

A THICK FILM HYBRID CIRCUIT LABORATORY MANUAL

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by

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B.S., Kansas State University, 1969

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

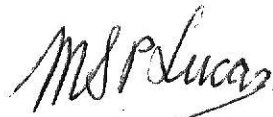
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LABORATORY MANUAL

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THESIS

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ACKNOWLEDGMENTS

I should first of all like to thank my parents for making it possible for me to be here to do this work. I should also like to express my deepest thanks to Dr. M.S.P. Lucas who, as my advisor, suggested the topic for the thesis, and who provided both guidance and encouragement during the writing of the thesis.

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Michael R. Casey

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I. INTRODUCTION

1.1 PURPOSE OF THIS MANUAL

The purpose of this manual is to provide the student in the Integrated Circuits Engineering course at Kansas State University with a laboratory manual that describes the design and fabrication of hybrid microelectronic circuits.

A primary objective in each class is to motivate the student to work on his own without the constant guidance of the instructor. After several semesters of instruction in the laboratory, the author believes that a successful approach to this problem is as follows:

- I. To present a step-by-step procedure by which an actual hybrid circuit is designed and fabricated, with only brief explanations given of the processes involved. In this way the student should be able to go into the laboratory and build a hybrid circuit without knowing, in great detail, each of the processes involved.
- II. To give more detailed explanations of the major processes after the student is familiar with the basic design and fabrication steps for hybrid circuits.
- III. Finally, to include a glossary of some words and terms commonly used in the industry; and to include a list of components and materials (with their associated manufacturers) used in the fabrication process.

1.2 DEFINITION OF A THICK FILM HYBRID CIRCUIT

The first thing we must do is define a hybrid circuit (microcircuit). Webster's Dictionary defines a hybrid as "anything of mixed origin". For our purposes, as well as for paralleling industry's nomenclature, we will define a hybrid circuit as any electronic circuit composed of more than one kind of circuit element. Also, we will require that the circuit elements be fabricated on or attached to a base, called a substrate. The circuit elements may be either active or passive but they may not all be fabricated using the same technology (e.g., discrete-device, thick film, thin film, or silicon technology).

According to this definition, a circuit composed of a discrete resistor and a discrete capacitor would not be a hybrid circuit, unless the components were attached to thick film or thin film conductors on a substrate. However, a circuit composed of a discrete capacitor (such as a chip capacitor) and a thick film resistor would be a hybrid circuit (or equivalently, a hybrid microcircuit).

This definition may seem somewhat limiting, but as you read different electronic publications you will notice that nearly all hybrid circuits follow the above definition. However, you will find some exceptions because industry as a whole does not seem to have a precise definition of a hybrid circuit; consequently a definition must be established that is consistent with the majority of the electronics industry,

and one that can be used in the design and fabrication of hybrid circuits.

Before proceeding, we must also decide how each circuit component will be fabricated, or where it will originate from. The general rules for determining the origin of each circuit component (or element) are as follows:

- A. Resistors and their interconnecting conductor paths will be fabricated by thick film techniques whenever possible. The exceptions will be extremely high resistance values (typically greater than 10 megohms), and very closely-matched resistors (any or all properties), where discrete resistors will be used.
- B. Capacitors will be of the ceramic or tantalum chip variety designed specifically for hybrid circuit applications, except for large capacitance values (typically greater than 50 mfd.), in which case discrete capacitors will be used.
- C. Inductors will be either hand wound or commercially available units.
- D. Active devices will be any of those commercially available from industry, and preferably those in the micro-miniature packages designed specifically for hybrid circuit applications.

Sometimes you may have to interconnect two or more hybrid circuits which you have made. This is usually done by fabricating a printed circuit (PC) board and then

attaching the hybrid circuits, and possibly other components, to the PC board. In this case, we will refer to the finished product as a hybrid system.

The remainder of this section will concentrate on the steps involved in the design and fabrication of a typical hybrid circuit. The flow diagram in Figure 1 outlines the basic steps to be followed in this process. .

The student should be aware that the circuits to be designed using the following steps will have a frequency range from dc to 10 MHz in general. For higher operating frequencies the circuit designer must consider additional factors, such as stray capacitance, mutual inductance, and even the physical properties of the materials and components used in the design, which usually don't need to be considered in low frequency designs.

