metals attached to the filament will melt just before evaporating, they are held to the filament by surface tension. As silver and copper do not wet the tungsten filament very well, tantalum or molybdenum may be substituted when using these metals.

Thermal evaporation may be accomplished in a more practical way without the use of electric filaments. The simplest method is to place the metal in a vessel and heat it to vaporizing temperature. The heat may be applied either by means of a flame or by induction heating [40, 41]. In the induction heating method, the metal may be placed in an insulated crucible either in the form of powder or larger granules or as a chemical compound and the induction coils placed around the crucible. Heat generated in the metal by eddy currents causes it to be melted. The plates to be coated may be placed upside down on a supporting grid over the crucible. Metal stencils or masks may be used. Mica sheets have also proven satisfactory. If handled properly, the masks may be used over again, cleaning being accomplished by washing in dilute nitric acid. The use of a shadow stencil, that is a single stencil permanently placed over the crucible to throw a shadow pattern of metal over the plate to be coated, may prove satisfactory. Obvious and perhaps difficult precautions attend this method.

The practice of evaporation is not limited to small assemblies. Long used to silver or chromium plate mirrors, vacuum chambers have been built to handle work several square feet in area. If the electronic subassemblies are small, a number of them may be placed on the tray in the chamber

and coated simultaneously either by the evaporating or sputtering process.

Electric shields and other equipment have been made up by evaporating aluminum onto a non-conducting surface. After the proper conductive layer has been achieved, air is allowed to enter the chamber while the evaporation continues. Thus, a thin layer of aluminum oxide is formed over the conducting surface to provide a good insulator. Practices such as these are forerunners of new printed circuit techniques.

A German method of coating the inner surface of a fluorescent screen with a very thin film of aluminum [3] embodies principles of interest to printed circuit investigators. The film serves as a reflector of light behind the screen yet must allow electrons to pass through it without too much loss in velocity. The technique of producing this film is rather delicate. The first step is to form a thin water insoluble film of organic material, such as collodion, paraffin or an acetate, over a thin layer of water covering the screen. This is done by placing a small amount of liquid solution of the material on the water. The solvent evaporates and leaves a thin, smooth film on the water. After a drying process, the film drops snugly onto the screen. The aluminum is then evaporated onto this film of organic material. When the tube is processed later, the heating breaks down the organic film, which is vaporized and pumped out, leaving the aluminum film attached to the fluorescent screen.

3. Resistors

The thin films formed by sputtering or evaporation may also serve as resistors.²² In this case, plating is not used. The approximate resistance may be calculated from the resistivity of the metal evaporated and its dimensions. Stencils are used to confine the metal to the proper position and area desired. Wave guide attenuators have been made in this way by evaporating a very thin film of nichrome on pyrex or soft plate glass. In one process [42] the nichrome film is covered with a protective layer of magnesium fluoride applied directly to the nichrome film while the chamber is still evacuated. The protective layer prevents oxidation and corrosion of the resistance film. The low temperature coefficient of the nichrome is preserved in this method.

Accurately defined areas may be coated by the

²² Carbon film resistors on ceramic rods have also been produced by cracking hydrocarbons at high temperature. Resistors with temperature coefficient of the order of 0.1 percent per degree centigrade are made this way. The resistance film is formed by cracking vaporized benzol in a carbon dioxide atmosphere at 950° C. This produces a carbon film approximately 0.0004 in. thick on the ceramic rod. Carbon dioxide is used to improve the uniformity of the carbon film. It is reported that 80 percent of the resistors fall within plus or minus 20 percent tolerance limits. Values up to 2 megohms have been produced. The resistance is controlled by the volume of benzol used and the oven temperature.

evaporation process thus improving the uniformity of the resistors. A practice that works well when the number of resistors to be evaporated onto an insulating panel is small, is to wire the panel to a resistance bridge. As the resistor is

deposited the bridge indicator drops gradually until the precise resistance is attained, at which time the evaporator is automatically shut off. The resistor in figure 14 was applied by evaporating silver onto bakelite.

VI. Die-Stamping

1. Preformed Conductors

In the production of electronic assemblies for certain types of proximity fuzes during the war, it was found advantageous to preform the connecting wires and component leads. These were dropped into position in a plastic chassis in such a manner that all terminals requiring soldering appeared opposite each other. Soldering of the terminals completed the assembly.

Similar methods have been employed successfully elsewhere in industry. Punch presses are used to preform stiff copper wires into shape. The formed wires are automatically dropped in a jig containing all the electrical components. A multiple welding device is lowered and all junctions are spot welded in one or two operations. The mechanization is carried a step further by feeding the electrical components into the jig by means of properly designed hoppers or with pneumatic guns.

Thin copper strips can be substituted for the leads in the previous operation. They may be die-stamped into the same form as the preformed leads and welded in the same manner. Strips are coated with an insulating lacquer to prevent short circuits in cross-over. One manufacturer punches a grid out of $\frac{1}{16}$ in. copper plate. After silver plating, the grid is placed over an array of projecting lugs attached to various electrical components. It is soldered to all the lugs in a single automatic operation. Those parts of the grid not desired are clipped out and the remainder form the complete wiring of a telephone set.

Metal foil, either plain or paper-backed, may be used for stamping out the complete wiring for the electronic circuit. To avoid damaging the foil when complex circuits are stamped from thin metal sheets, the stamping may be carried out in two or more operations, using metal dies in parallel. High-frequency induction heating methods may be used to solder leads to the foil.

2. Stamped-embossing

Radio set manufacturers are now employing spiral loop antennas die-stamped from a copper or aluminum sheet a few thousandths of an inch thick [43]. One design shown in figure 15 is formed by feeding into an automatic punch press a composition or plastic panel with the metal sheet over it. The press has a vertical reciprocating

steel die with a continuous helical cutting edge. The latter is in the form of convolutions of gradually decreasing diameter. In a single stroke the die cuts the metal sheet and attaches it to the panel. The metal foil is coated on one side with a thermoplastic cement. The heated die sets the cement. The result is a combined antenna and back or housing for a receiver. The shape of the die is such that not only is the metal cut, but a cross section will show it to be arcuated and thus approximately a semicylindrical hollow conductor. The die may also be V instead of arc-shaped. The severed edges are separated, leaving an air gap between the turns. Pressed fibreboard, wood, plastic, Lucite, and a wide variety of materials may be used for the supporting panel.

Compared with the conventional solenoid or basket-weave types of loop antennas, this stamped-embossed design not only is more economical but has comparable or better electrical performance [44]. For radio receiver application, the usual insulation between turns is omitted, resulting in lower distributed capacity and higher effective Q than the other types. The dielectric and loss factors of the panel material, of course, have an im-

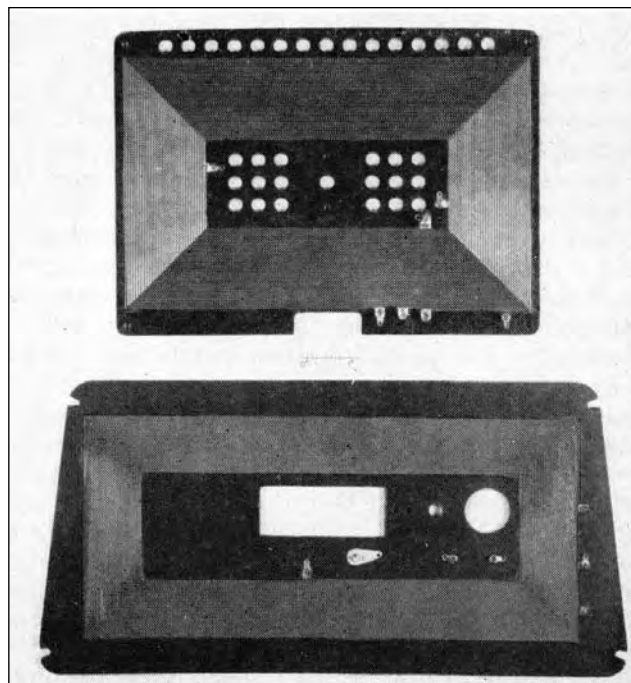


FIGURE 15. Loop antennas stamped from single pieces of sheet copper onto insulated bases.

portant effect on the Q because the panel is situated in the field of the inductor. Not only antennas but high-frequency inductors, electrostatic shields and similar electronic equipment may be manufactured by this process.

A similar development [45] may be used for circuit wiring. A thin sheet of insulating material has a series of parallel conductors fastened to it by the stamping process described above. The other side has a similar series at right angles. The circuit is made by making connections through the plate at appropriate places by eyelets or pins. Tube sockets and components may be fastened in place by similar methods.

3. Hot Stamping

The hot stamping process used in the marking of leather and plastic materials lends itself to the mechanization of electronic circuit manufacture. In this method a hot die engraved with the pattern of the conductors, including inductors, is pressed onto the plastic with a thin sheet of gold, silver or other conducting foil between the hot die and the plastic. The foil adheres to the plastic where

the pressure and heat from the die have been applied, and can be brushed away at other places, leaving a pattern of conductors. Samples produced for the Bureau using gold foil were very satisfactory. The resistors may be applied in the same way using resistor material deposited on a film of plastic previous to the hot stamping operation. As foils as thick as 0.002 in. may be used, very good electrical properties are obtained, particularly with inductors made by this method. Other components to complete the electronic circuit may be added by riveting, soldering or spot welding.

It is possible to produce a strongly adhering metal film on rubber by placing metal foil (stamped in any desired configuration) in a mold with the rubber and vulcanizing [46]. When the foil is removed, a layer of metal sulfide is left on the rubber sharply defined by the foil contour. The surface is then treated with a reducing agent such as by immersing in a copper cyanide bath. Thus, the sulfide is converted to metal that may be used with or without plating. In place of the foil, silver oxide paint may be painted or sprayed on the rubber through a stencil. It is reduced in the same manner after vulcanization.

VII. Dusting

The dusting techniques lend themselves favorably to the printing of electronic circuits. Tungsten and molybdenum powder have been used to metallize ceramic bodies by dusting the powder and binder on the surface and firing. In electroplating nonconducting materials, metal powders have been used to form a conducting film for the plating. An initial layer of bonding material or adhesive ink holds the powder in place. It is applied with a rubber stamp or by similar printing means [47].

To extend the technique to printing circuits, somewhat the same procedure is followed. A suitable bonding material is selected such as shellac, wax or any of the synthetic resins, dissolved in alcohol or benzine and sprayed or painted onto the surface. A stencil bearing the circuit pattern is placed over it and leafed silver powder dusted on. A variation is to apply the bonding material instead of the paint through the stencil. The powder is sprinkled on after the stencil is removed and while the bonding surface remains somewhat tacky. The bonding film should be kept as thin as possible, consistent with absorbing enough metal to yield the desired conductivity. The unit is then subjected to a temperature that drives off the bonding material and fuses the metal to the plate. If the bonding material is mixed with the powder and applied, it must have enough of a gummy property to adhere to the surface and hold the metal powders in place.

Another way of dusting an electrical circuit onto a nonconducting surface is to sprinkle a thin layer of metal powder through a thin noninflammable stencil. The metal is melted by flashing a flame over the stencil. Such a technique requires expert care in applying, hence its practicability may be limited.