FABRICATION STEPS FOR A TYPICAL THICK FILM HYBRID CIRCUIT

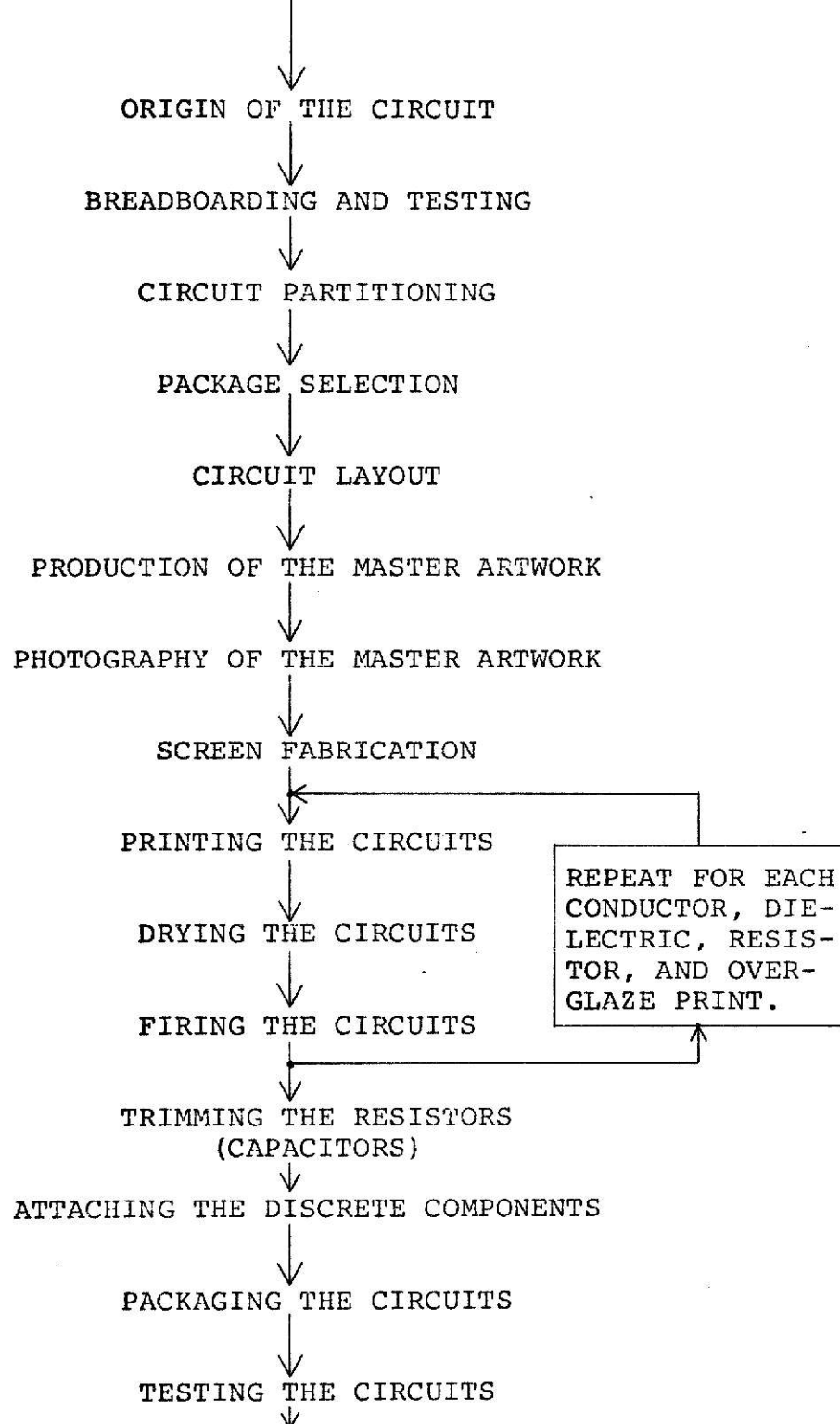


Figure 1. A flow chart of the process steps to be followed in the design and fabrication of a hybrid circuit.

II. THE FABRICATION OF A THICK FILM HYBRID CIRCUIT

2.1 ORIGIN OF THE CIRCUIT

Most hybrid circuits originate as parts of more complicated systems. In industry the circuit is usually either designed by a customer and then sent to the hybrid circuit designer for custom fabrication, or it is designed within the custom circuit fabrication house. In either case it is up to the hybrid circuit designer to start with the schematic diagram of the circuit and transform it into a hybrid circuit that can be easily manufactured.

Sometimes the circuit will merely have to be sketched from the schematic diagram. In other instances the schematic diagram will have to be divided, or partitioned, into sections that can be economically manufactured. In some instances the circuit may be such that it cannot be manufactured as a thick film hybrid. In any case it is up to the thick film hybrid circuit designer to decide just how each circuit can be designed and manufactured in the most economical way.

A typical thick film hybrid circuit is shown schematically in Figure 2. The circuit shown is an astable multivibrator that is used to alternately light two light-emitting diodes to produce a flashing light display. The main reason for the choice of this circuit was to enable the student to build a simple hybrid circuit using all of the basic processes without becoming lost in the electrical design of the circuit. This circuit, when completed, will provide visual

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evidence, without the aid of any instrumentation, of the success of the design and fabrication processes.