An electrophotographic method has been developed [48] to hold the powder to the surface in the proper pattern prior to flashing. It is applicable to any of the usual nonconducting surfaces, including paper. The surface is first coated with a 1 mil layer of photoconductive material such as sulfur or anthracene, then placed under an electrostatic charging device. The electrostatic field introduces a charge on the photosensitive material. Exposure to light through a positive photograph of the circuit desired removes the charge from that portion of the photosensitive material illuminated and leaves an electrostatic latent image. A mixture of leafed silver powder and a binder dusted onto the surface adheres only to the charged image. Flashing with a flame melts the silver into place, completing the wiring.

If after the silver is dusted over the plate, a paper sheet is placed on top and the combination inserted into another charging field, the paper attracts the metal powder and holds it securely until it is flashed permanently into place. As many as five copies can be made from one original. The

process appears to adapt itself to the manufacture of printed circuit decalcomanias. Photosensitive materials are available that hold their charge for as long as 500 hours and produce useful prints

after that time. Although some work has been done in applying electrophotography to printing electronic circuits, practical details have yet to be worked out.

VIII. Performance

1. Conductors

The principal desirable characteristics of the conductors are high conductance, adequate current carrying capacity and good adhesion to the base plate. The resistance may be computed from the cross section, length, and the specific resistance of the material (0.626 micro-ohm inch at 20° C for pure silver). The computed resistance is usually lower than the measured value, depending on the manner of application, the binders used, and the type of drying or firing. For silver fired on steatite, the measured resistance may be as much as twice the value computed for pure silver.

A silver conductor 0.062 in. wide and 0.0005 in. thick will have a computed resistance of 0.02 ohm per inch which is equivalent to number 36 copper wire.²³ The current carrying capacity of such a conductor is more than sufficient for all currents used in low power electronic circuits. A silver conductor 0.125 in. wide and about 0.0005 in. thick fired on steatite did not fuse until the current reached 18 amp, while another 0.0625 in. wide carried 8 amp for 9 minutes before fusing.

Figure 16 shows a loading curve for a typical conductor on steatite having a length of 0.841 in., a width of 0.041 in. and an estimated thickness of 0.001 in. Tests were made with the steatite plate in open air, without forced circulation. The current was allowed to flow for several hours at each value or until no further increase in resistance was observed. The conductor carried 8 amp for several hours, showing an over-all increase in resistance of 15 percent, but when the current was increased to 9 amp it failed after 35 minutes. This conductor has a current carrying capacity equivalent to a number 32 copper wire. This performance shows the effect of the close thermal contact between the silver and the steatite base material and the increased radiating properties of the flat printed strip. For silver fired on steatite, the heat dissipating ability together with the short over-all length of the printed conductors make them equivalent in performance to electronic circuits wired with conventional copper wire.

On plastic bases, where firing is not possible, the printed leads have a higher resistance. A lead 1 in. long and 5/64 in. wide showed a resistance of 1/2 ohm and a current carrying capacity of only 1/2 amp before the plastic base softened and the silver peeled off. Even this exceeds the currents

usually flowing in low power electronic circuits. However, as heating tends to loosen the bond between the deposited metal and the plastic base, an experimental determination of the current carrying capacity should be made for each particular case. Lower and more consistent values of resistance are to be had simply by increasing the number of coats of paint or by plating.

In some cases, such as inductors that require a high Q value, the resistance of the conductor may not be low enough. It is quite practical to decrease the resistance to almost any desired value by electroplating silver or other metals over the conductor printed on the base material.

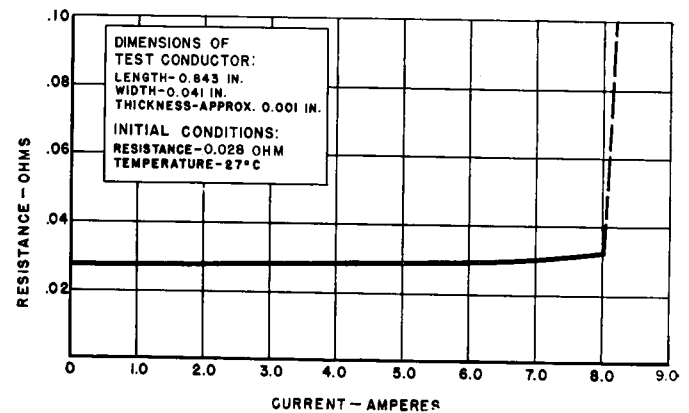


FIGURE 16. Change in resistance with current of silver conductor fired on steatite.

Conductor patterns made by the spraying or die-casting process have a large enough cross-section so that their resistance will be low enough even though the metal does not have as low a specific resistivity as pure silver or copper. This may not be true for certain types of sprayed or die-cast inductors, where if high Q is required it may be necessary to resort to silver plating. Circuits made by the die-stamping process, where materials such as silver or copper of thickness in the range of 0.002 in. to 0.005 in. are used, produce inductors that are usually satisfactory without further processing.

2. Resistors

A. Load Characteristics

Among the principal factors affecting the power dissipated by a resistor are the paint mixture, the base material on which it is printed, and the surface area. The paint itself determines the maxi-

²³ Wire size numbers are AWG (B & S).

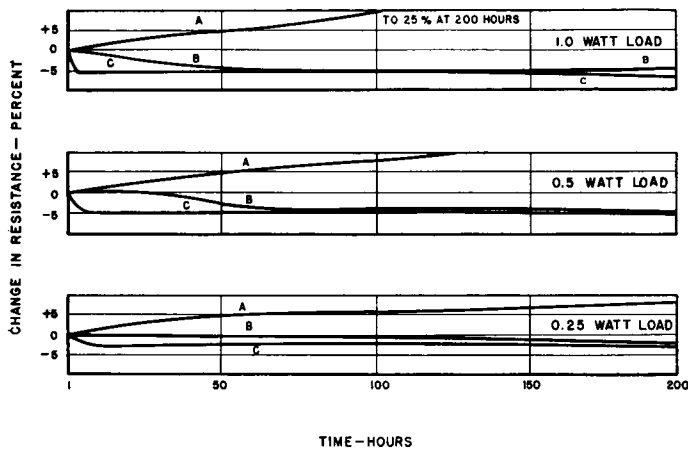


FIGURE 17. Load tests on printed and commercial carbon resistors having a nominal value of 100,000 ohms.

Printed resistors were 0.38 in. long, 0.10 in. wide, and 0.002 in. thick. Curves A are for a commercial 0.25-watt resistor, curves B are for a 0.5-watt resistor, and curve C for a printed resistor.

imum temperature to which the resistor may safely be raised; the composition of the base material, the area of the resistor, and to some extent its color, determine the rate at which the heat is conducted away. The close contact of the printed resistor with the base material in the case of glass or ceramic, prevents local heating and gives the resistor better power dissipation than might be expected. Resistors painted on plastics tend to loosen from the base material on heating, hence must be operated at lower power levels.

Intermittent load tests of 1,000 hours duration were made on several 1/2-megohm resistors painted on steatite. The load was applied for 1.5 hours then turned off for 1/2 hour and the cycle repeated [49]. Commercial paint types²⁴ I and II were applied to make resistors 0.25 in. x 0.078 in. (area 0.02 sq. in.). For paint type I and power loads of 0.10 and 0.15 watt, after 1,000 hours of operation the resistance decreased 0.4 and 0.7 percent, respectively; with resistors made of type II paint the decrease was 10.0 and 12.0 percent respectively. These tests illustrate the dependence of resistor performance on paint mix.

Although no standard method of rating the printed resistors for power dissipation has yet been established, it is important that steps be taken to do this soon. Figure 17 shows typical results of an intermittent load test using higher wattages than on the previous test and 100,000-ohm carbon resistors 0.002 in. thick and 0.038 sq in. area (0.1 in. x 0.38 in.) painted on steatite. The resistors were operated for 200 hours at loads of 0.25, 0.50 and 1 watt respectively. As a control, commercial fixed composition 0.25 watt and 0.50 watt carbon resistors were also subjected to the same loads. The curves show clearly that the printed resistors perform very well compared to the commercial resistors. Although the resistance of the

²⁴ Data supplied by Centralab Division, Globe-Union, Inc.

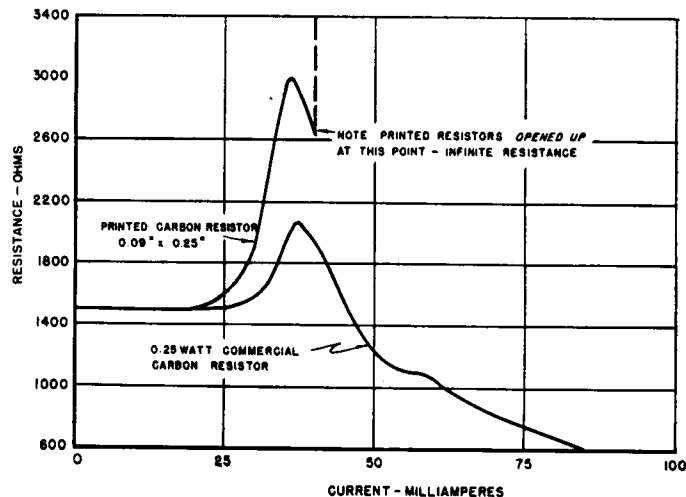


FIGURE 18. Comparison of current-carrying capacity of average carbon resistor with 0.25 watt commercial carbon resistor.

Both are nominally 1,500 ohms.

printed resistors decreases 3 to 5 percent it soon stabilizes at a constant value.

Typical results of another determination of power dissipation are shown in figure 18. Two 1,500-ohm resistors, one printed, and one 0.25 watt fixed composition were subjected to increasing current until they failed. The current was increased in small steps and allowed to stabilize at each value before going to the next. Both resistors withstood 20 ma (0.6 watt) before any effective change in resistance took place. Further increase in current caused both to increase in resistance rapidly, peaking at approximately 37 ma and then decreasing. This increased current apparently causes a change in some of the constituents of the resistors. It is important to note that the printed resistor opened on excess current, whereas the fixed composition resistor decreased in value. The opening of the printed resistor under excess load may be a desirable property as it will not sustain heavy overload currents with the consequent damaging of other parts of the circuit. The conclusion to be reached from these tests is that printed resistors compare favorably under load with those of the commercial fixed composition type.

As the size of the printed resistors is not standard, it is not practical to specify its power rating in terms of watts per resistor. It can be specified as watts per square inch of area exposed to the air. In the first of the two tests reported above, an area of 0.038 sq in. dissipated 1 watt, giving a dissipation of 26 watts per square inch, while in the second test an area of 0.023 sq in. dissipated 0.6 watt giving the same dissipation factor. This factor has been considered representative of average performance.

Allowing a reasonable factor of safety, the carbon resistors described above may be rated at 10 watts per square inch. A 1/4-watt resistor will then occupy an area of 0.025 sq in. and may be printed

on a strip 0.1 in. wide by 0.25 in. long. A strip 0.1 in. wide will have a power rating equal to its length in inches. The power rating cannot be applied generally to all types of printed resistors. Ratings of other types of printed resistors will depend on the several factors outlined earlier.

B. Noise Characteristics

Comparative noise measurements were made²⁵ between 1-megohm resistors painted on steatite and the quietest of the commercial, fixed composition, cylindrical 0.5-watt carbon resistors. The test was made by applying a 45-v direct-current bias to the resistor and measuring the noise voltage. Using the commercial resistor as a reference, the noise level of two painted resistors made with the commercial paint formula, type I was found to be +3 and +5 db for resistors 0.375 in. x 0.94 in. and 0.25 in. x 0.78 in. respectively. When the paint formula was altered to type II, the noise level of the 0.25 in. x 0.78 in. resistor increased from +5 db to +35 db, illustrating the need for careful formulation when quiet resistors are desired. These results are typical for these resistor paints. Type I paints may be used in hearing aids and other circuits of high gain level. Type II is satisfactory for low gain amplifiers and electronic control units.

C. Temperature Characteristics

The selection of a good resistance formula requires careful attention to the character, quality

and quantity of the ingredients. An example of the variations in behavior to be expected is shown by curve B in figure 19 obtained from resistors made with the formula 12.5 percent of colloidal graphite, 4.5 percent of lampblack and 83 percent of Dow resin 993. The wide variation on the same temperature cycling exposure may or may not be considered desirable depending on the application. Where normally a flat temperature characteristic is desired, the shaped response of formula B might be very useful in compensating against a negative temperature response caused by other elements in the circuit. It also serves as an excellent temperature indicating element over the range plotted and may find use in devices such as the radio sonde. The resistance-temperature characteristics for a wide range of production line resistors painted on steatite are shown in figure 20. Over the extreme temperature range plotted, the maximum variation in resistance from the average is seen to be of the order of ± 5 percent.

Any particular formulation must be checked for its ability to adhere to the base material. This is usually done by temperature cycling tests. If the conductor and resistor paints still adhere after several temperature cycles over a range exceeding that to be encountered in practice, they may be considered satisfactory.

3. Capacitors

The aging of titanium oxide ceramic capacitors generally follows an exponential relation between time and capacitance. The constants depend on the particular material used for the dielectric. The temperature coefficient of these capacitors

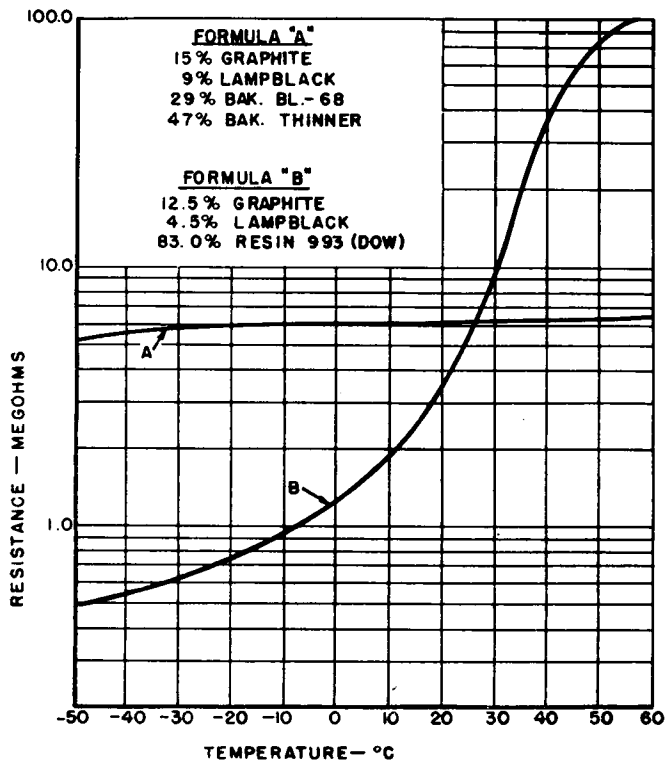


FIGURE 19. Effect of composition on resistance-temperature characteristics of printed resistors.

²⁵ Data supplied by Centralab Division, Globe-Union, Inc.

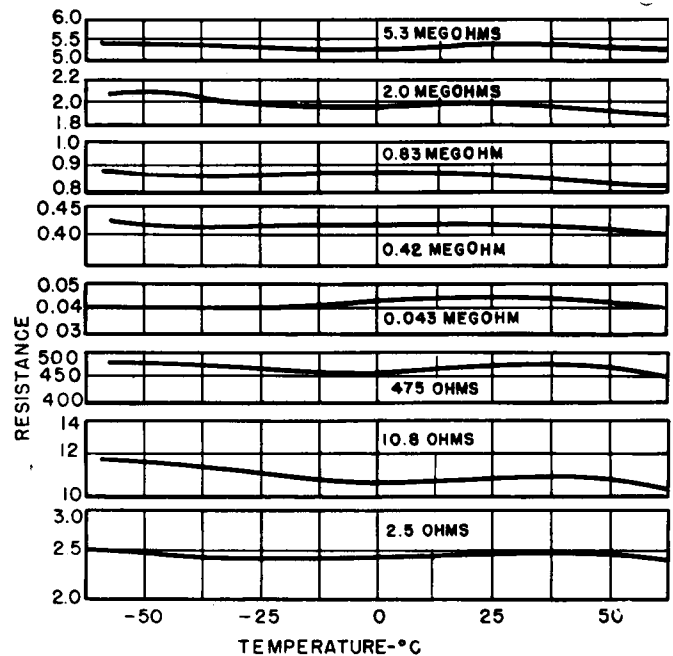


FIGURE 20. Resistance-temperature characteristics of printed resistors.

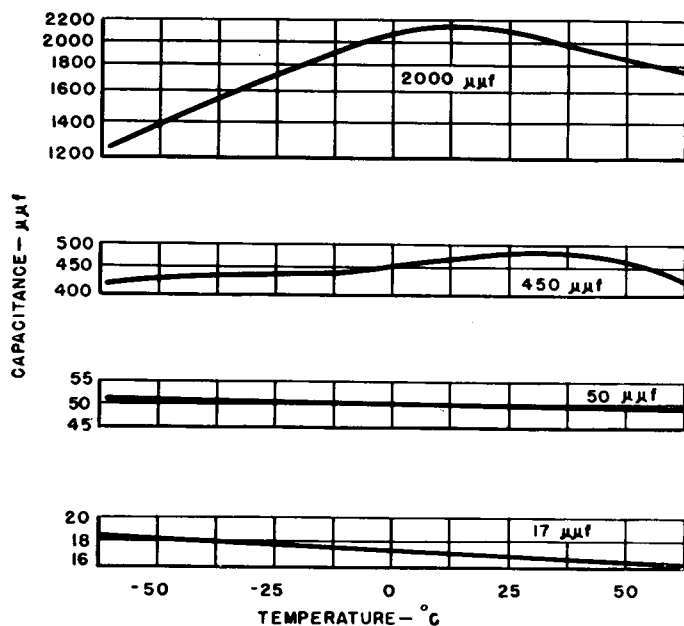


FIGURE 21. Capacitance-temperature characteristics of ceramic disk capacitors.

must be carefully chosen for the particular application. Some of the higher dielectric constant materials display peaks in their temperature-capacitance curve. These peaks may change the value of the capacitor by a factor of 5 or 10 and may be very sharp. They can often be shifted to different temperature regions by a change in composition. These characteristics may be used in providing temperature compensation for circuits where required. A variety of slopes are available by properly choosing the composition. Typical temperature-capacitance curves are shown in figure 21, and a sharper peaked curve of the type used for temperature compensation is shown in the dielectric constant-temperature curve of figure 22. In case the characteristics of a single capacitor are not satisfactory, several units having peaks at different temperatures may be connected in parallel so that the combined effect is the one desired.

As the ceramic materials in these capacitors are not hygroscopic, there should be no particularly adverse humidity effects even in the unprotected state. The effects of humidity and fungus may be reduced by a wax dipping or lacquer.

The dissipation factor also may vary through wide limits over the usual temperature range. The losses are higher for the capacitors using the higher dielectric constant materials, and for that reason they are not always suitable for all applications. Q values between 400 and 10,000 are typical. The direct-current resistance (insulation resistance) is closely associated with the dissipation factor. In cases where high insulation resistance is necessary, such as grid-coupling capacitors, the ceramic capacitors should be checked prior to use. The voltage rating is higher on ceramic capacitors

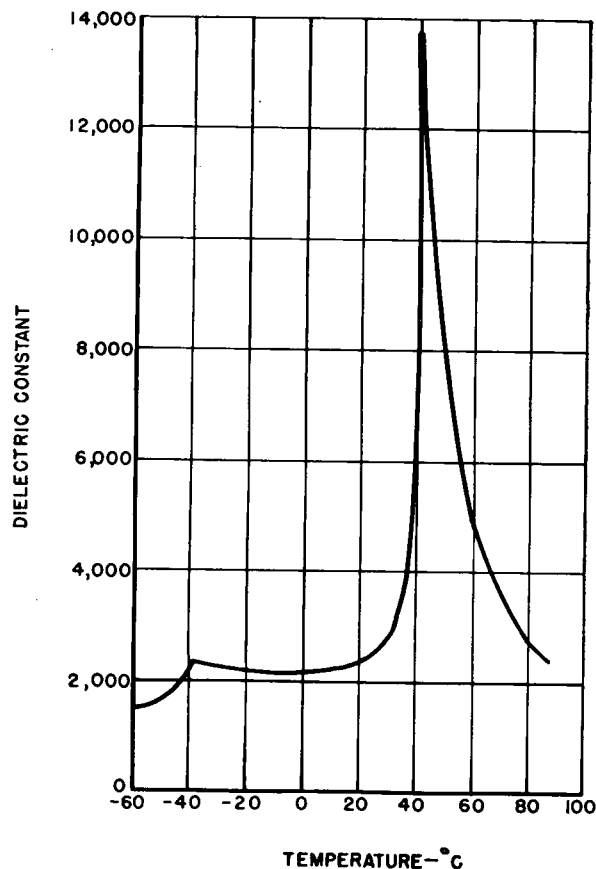


FIGURE 22. An example of the sharp peaks in the dielectric constant-temperature characteristics of very high dielectric constant ceramic capacitors.

than on small units of most other types, so that for printed circuit applications capacitors of the usual thickness 0.02 in. to 0.04 in. have a working voltage of 300 to 600 v direct current. Capacitors in the ranges from 7 to 10,000 μmf are readily manufactured to tolerances of ± 5 percent, ± 10 percent and ± 20 percent.

4. Inductors

A. Temperature Characteristics

Inductors having thin metallic lines on a ceramic form show very small variations in inductance with temperature. The fused-on coating being thin and somewhat elastic does not tear away from the ceramic surface when subjected to extreme temperature cycling. This is true even though the thermal expansion coefficient of the metal is greater than that of the ceramic. For all practical purposes, a combination of metal on ceramic behaves as though the expansion were due to the ceramic alone. Inductors of this type are reported to have been produced in quantity in Germany.