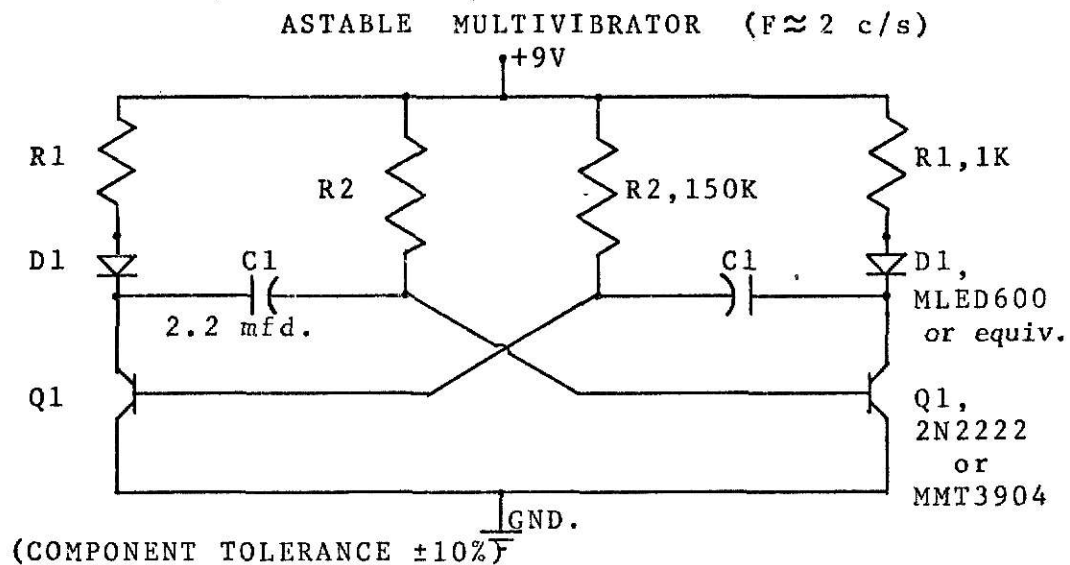


Figure 2. Schematic diagram of sample hybrid circuit.

2.2 CIRCUIT BREADBOARDING AND TESTING

The circuit should be assembled on a piece of perforated circuit board, such as phenolic Vectorbord*, using discrete components. The circuit thus formed is called a breadboard circuit.

The components should be arranged so that crossovers are kept to a minimum since crossovers on the final hybrid will require additional processing steps, thus increasing the cost and decreasing the probability of producing a good circuit.

Once the breadboard is assembled, check the wiring for errors, and then apply power and test the circuit's perform-

*Reg. T.M. of Vector, Inc.

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ance. Test the breadboard under conditions as close as possible to those it will be subjected to in its intended application. Any problems that arise must be corrected at this time. DO NOT go on with the design until the breadboard works satisfactorily. If the breadboard does not function properly the hybrid circuit is unlikely to function either. On the other hand, if the breadboard works properly you can be reasonably sure that the finished hybrid will also function at least as well. Actually, the hybrid will usually function better than the breadboard because stray capacitances and mutual inductances will be stabilized due to the low profile and small physical size of the circuit. See Figure 3 for the breadboard model of the circuit shown schematically in Figure 2.

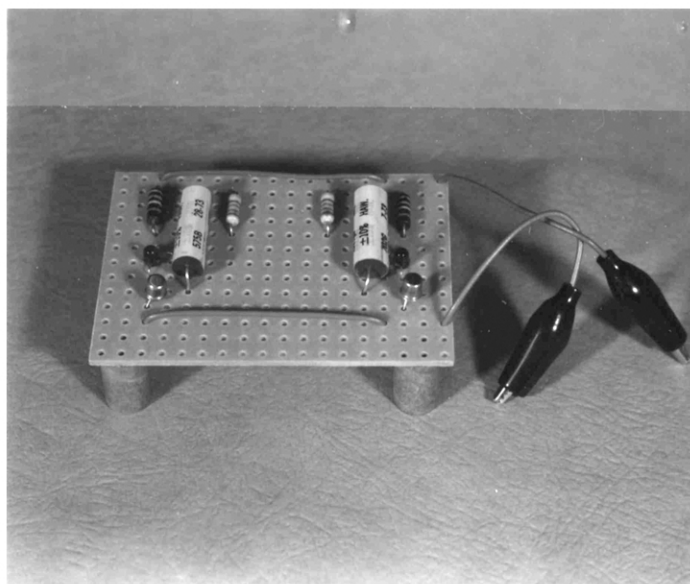


Figure 3. The circuit breadboard.

In addition to building and testing the breadboard, you must also establish suitable working tolerances for the circuit components which may be different from those specified

by the original designer. This can be done by substituting different component values into the breadboard and checking the resulting performance of the circuit. Or, a computer analysis can be run on the circuit to determine component tolerances and sensitivities if the facilities are available.

Always keep the tolerances on the components as large as possible since low tolerance components are more expensive to buy and are harder to build than are large tolerance components. For thick film resistors, a tolerance of $\pm 1\%$ is the lowest tolerance the novice designer should try to use. Lower tolerances can be obtained on thick film resistors but additional process steps must be performed on the circuits if the resulting resistors are to have good stability for long periods of time. If tolerances are kept within the range of $\pm 1\%$ to $\pm 10\%$, little problem with resistors drifting out of tolerance will be noticed for the normal lifetime of the hybrid circuit.

The same precautions hold for the other components which will be used on the hybrid circuit. In the case of purchased components you will usually have to accept what you get from the manufacturer and design around those components to get the circuit characteristics that you need.

2.3 CIRCUIT PARTITIONING

With the initial testing out of the way, you are ready to divide, or partition, the circuit into small blocks that can be easily fabricated as hybrid circuits.

If the circuit is a simple one, you may not need to do any partitioning; but if the circuit is very complex you will need to divide it into small, easily fabricated blocks.

For efficient partitioning, you must exercise some degree of common sense as you work. If you must divide the circuit, divide it into blocks that perform standard functions whenever possible. Also, use standard integrated circuits in such blocks as amplifiers, voltage-to-current converters, etc., whenever possible.

Don't try to incorporate devices into the hybrid circuit that don't belong there, such as 1000mfd. capacitors, or large transformers. Mount them on the PC board along with the other parts that make up the total system.

As a final point, don't divide the circuit into very small blocks, since you will eventually reach the point of "diminishing returns" with the design. You can even lose the advantages of building the circuit as a hybrid if you divide it too finely.

In the case of the sample astable multivibrator circuit, it is simple enough so that no partitioning needs to be done.

2.4 PACKAGE SELECTION

At this time we should stop for a moment and consider as aspect of the design that is usually left until last; namely, the choice of the final package for the hybrid circuit.

Several items must be considered, among them being the final location of the operating circuit, the minimum amount of space needed for the various circuit components, and the environmental conditions that the working unit will encounter.

If possible a package should be selected that is a standard in the electronics industry. If this is not possible a package should be designed that has many features that are characteristic of standard packages, such as lead type and spacing, or physical dimensions.

Once the package has been decided upon, the maximum substrate size allowable will be evident. Then a substrate must be selected that is large enough for the circuit but still small enough to fit into the package.

Most substrate manufacturers stock some standard sizes of substrates and these are the most economical for the low volume user. See Table 1 for some standard sizes of 96% Alumina (Al_2O_3) substrates, the kind most often used for thick film circuits.

LENGTH	X	WIDTH	X	THICKNESS
--------	---	-------	---	-----------

.500		.500		.025
.750		.750		.025
1.000		1.000		.025
2.000		2.000		.025

(all dimensions in inches)

Table 1. Standard substrate sizes.

In the case of the sample circuit, the package chosen is shown in Figure 4. Since this circuit is for demonstration only, it was not designed to fit a standard package size; the only requirement was that the power supply connections be easily accessible.

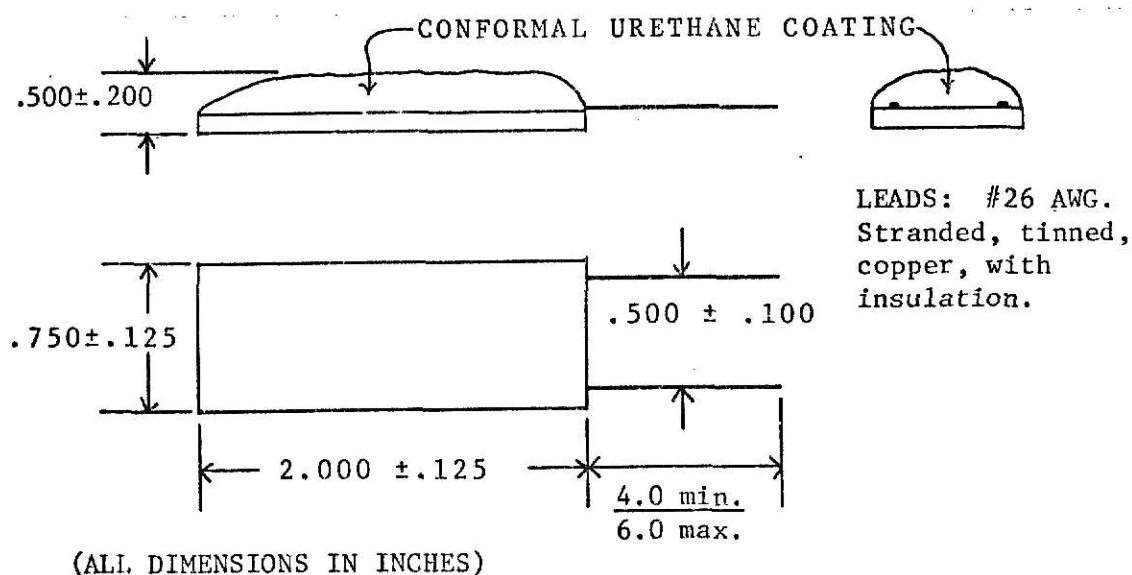


Figure 4. The package chosen for the sample hybrid circuit.

The coating material chosen for the circuit is a transparent urethane encapsulant called Solithane*. It is an amber-colored material that cures to form a tough, rubbery, urethane coating. It provides the properties of moisture protection

*Reg. T.M. of the Thiokol Chemical Corp.

and good mechanical flexibility with the extra feature of transparency so the circuit can be seen through the coating.

2.5 CIRCUIT LAYOUT

The circuit layout will be a large scale drawing of the actual working circuit. All of the discrete components, as well as the thick film elements, will be drawn to scale on the layout. As a final feature, the layout will be identified by a title block and legend. The layout should be drawn on good drafting paper with 5, 10, or 20 accurate divisions per inch and with good dimensional stability.

For most hybrid circuits a layout of 5 times the normal size will be sufficient. The various layout guidelines are listed in Chapter III and although they are lengthy and somewhat detailed the student should keep in mind that they are merely guidelines and a certain amount of common sense must prevail in the designer's mind as the layout is made. The sample circuit was designed as a 5X drawing and is shown in Figure 5, somewhat reduced in size.