B. Loss Characteristics

The design of oscillators usually requires a high value of Q in the tank circuit inductor. Printed inductors for oscillators, therefore, are often

plated to yield high Q . A spiral inductor made of silver lines 0.03 in. wide and 0.0003 in. thick printed on steatite had a Q of 25. Electroplating the inductor to a thickness of 0.001 in. increased the Q to 125. Silver inductors painted on fused quartz were also developed during the war for the Signal Corps. These inductors, spirals on a flat surface, had a Q of 80 after firing. The Q was increased to between 150 and 200 by electroplating. Where inductors are printed on glass or ceramic tubes and the conductor built up by electroplating to a thick layer, Q 's of 175 to 200 are not hard to obtain [50]. As the metal parts of the vacuum tube are located inside the inductor, the Q of inductors painted on tube envelopes is actually lower than this.

In special cases, the Q of a solenoidal inductor on a ceramic form has been increased by grinding away the ceramic material between the conductors, leaving practically an air core inductor that is supported by a ceramic material having a low coefficient of thermal expansion. When used in an oscillator in combination with a capacitor having a negative temperature coefficient equal to the small positive coefficient of the ceramic inductor, a frequency stability approaching that of quartz crystals was obtained.

Like spiral inductors, the inductance of solenoidal inductors may be increased by painting magnetic paint between the conductors or on the inside and outside of the solenoid.

The distributed capacitance of these inductors is relatively large, and depends on the spacing between turns, the thickness of the conductor and the dielectric constant of the base material.

C. Tuning Adjustment

The tuning or factory adjustment of spiral inductors can be accomplished in several ways. A metallic plate brought into close proximity to the inductor will change its inductance. In one case an inductor having an inductance of 0.22 μ h was reduced to 0.12 when a thick brass plate having an area 30 percent of that of the inductor was moved within 0.1 in. of the inductor. The Q dropped from 100 to 50.

A powdered metal screw in the center of the inductor may be used for tuning. This works well as a means of increasing the mutual coupling between two plane spiral inductors painted one above the other. Another expedient is a mechanical contact arm that makes contact over the last turn of the inductor.

A magnetic powder may be painted over the inductor or an intertwined spiral of magnetic paint located between the turns of the inductor. Adjustment is made by scraping off the required amount of magnetic material to reduce the inductance to the desired value.

It is evident that the above tuning methods re-

duce the Q of the inductor when used to produce large changes in inductance. They should be used only when small adjustments are necessary and when some loss of Q may be tolerated.

5. Printed Assemblies

A. Temperature Characteristics

The temperature performance of printed amplifiers has been studied and reveals some interesting possibilities in correcting adverse temperature characteristics. The average gain vs. temperature and peak-frequency vs. temperature curves of a group of printed amplifiers employing disk capacitors are shown in figure 23. Note the rise followed by a rapid drop as the temperature is increased. For comparison, an amplifier made up of standard (not printed) components is shown in figure 24. It is evident that some temperature

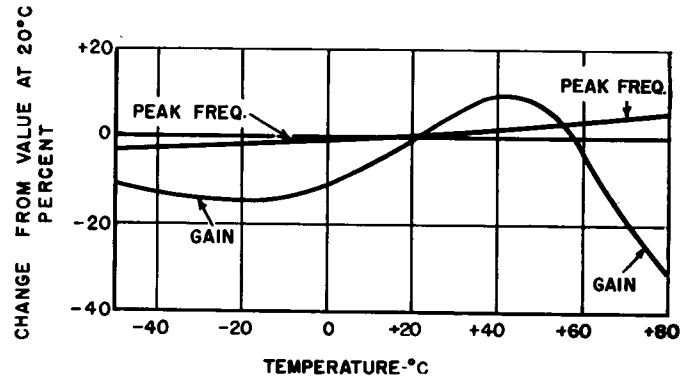


FIGURE 23. Change in peak frequency and gain with temperature of printed amplifier on a steatite plate.

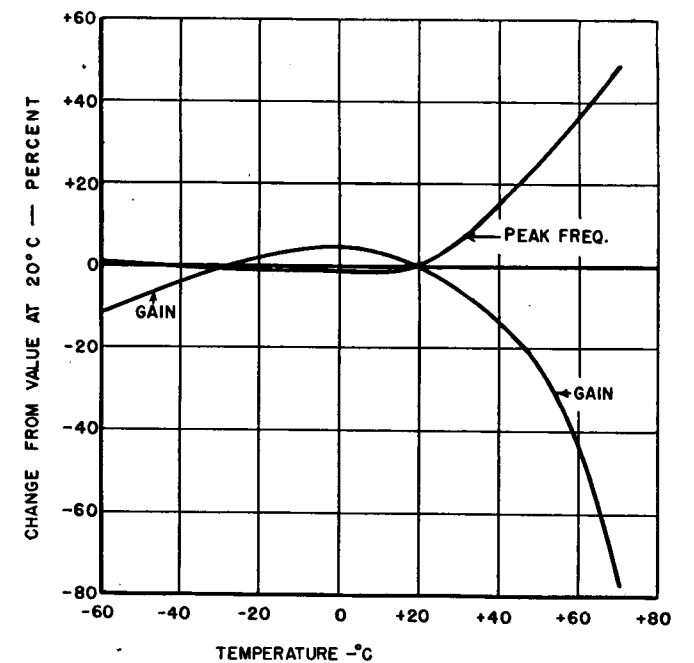


FIGURE 24. Change in peak frequency and gain with temperature of amplifier constructed with standard miniature components.

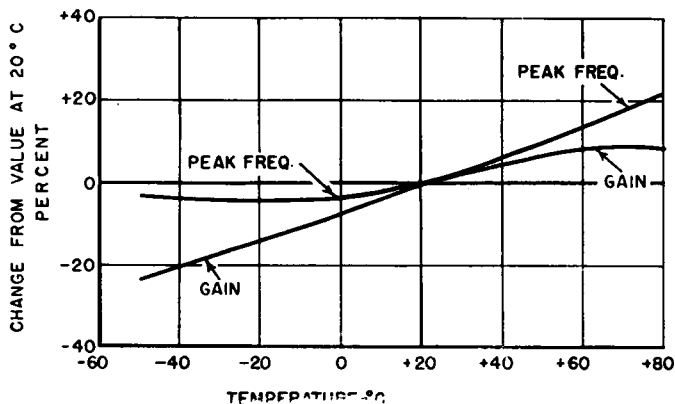


FIGURE 25. Peak frequency and gain characteristics of corrected printed amplifier.

compensation has already been obtained by printing the amplifier. A study of the temperature coefficient of the coupling and output capacitors led to the choice of dielectrics with special temperature characteristics, with the result shown in figure 25, in which the gain curve is boosted at high temperatures as desired and straightened out without seriously affecting the peak-frequency curve.

B. Aging Characteristics

The aging of audio amplifiers printed on steatite plates was studied over a period of 75 days.²⁶

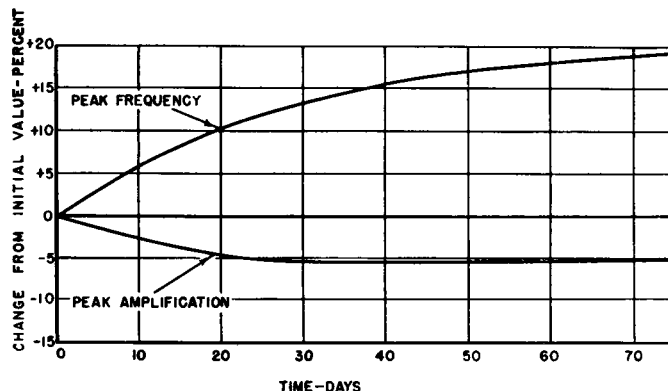


FIGURE 26. Age characteristics of printed amplifier.

The units tested had essentially an inverted V shaped gain-frequency characteristic, making it possible to study not only the change in peak amplification with time but also the change in the frequency of peak amplification. The results shown in figure 26 are the average of eight units tested. The total decrease in peak amplification over this period was 6 percent, and the peak-frequency drifted upwards 19 percent. Most of the change occurred in the first 25 days. This is considered good performance as it includes the aging effects of not only the printed wiring and resistors but the capacitors (ceramic type), the sub-miniature tubes, and the steatite base plate.

IX. Applications

Experimentation at the National Bureau of Standards has proven the practicability of applying the new methods to the manufacture of radio and electronic equipment. Several types of amplifiers, special electronic sets, and small radio transmitters and receivers made in the Bureau's laboratories have shown performance qualities comparable to equipment built along conventional lines, as well as improved miniturization and ruggedness. Complete circuits may now be printed not only on flat surfaces but on cylinders surrounding a radio tube or on the tube envelope itself.

Now actively being developed by various laboratories are printed circuits for electronic controls using gas filled tubes, electronic units for hearing aids, I. F. strips for radar and UHF equipment, subminiature portable radio transceivers, electronic circuits for business machines, electronic switching and recording equipment, including telephone apparatus and devices such as the radio sonde. Other activity includes manufacture special components such as antennas, interstage coupling units, microwave components, shields, etc., and the printing of graphs with conducting

lines over which contacting arms move to select answers to functions of one or more independent variables.

1. Amplifiers and Subassemblies

Several steatite plates with circuits printed on them are shown in figure 27A. This illustrates to a small extent the variety of shapes and figures to which the process is adaptable. All but the cylindrical amplifier in the lower left corner were applied with stencilled screens. The cylindrical unit was painted with a brush. The resistors (black rectangles) bear coats of protective lacquer. Note the circular and rectangular spiral inductors. The pair second from the top are the front and back sides of a plate for an oscillator unit. Note the horizontal rectangular spiral inductor (on the right) is coupled to the two vertical rectangular spirals (on the left) through the ceramic plate. These are the plate, grid, and antenna coupling inductors of a short wave transmitter. The plates illustrate methods of attaching foil strips to the disk capacitors, and some examples of how cross-overs are accomplished in the wiring. Five completed printed assemblies are shown in figure 27B. Subminiature tubes are used. The two stage re-

²⁶ Data supplied by Centralab Division, Globe-Union, Inc.