2.6 PRODUCTION OF THE MASTER ARTWORK

Certain portions of the circuit layout are identified as the conductor pattern, the resistor pattern, and the overglaze pattern. The purpose of the master artwork is to provide you with a large-scale high-contrast picture of each of those patterns, which can later be photographically reduced to the

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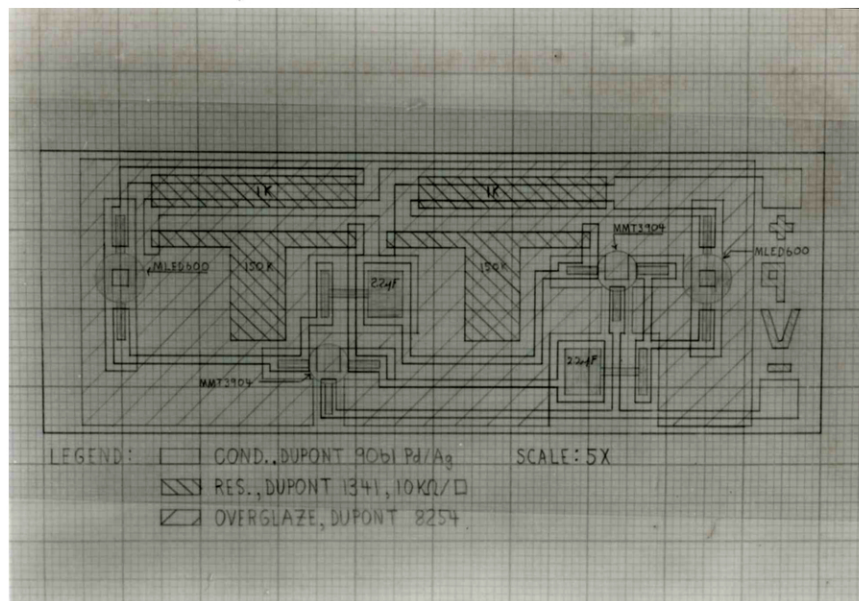


Figure 5. The circuit layout.

proper size. They will later be used to produce the patterns on the printing screens.

One material from which the artwork can be made is called Rubylith*. A similar material, called Amberlith*, can also be used. Rubylith is a lamination of two materials; a thick back layer of clear polyester sheeting and a thin top layer of red film. Amberlith is similar except that the top film is amber in color instead of red.

The process of "cutting the artwork" is as follows: Tape the circuit layout to a smooth table top with masking tape. Slide a piece of white paper under the layout to add contrast to the lines on the drawing. Tape a piece of Rubylith over the layout, with the red side up. Place a ruler along the line to be cut out and then cut the line with a

*Reg. T.M. of The Ulano Companies.

knife or needle-pointed cutting tool. A dissecting needle of the kind used in biology labs works very well. A long hat-pin loaded into a mechanical drawing pencil also makes a very good cutting tool for Rubylith.

After the lines have been cut they can be peeled off the polyester backing with a pair of tweezers.

It is assumed that the finished artwork will consist of the circuit patterns appearing as clear areas on a red field. However, this is not always the case since other processing steps must be considered, such as the type of film used in the photographic reduction step, and the type of emulsion used on the printing screen. These exceptions will be discussed in Chapter III.

Once all of the artwork has been cut it should be examined for mistakes and if any are found they must be corrected. You should also make sure that the identifying name or number of the artwork, and the scale factor of the artwork, appear on each Rubylith sheet.

After all of the sheets of artwork have been checked and accepted they should be placed in an envelope to protect them from damage. The artwork is now ready to be photographically reduced to the proper size. The artwork for the sample circuit is shown in Figure 6, together with a copy of the negatives that were made from the artwork.

2.7 PHOTOGRAPHING THE ARTWORK

The artwork must now be photographically reduced to the proper size for the final circuit. The photographic techniques required for the production of top quality negatives are quite straightforward and are discussed in Chapter III.

Be sure to obtain two negatives of each piece of the final artwork so that if one is damaged you will have a replacement copy on hand.

Check the negatives carefully for proper size and for any defects before proceeding with the screen fabrication. The unused negatives should be placed in a clean envelope and stored for safekeeping. See Figure 6 for a picture of the negatives of the sample circuit.

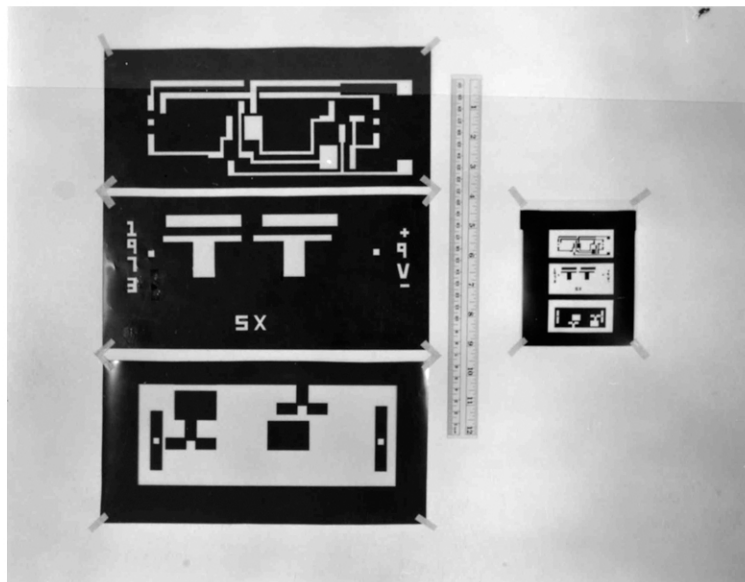


Figure 6. The master artwork and the negatives for the sample circuit.

2.8 SCREEN FABRICATION

Several types of screens are available for the "screen printing" of thick film circuits, depending on the type of frame used, the type of fabric used, and the type of photo emulsion used.

For a typical student laboratory project, a screen composed of a wooden frame, a sheet of plain weave 175-mesh monofilament polyester fabric, and an indirect photo emulsion will be used. For the advanced student project the screen will be composed of a metal frame, one of several sizes of plain weave monofilament polyester fabric, and a direct photo emulsion. In some extreme cases a stainless steel fabric will be used in place of the polyester fabric, but only as a last resort since it is more expensive and is more apt to suffer from abuse than polyester fabric.

Figure 7 shows a screen for a typical student project. The emulsion on this screen is an indirect emulsion called Ulanocron RX200*. Figure 8 shows a screen for the advanced student project, made with a direct emulsion called Azocol R**.

With either screen a cross section of the pattern on the screen should appear as shown in Figure 9. This figure shows the screen fabric with the emulsion buildup on the printing side of the fabric. This emulsion buildup is necessary if good prints are to be obtained, since it serves as a gasket for the paste during the printing operation.

*Reg. T.M. of the Ulano Companies.

**Reg. T.M. of Colonial Printing Ink Co.

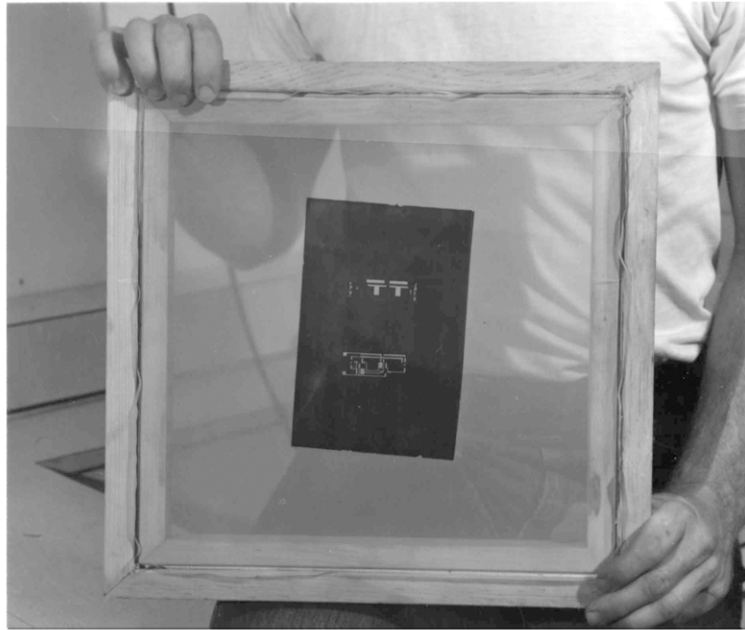


Figure 7. A typical printing screen composed of a wooden frame, 175-mesh polyester fabric, and an indirect photo emulsion.

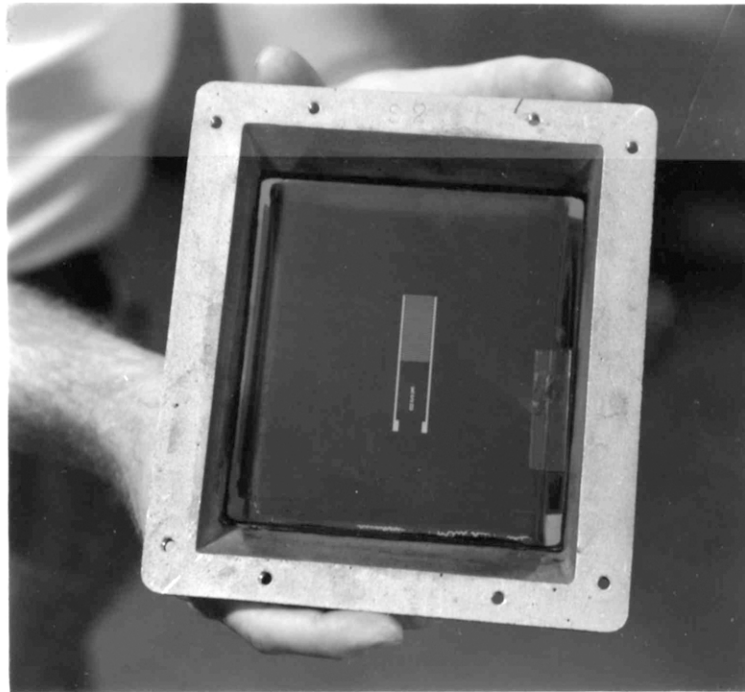


Figure 8. A typical printing screen composed of a metal frame, 175-mesh polyester fabric, and a direct photo emulsion.

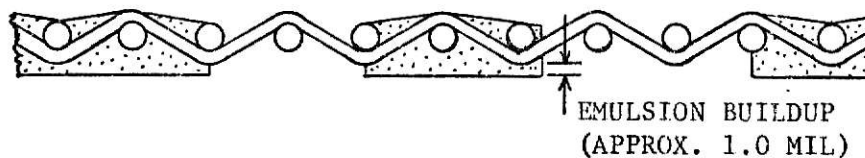


Figure 9. A cross-sectional view of a typical screen.

2.9 PRINTING THE THICK FILM CIRCUITS

This step is one of the most critical in the entire fabrication process. In order for all of the thick film circuits to have similar characteristics, and for all of the circuit elements to have approximately the same values (for similar circuit elements), all of the circuits must be printed identically. This requires that the printing be done very carefully.