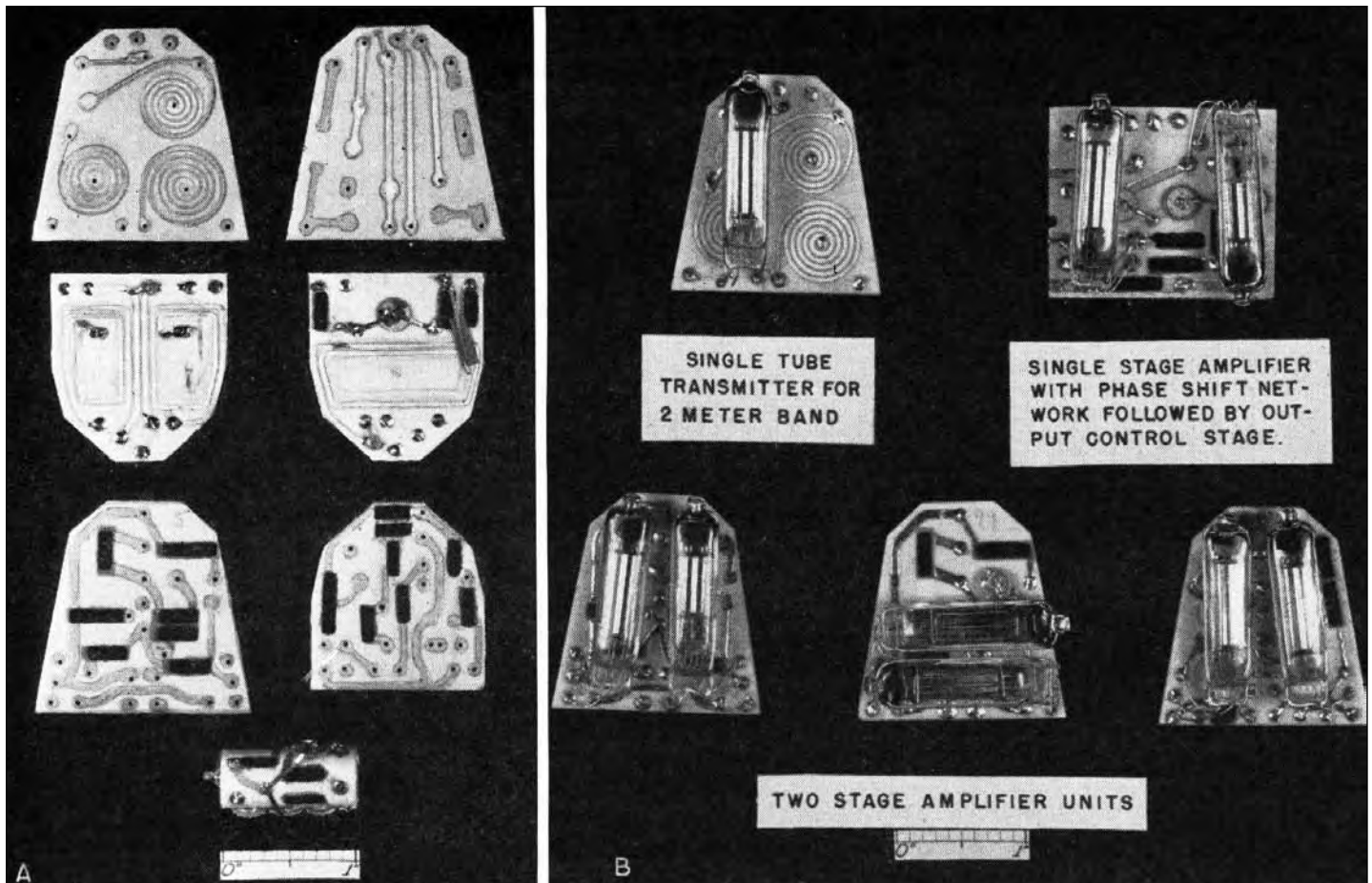


FIGURE 27. *Electronic circuits printed on steatite plates and cylinders by the stencilled-screen process.*

A, Partially completed units. Light lines are silver conductors and inductors; dark rectangles are resistors; circular disks are ceramic capacitors. B, Finished subassemblies. Subminiature tubes are employed to minimize size.

sistance coupled amplifier of figure 2 is printed on a thin steatite plate 1.5 in. wide and 2 in. long. Both the silver circuit wiring and graphite resistors were printed using stencils and a squeegee. This unit employs a pair of CK-505AX subminiature voltage amplifier pentodes [51].

Figure 28 shows a two-stage amplifier painted on the envelope of a miniature 6J6 tube. This is a complete unit requiring only plugging into a power supply to operate. The circuit wiring was applied with a stencil wrapped around the tube. The developed stencil and wiring arrangement are shown in figure 29. For painting circuits on tube envelopes, paints are used that do not require baking at extremely high temperatures to drive out binder and solvents. In this way tube performance is not deteriorated by gases that may be released from its metal parts by the heat. The circuit may be applied to the tube envelope either before or after the tube elements are in place. A glass tube was employed in the unit of figure 28, although a metal tube might have been used after

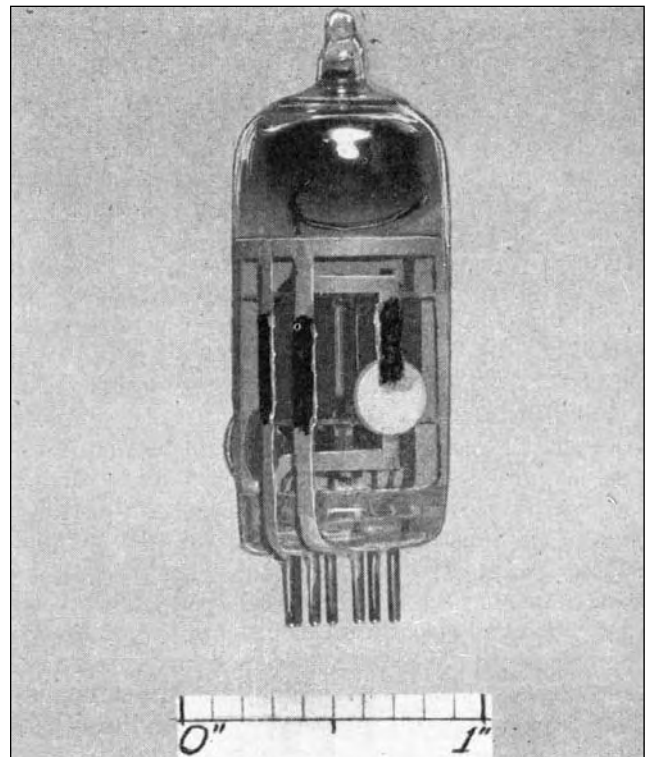


FIGURE 28. *Two-stage amplifier painted on the glass envelope of twin-triode miniature vacuum tube (type 6J6) using stencilled-screen.*

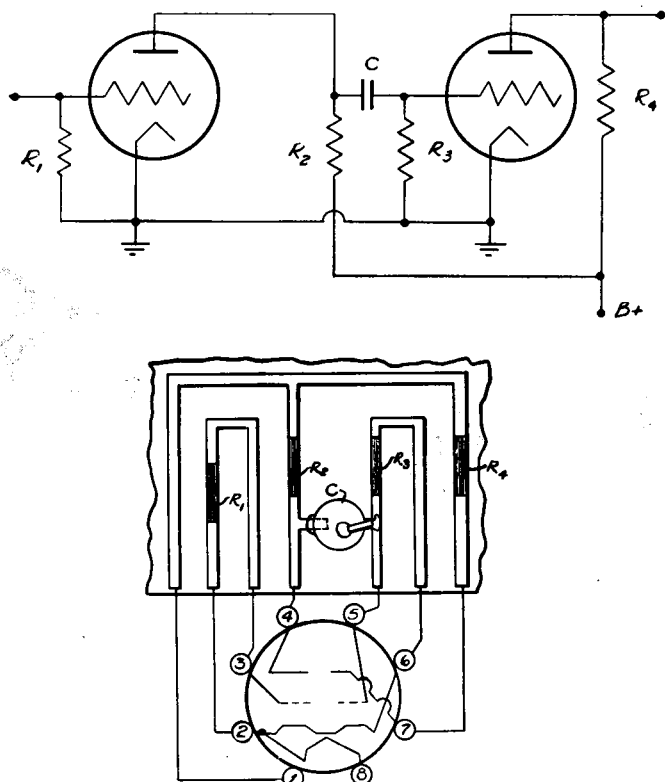


FIGURE 29. Circuit diagram and developed stencil for two-stage amplifier of figure 28

first coating the metal envelope with a layer of lacquer or other insulating material. A tube with ceramic envelope may be used. Lead wires from the circuit to the tube prongs are painted on with a brush. Leads may also be soldered to points on the tube envelope itself, ribbon-type leads usually being employed. Lead cross-overs are to be avoided in the printing. When this is impossible, cross-overs on glass may be made by painting a thin layer of insulating lacquer over the lead to be crossed and when the lacquer has dried, painting the cross-over lead on top of it. Another method is to place or cement a thin insulated strip such as scotch tape over the lead and run a foil strip or ribbon over it. The cross-over ribbon is connected to the circuit by a drop of silver paint or solder at its ends. (See figure 27A, unit second from top, at right.) The wiring of the unit of figure 28 was accomplished without cross-overs.

The idea can be applied to any nonconducting surface. Thus, electric circuits can be printed on the ceramic covers of electric components such as the normal type of IF inductor cases, or on the inside of the plastic cabinet of a radio or other piece of radio or electronic equipment. Another suggestion of perhaps limited practicability is that special radio and electronic circuits may be printed on flexible or nonflexible sheets, such as the page of a magazine and issued periodically in the same manner as cross word puzzles. Eyelets would be placed on the pages at appropriate points to which

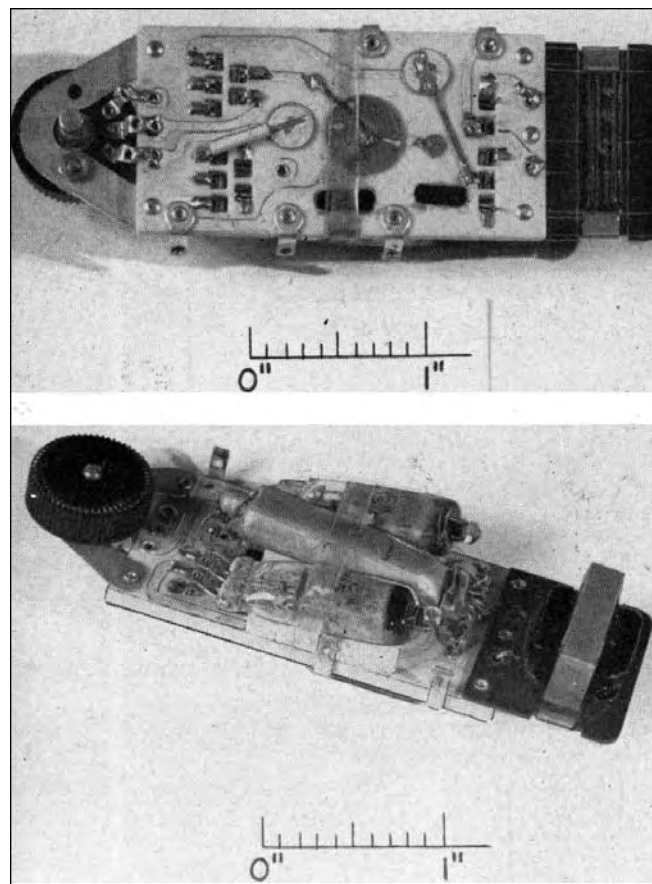


FIGURE 30. Hearing aid type amplifier printed on ceramic plate.

radio tubes, speaker, power supply, and other components may be soldered to complete the circuit. These circuits might be useful to experimenters provided the currents used are small.

Figure 30 shows an amplifier printed by one manufacturer as a unit suitable for a hearing aid.²⁷ It is a three-stage amplifier with a gain of 10,000. Included are a miniature volume control and specially designed clips to hold the subminiature tubes. It was printed on a ceramic plate by the stencilled-screen process. The single-stage amplifiers of figure 5 were also made by this process.