In industry, thick film screen printing is done by machine so that the printing variables can be held as constant as possible. However, the printing can also be done by hand (manually), as in a student laboratory situation where a printing machine is not available. When the printing is done manually, careful attention must be paid to the precise location of the screen over the substrate, the angle-of-attack

of the squeegee during the printing stroke, and many other variables.

The first step in the screen printing process is to build a "nest" for the substrates that will be printed. The nest is just a small cavity fixed to the printing frame holder that locates each substrate, during printing, precisely with respect to the holder. The nest can be formed by placing several substrates around the one to be printed and taping them down with masking tape. A piece of double-sided tape can be placed in the bottom of the nest (if a vacuum chuck is not available) to hold each substrate in place as it is printed.

When the nest is finished, each substrate to be printed should fit easily into the nest with its top surface 3 to 5 mils higher than the sides of the nest.

The printing screen can now be positioned over the substrate to be printed by placing it against the three adjustment screws on the printing frame holder (assuming that the printing is to be done manually). The adjustment screws can be adjusted to position the pattern on the screen precisely over the substrate. See Figure 10 for a top view of the screen in place on the printing frame holder with the nest centered under the screen.

The next step is to place a small quantity of paste (about 1 teaspoonfull) on the screen and gently spread it over the pattern with the squeegee, without pressing down very hard on the squeegee as you spread the paste. This is

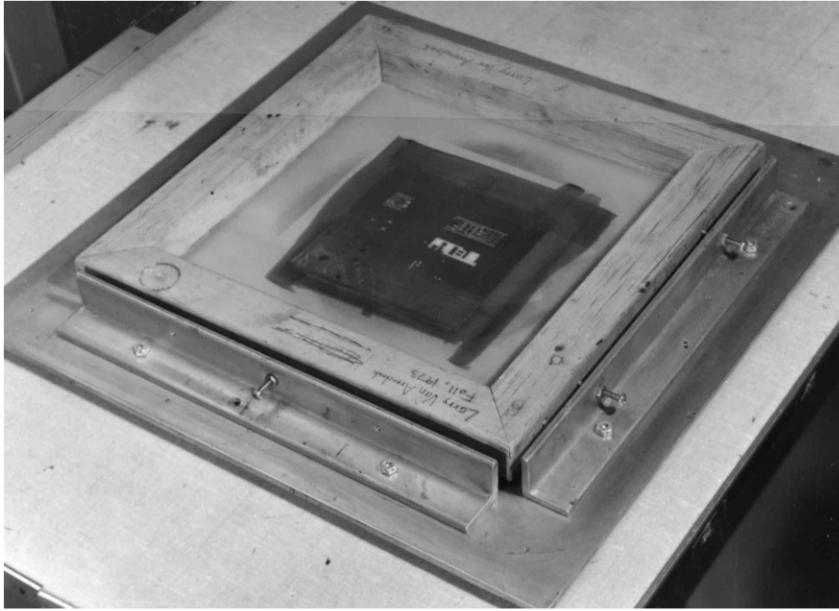


Figure 10. The printing screen positioned on the frame holder.

referred to as the flood stroke since the pattern is being covered (flooded) with this stroke of the squeegee. Once the pattern is covered with paste you are ready to print the first substrate.

Hold the squeegee firmly in your hand, tilt it at about a 45 degree angle in the direction it will move during the print stroke (toward you), press down on the squeegee until it touches the nest firmly, and then draw it smoothly across the pattern with a quick sweep of your hand. If the pattern printed properly you should notice that the paste was all removed from the pattern just as it snapped back up from the substrate immediately behind the squeegee. If the pattern did not print properly, you will have to practice until it does.

Immediately after the print stroke, re-flood the pattern

so that the paste will not dry out over the pattern or in it. See Figure 11 for a cross section of a typical manual printing setup during the print stroke.

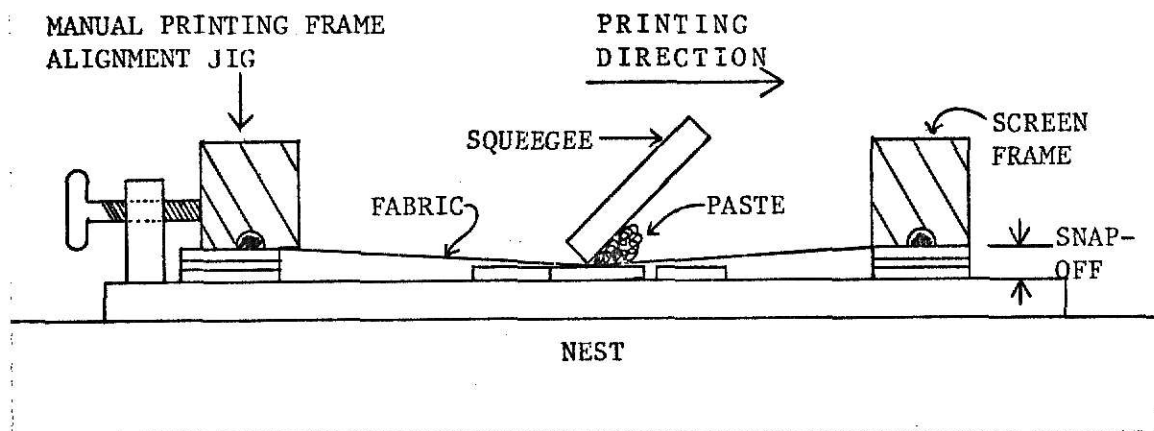


Figure 11. A typical manual printing setup.