One manufacturer has placed on the market a variety of printed coupling circuits in which the dielectric material²⁸ for the capacitors is the base plate itself. Conductors and capacitors are printed in the same stencilling operation. The result is an unusually compact unit. Even when entirely coated with a protective plastic cover, the units are only approximately 0.06 in. thick. A diode filter circuit consisting of a resistor and two capacitors is 0.19 in. wide and 0.5 in. long. Other units such as audio coupling circuits and alternating-

²⁷ Several hearing aid companies are developing subminiature hearing aids with printed circuits. One hearing aid manufacturer has scheduled production of printed sets.

²⁸ The dielectric constant of the base plates may be as high as 90,000.

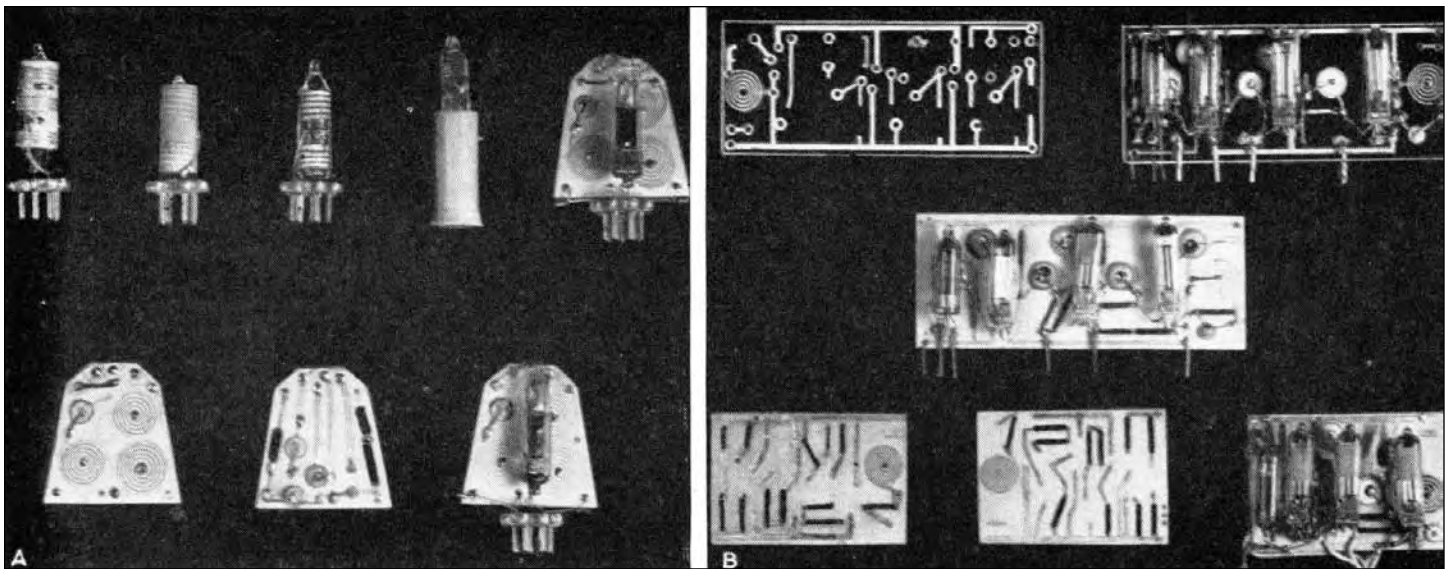


FIGURE 31. *Printed subminiature radio transmitters and receivers*

A, Top row, five types of 132–144 mc transmitters. All are grid modulated and require only connection to microphone and battery to operate. Oscillator circuits of two units at left are printed on outer surface of thin steatite cylinder housing subminiature tube. Circuit of center unit is painted on the glass envelope of 6K4 subminiature triode $\frac{3}{8}$ in. in diameter and $1\frac{1}{4}$ in. long. Transmitter second from right is painted on glass envelope of T-2 tube, $\frac{1}{4}$ in. in diameter and 1 in. in length. Circuit of transmitter at extreme right is painted on $\frac{3}{32}$ in. steatite plate, 1.5 in. wide and the same in length. Bottom row, developmental stages of a steatite plate transmitter. Plate at left carries three silvered spiral inductors and single high dielectric constant ceramic capacitor. Reverse side of plate (center) shows silver wiring, three (black rectangular) resistors, and four circular ceramic capacitors. Next is complete transmitter with subminiature tube and battery plug.

B, Top row, four-tube receiver printed on $\frac{3}{32}$ in. Lucite plate, 2 in. wide and 5 in. long. Stencilled silver circuit wiring is shown in plate at left, with completed receiver at right. Battery and speaker are omitted. Center row, four-tube receiver printed on thin steatite plate. All receivers have four stages consisting of square law detector, two stages of pentode amplification and triode output stage feeding permanent-magnet type speaker. Bottom row, two developmental stages of a four-tube receiver printed on thin steatite plate, 2 in. wide and 3 in. long. Plate at left shows complete circuit wiring (without tubes and capacitors) applied with camel's-hair brush except for spiral inductors. Wiring on center plate was applied by stencilling process. Leads from complete receiver at right connect to battery and speaker.

direct-current radio and subassemblies consisting of three resistors and three capacitors are 0.5 in. wide and 1.0 in. long.

2. Transmitters and Receivers

Figures 31 and 32 show a number of radio transmitters and receivers produced by the printed circuit technique. Designed to operate in the band 132–144 megacycles—these examples illustrate only a few of the wide number of variations possible in printing circuits [52, 53, 54, 55]. Silver and carbon paints were used to make the sets.

The five types of transmitters shown in the upper half of figure 31A are single tube grid-modulated units and require only connection to modulator and battery to operate. Electrical circuit diagrams for the transmitters together with design details are shown in figure 33. In the two units at the top left of figure 31A the oscillator circuit is printed on the outer surface of a thin steatite cylinder. The tube is inserted within the cylinder and the combination wired to a battery plug. A close-up view of this unit is shown at the right in figure 34.

The unit in the top center of figure 31A is a transmitter with circuit painted on the envelope of the subminiature tube, a 6K4. It was made by first wrapping a stencil of the inductor pat-

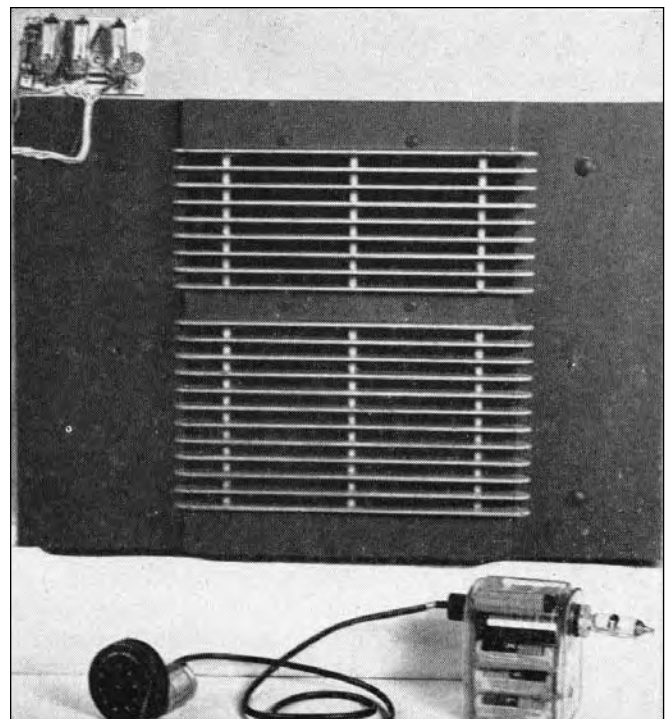


FIGURE 32. *Subminiature printed transmitter and receiver.*

The 2 in. by 3 in. printed receiver (top) has sufficient power to operate the standard 10-in. console speaker. The transmitter assembly (below) consists of a power peak with the tube transmitter and microphone cable plugged into opposite sides.

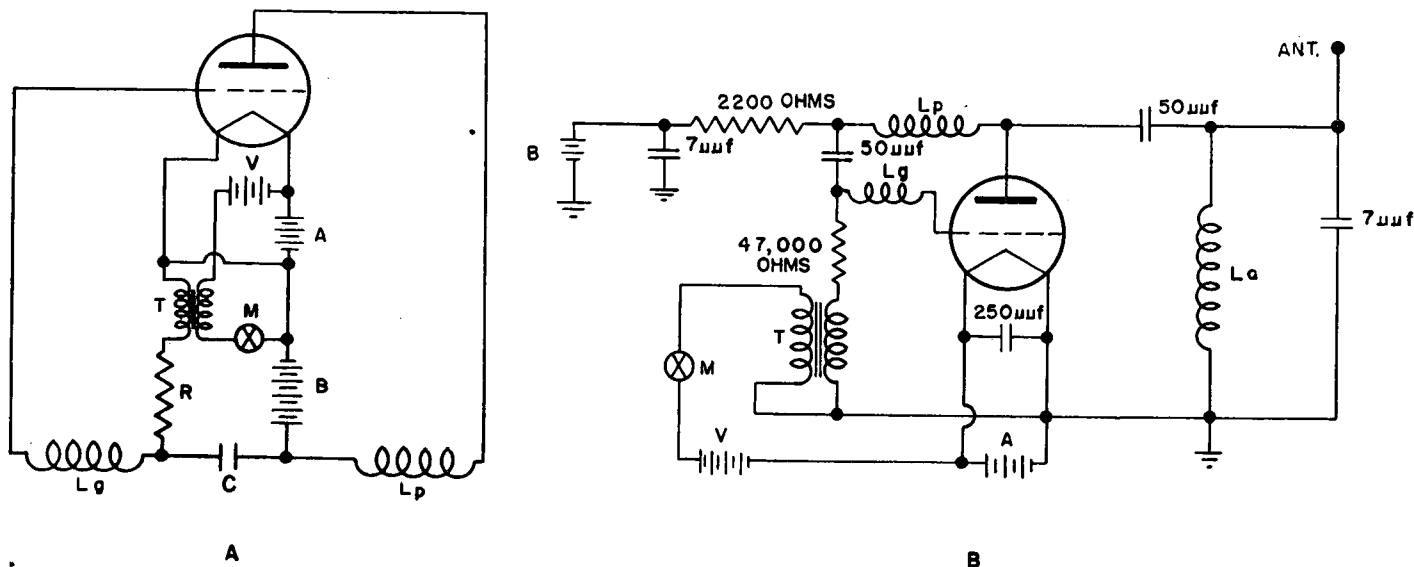


FIGURE 33.—Circuit diagram and design data for three types of subminiature radio transmitters.

A, Circuit diagram and design data for two types of subminiature printed transmitters. Type 1 has the electronic circuit painted on glass envelope of a miniature triode, and has the following circuit-constants: Tube 6K4 Sylvania subminiature triode; A, 6 volts; B, 120 volts; C, 7.5 μ u-subminiature high dielectric constant ceramic capacitor 0.125 in./diameter by 0.030 in. thick, attached to tube envelope; R, 50,000 ohms—painted on tube envelope 0.1 in. by 0.3 in. (graphite paint); Lg, four turns painted on tube envelope (15 turns per in.) silver paint; Lp, five turns painted on tube envelope; M, carbon microphone; T, miniature transformer; V, 0; frequency, 136 mc; plate current, 3 ma; filament, 200 ma.

Type 2 has the electronic circuit painted on thin steatite cylinder with a subminiature tube inside the cylinder, and has the following circuit constants: Tube, Raytheon subminiature triode; A, 1.5 volts; B, 120 volts; C, 7.5 μ u ceramic capacitor attached to steatite cylinder (cylinder is 1 in. long, 0.5 in. outside diameter, 0.03 in. wall thickness); R, 50,000 ohms painted on steatite cylinder; Lg, three turns painted on steatite cylinder (16 turns per in.); Lp, six turns painted on steatite cylinder (16 turns per in.); M, carbon microphone; T, miniature transformer; V, 4.5 volts; frequency, 116 mc; plate current, 3 ma; filament current, 200 ma.

B, Circuit diagram and design data for a subminiature radio transmitter painted on a flat steatite plate.

Tube, Raytheon subminiature triode; A, 1.5 volts; B, 120 volts; Lg, 4 $\frac{1}{4}$ turns, spiral wound on steatite plate, $\frac{7}{16}$ in. outside diameter; Lp, 4 $\frac{1}{4}$ turns, spiral wound on steatite plate, $\frac{7}{16}$ in. outside diameter; La, 5 $\frac{1}{2}$ turns, spiral wound on steatite plate, $\frac{5}{8}$ in. outside diameter; M, carbon microphone; T, miniature transformer; V, 4.5 volts; frequency, 140 mc; plate current, 3 ma; filament current, 200 ma. Capacitors are ceramic disk type attached to steatite plate. Resistors are painted on steatite plate.

tern around the tube using masking tape. The glass envelope was then etched in fumes of hydrofluoric acid. After etching, the hydrofluoric acid was neutralized with strong caustic soda solution, and the envelope washed thoroughly with soap and water and rinsed in distilled water. The conducting paint²⁹ was applied to the etched surface and allowed to dry in the air. To improve the Q of the inductor, it was silver plated in a silver-cyanide bath by applying a current of 0.2 amp for 15 minutes depositing a layer approximately 0.003 in. thick.³⁰ The grid-leak resistor was painted on using carbon paint and dried at a temperature of 50°C under an infrared lamp. The addition of a tiny high-dielectric ceramic capacitor completed the circuit on the tube envelope.

The circuit for the unit second from the top right in Figure 31A is painted on the glass envelope of a T-2 tube measuring $\frac{1}{4}$ in. in diameter and 1 in. in length. The silver inductors were applied with a ruling pen mounted on a lathe with the tube held in the chuck and rotated by hand. Samples of this work are shown in figure 35. Both tube and

circuit have been coated with a thin layer of plastic cement to protect against rough handling and humidity. A close-up of the tube and circuit is shown at the left in figure 34. The wiring diagram is in figure 33A. The manner in which the leads are brought out from the circuit to the batteries, microphone, and antenna is illustrated in figure 36. The unit is housed in a small plastic container.

The circuit of the transmitter at the top right in figure 31A was stencilled on a $\frac{3}{32}$ -in. steatite plate 1.5 in. wide and the same in length. The circuit for this transmitter is that of figure 33B. The development of the flat-plate transmitter (both sides) is shown at the bottom of figure 31A. The top side carries the three spiral inductors and a 50 μ coupling capacitor. The bottom side bears the remainder of the circuit wiring including three resistors (the dark rectangles) and four capacitors. One of the resistors, though not shown in the circuit diagram, is connected to the grid inductor. It serves as a blocking resistor for measuring the oscillator grid voltage. Wiring of the units was completed by soldering the subminiature tubes and leads for the antenna, batteries, and microphone directly to the silver wiring on the plate.

The receivers shown in figure 31B are all wired with the circuit of figure 37. Two of the units are

²⁹ Sauerisen Conductalut.

³⁰ Where strong adhesion is desired, it has been found advantageous to copper plate over the initial painted inductors prior to silver plating. A simple copper-sulfate bath may be used. Plating at 4 amp. for about $\frac{1}{2}$ minute will deposit approximately 0.0005 in. copper film.

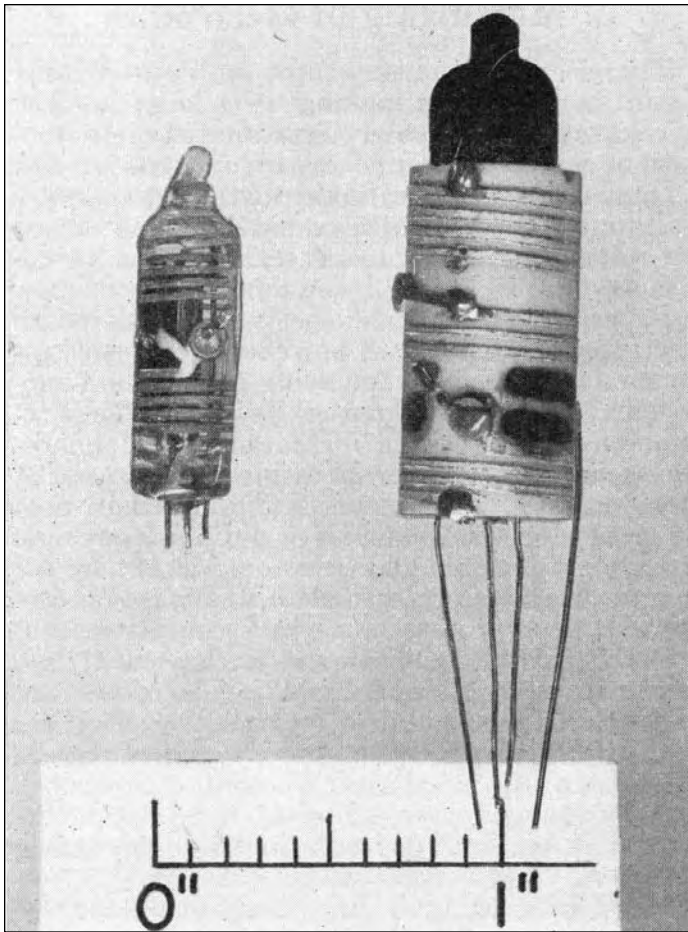


FIGURE 34. Close-up view of printed transmitters; left, circuit painted on glass envelope of subminiature tube using ceramic disk capacitor; right, circuit on thin ceramic cylinder housing subminiature triode.

on steatite plates 2 by 3 in. and 2 by 5 in. (bottom and center respectively), and the third is on a 2 by 5 in. lucite plate. They employ a square law detector stage followed by two stages of pentode amplification and a triode output stage feeding the loud speaker. The input tuning is broad so as to allow reception over the complete band of 132 to 144 megacycles. All but the unit in the lower left corner were made by the stencilled-screen process. The circuit of the other with the exception of the spiral inductor was painted on with a camel's hair brush. The spiral inductors have all been silver plated. As silver plating is relatively easy, it was found convenient to plate all wiring on the base in the same operation at a rate of 0.2 amp. for 15 minutes in a silver-cyanide bath. After the resistors were applied through a stencil and the capacitors soldered to eyelets in the Lucite plate, the complete surface was coated with a thin layer of Lucite cement for protection against humidity and other effects.

Standard miniature microphones, speakers, and batteries complete the operating units. The

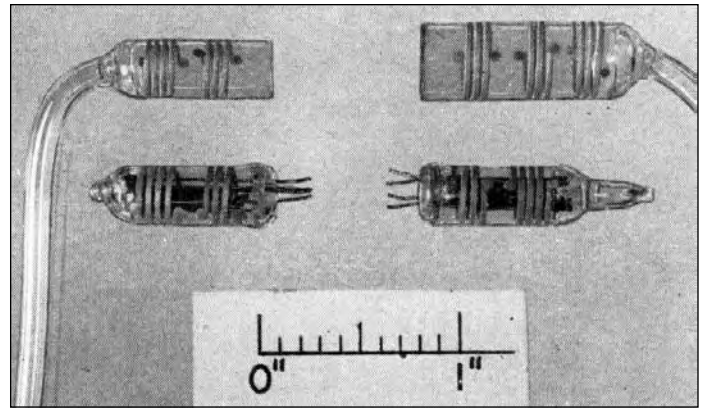


FIGURE 35. Examples of inductors applied to glass tube envelopes with ruling pen and lathe.

units also operate satisfactorily with standard large size microphones or speakers. The transmitter of figure 32 is plugged into a power pack, and the standard size carbon microphone with matching transformer is plugged into the other end. The 2 by 3 in. receiver mounted on the 10-in. console speaker has sufficient power to operate the speaker so that it may be heard throughout a fair sized auditorium.³¹

The radio proximity fuze of figure 1 incorporates both a transmitter and receiver made by the printed circuit technique [55]. An electronic control circuit is included in the steatite block B; the remainder of the circuit is printed on steatite plate A.

3. Printed Plug-in Units

The case of replacing defective printed subassemblies in an installation introduces new possibilities in manufacture and maintenance, particularly applicable to complex equipment and to rural and foreign markets where maintenance is a difficult problem. This advantage is realized by the use of printed plug-in subassemblies, an example of which appears in figure 38. Principal units of a set can be removed, tested, and replaced in the same manner as tubes are handled. It should be useful in areas where skilled repair men are not available and in applications where it is necessary to do trouble shooting under difficult conditions. With all major subassemblies wired in plug-in fashion, if necessary, the repair man can replace all the subassemblies in the set, taking the old units back to the shop for checking. The subassembly of figure 38 has been encased in a special casting resin [56] developed at the Bureau, useful at frequencies up to and beyond the VHF range. It is thus protected against manual and atmospheric abuse.

³¹ Personal transceivers incorporating printed circuits are being engineered and may shortly appear on the market. One manufacturer has designed them for the proposed Citizens Communication Band, 460-470 megacycles.

4. Metallizing in Electronics

The electrical industry now employs printed circuit techniques in making up a large number of electrical components. Typical are the production of silvered ceramic capacitors, lamps, and vacuum tubes such as cathode ray tubes with inner walls metallized, insulators partially metallized for soldering thereto, metal seals to glass or ceramics, etc. [57, 58, 59].

Paper and thin plastic sheets are prepared as electrostatic shields and as reflectors of electromagnetic waves by evaporating thin, almost molecular, layers of metal onto the surface. Glass attenuators for precision measurements of microwaves are made by evaporating thin layers of metal on glass. The thickness of film is controlled by measuring the conductance during deposition. Precision metallized glass resistors [58, 59] for use in pulse circuits are also made this way as are wave guide pads and other microwave equipment.

Both sputtering and evaporation have been used to plate crystals successfully [57]. The process not only affords a splendid way of making electrical contact to the crystal face, but by controlling the thickness of the metal layer, the crystal frequency may be changed over a limited range while the crystal is oscillating freely in the evaporating chamber.

Metal to glass seals have been made successfully by spraying a thin coat of aluminum onto glass heated to about 400° C [3]. The aluminum with its oxide is believed to dissolve partially in the glass to form a vacuum tight bond. Copper is sprayed over the aluminum to facilitate soldering thereto.

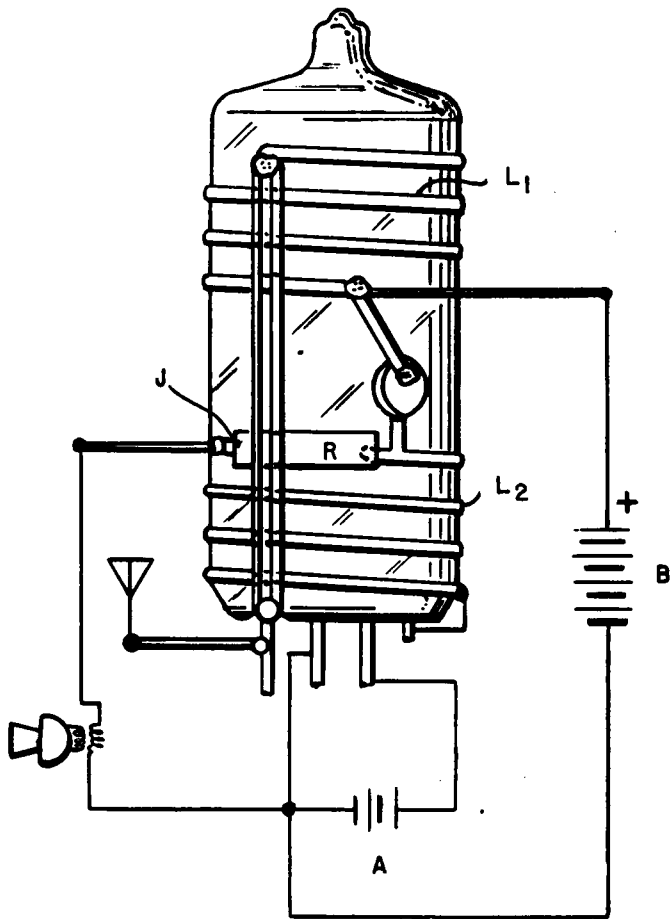


FIGURE 36. Schematic arrangement of transmitter shown at left of figure 34.

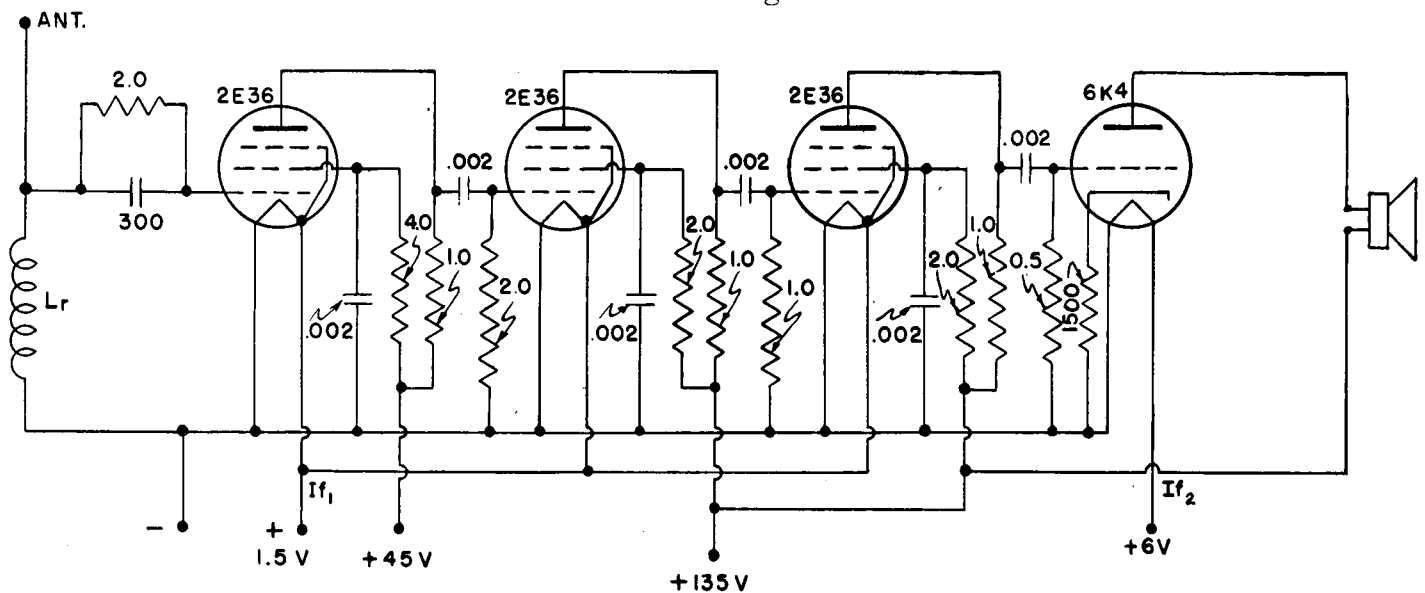


FIGURE 37.—Circuit diagram and design data for a subminiature radio receiver printed on a thin plate, 2 in. wide and 3 in. long.

The receiver has four stages consisting of an input stage of square law detection followed by two stages of pentode amplification and a triode output stage. I_{r1} , 120 ma, radio frequency, 140 mo/sec.; speaker, 6 to 12 in. diameter permanent magnet or miniature magnetic; I_{r2} , 200 ma; plate current through speaker, 2.5 ma; L , $4\frac{1}{2}$ turns, spiralwound, $\frac{3}{16}$ in. outside diameter. All resistor values are in megohms except cathode bias resistor which is 1,500 ohms. All capacitor values are in microfarads except the detector grid capacitor which is 300

The radio sonde switch of figure 39 shows a practical method of making electronic accessories. Conventionally made by laboriously assembling 80 thin rectangular metal strips separated by insulators, it affords a good example of the advantages of the new process. A plastic strip is molded with grooves as shown in the lower view. A conductive layer is then applied by chemical reduction of silver. (An alternative method would be to apply silver paint generously over the surface.) After drying, the top surface is ground down leaving the grid desired and completing the unit.

5. Electromechanical Application

Strain gages are used to measure changes in dimensions of mechanical systems. They may be made by applying a layer of resistance paint to the surface under study and measuring the change in resistance as the member is stressed. The paint is applied in the usual manner and coated with a protective layer to maintain the calibration independent of atmospheric conditions.

A novel application of this principle was made in developing an extremely lightweight phonograph pick-up [60]. It consists of a flexible cantilever beam $\frac{1}{2}$ in. long and approximately 0.06 in. square made of polystyrene. The needle is permanently attached to one end. The other end is anchored to the tone arm. A thin resistance layer is painted on the side of the beam. It runs out to the free end of the beam on the top half of the side and returns on the bottom half in horizontal U-shape manner. Lateral displacement of the needle as it rides over the record flexes the beam and produces a proportional variation in resistance of the layer. A voltage change proportional to the variation in resistance is fed to the amplifier. By running the resistance line out and back, connections to the needle end of the arm are avoided. In this design, connection to the resistance layer at the tone arm end of the beam is made by pressure contacts. These contacts could be eliminated by terminating the resistance lines into painted silver strips to which fine wires may be soldered directly.

Resistance values of 75,000 to 100,000 ohms are used. Duplicating the arrangement on the opposite side of the beam increases the sensitivity by taking advantage of a mechanical push-pull effect. It was found that the variation in resistance with strain was a linear function over a wider range than used in the phonograph pick-up. It is of interest to note the author's report that the resistance pick-up was completely free of hiss or background noise. A coat of lacquer protected the resistance so that actual immersion in water did not appreciably affect the performance.



FIGURE 38. Printed plug-in unit encased in NBS casting resin.

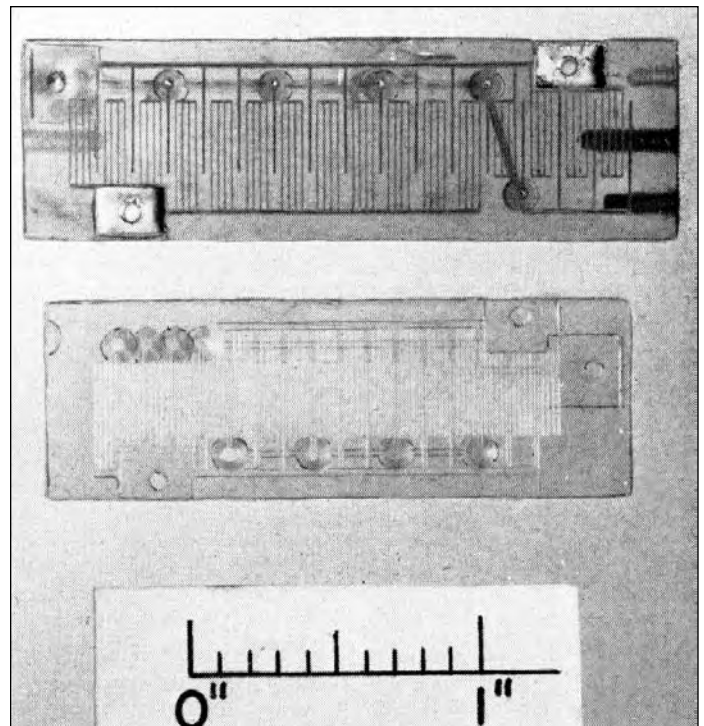


FIGURE 39. Radio-sonde commutator made by printed circuit technique.

X. Conclusion

The present status of printed circuits may be summed as follows. The conductors of an electronic circuit may readily be printed by any one of a large number of successful methods. Many of these methods, described herein, have been proven in practice on production lines. The principal item requiring further attention to achieve over-all perfection in printing circuits is the development of improved methods of printing resistors. Although much is known about printing resistors, and values have been printed in large scale production covering almost the entire range needed in modern electronic manufacturing, much remains to be learned about resistor manufacture before all of the extensive requirements imposed on them by their use in modern electronic sets may be met satisfactorily. Even here the present status is good. Mass production lines have been set up and are producing printed circuits in their entirety at the rate of thousands per day.

A manufacturer does not, however, need to set up his plant to produce sets that are printed in every electronic detail to take advantage of printed circuits. Some have introduced the novel process by printing only a subassembly or an interstage network of a complex set. Some have printed only the conductors, and have used standard resistors and capacitors for the remainder of the circuit. In this case the methods usually employed to date have been painting, spraying, and cold die-stamping. Hundreds of thousands of electronic sets of all types have been produced in this country and abroad utilizing these techniques in one or more subassemblies. Printing circuit conductors and using standard resistors and capacitors has proven an attractive way of adopting printed circuit practice with a minimum of disturbance to engineering and production. Engineering and production personnel have been quick to recognize the advantages to be gained in production by using printed circuit techniques that simplify, mechanize, and reduce the cost of assemblies.

The status of patents on printed circuit techniques is one that cannot be stated in explicit terms. As mentioned above, many of the techniques are adaptations of processes patented long ago, which patents have expired. Much of the technical information is classed as standard knowledge of the art and is unpatentable. Patents have been applied for by industrial organizations and some by the Government. Because of the large back-log of work in the Patent Office it is not expected that final decisions on these applications will be reached early. It is thought that most of the patents in process relate principally to specific and perhaps limited processes and applications. Patents applied for by the Government may ultimately be made available to industry on a nonexclusive basis without charge. Concerns planning to use printed circuits commercially are advised to check the patent situation in the same manner as would be employed in adapting any new manufacturing process.

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XI. References

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