Once each substrate has been printed it should be examined carefully with the aid of a microscope set at about 10X magnification, for possible imperfections in the print. Some minor defects are acceptable but if large ones occur, the substrate must be washed off with toluene and reprinted.

(Sometimes a faulty print can be corrected by placing a small drop of paste on the defective line with a small needle or toothpick.)

After examination, let each good printed substrate set at room temperature for about 10 minutes for the wet prints to level, and then dry them at a temperature of 100° to 125° C for 5 to 10 minutes. Once dry, the substrates can be stored in any clean dry place until they are fired.

2.10 FIRING THE THICK FILM CIRCUITS

The next step in the fabrication of thick film circuits is the firing of the printed substrates. Conductor firing schedules are not too critical but resistor firing schedules must be carefully controlled if the proper resistor characteristics are to be obtained.

Before firing the substrates be sure to check the temperature profile of the furnace. If it does not agree precisely with the profile suggested by the paste manufacturer it must be corrected before you proceed.

Once the conductors have been fired (according to their suggested schedule, or profile), the resistors can be printed and fired. For resistors, though, a sample of the print should be fired before all of the units are fired since the values of the resistors may not come out correctly the first time. If the values don't come out as they should, the remaining substrates will either have to be printed again with the same paste (double printed) or else they will have to be cleaned with toluene and printed with a different paste.

After all resistors have been fired, the overglaze can be printed and fired. Make sure that the furnace is set properly for overglaze firing since the overglaze firing temperature is usually much lower than the conductor and resistor firing temperatures. (The manufacturers specification sheets will tell you the proper firing times and temperatures for each of the thick film pastes that are used.)

Notice that no mention was made of dielectric prints such as those needed for crossovers or capacitors. If dielectrics are needed they should be printed and fired before the resistors are processed.

Once the overglaze has been fired the resistors are ready to be trimmed.

Figures 12, 13, and 14 show the sample circuit after the firing of the conductor, resistor, and overglaze prints, respectively.

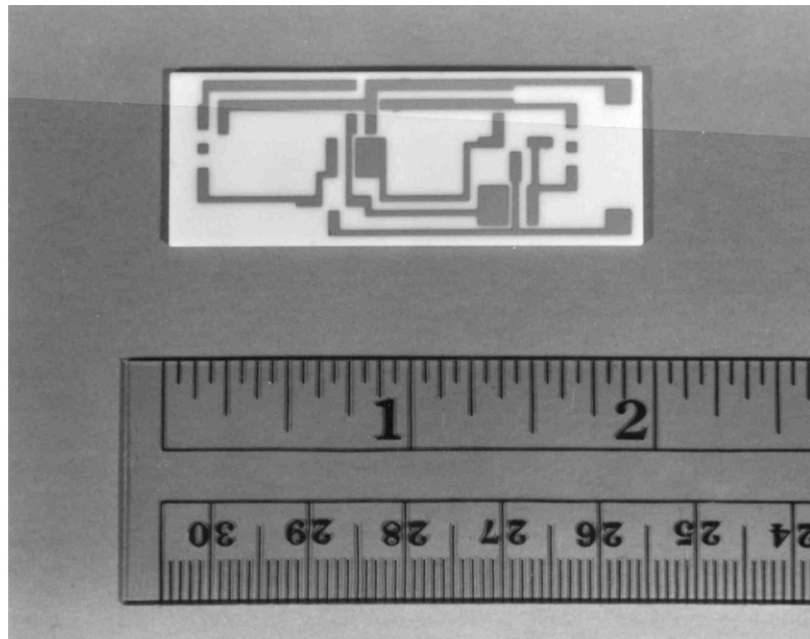


Figure 12. The fired conductor print.

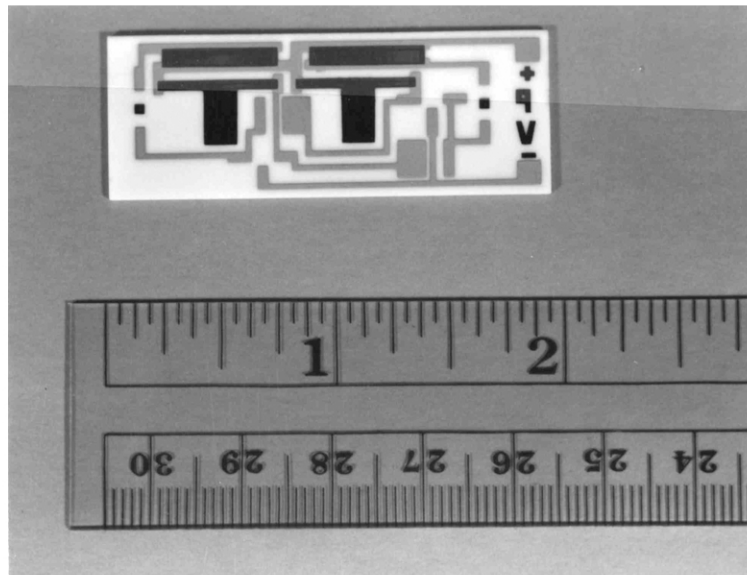


Figure 13. The fired resistor print.

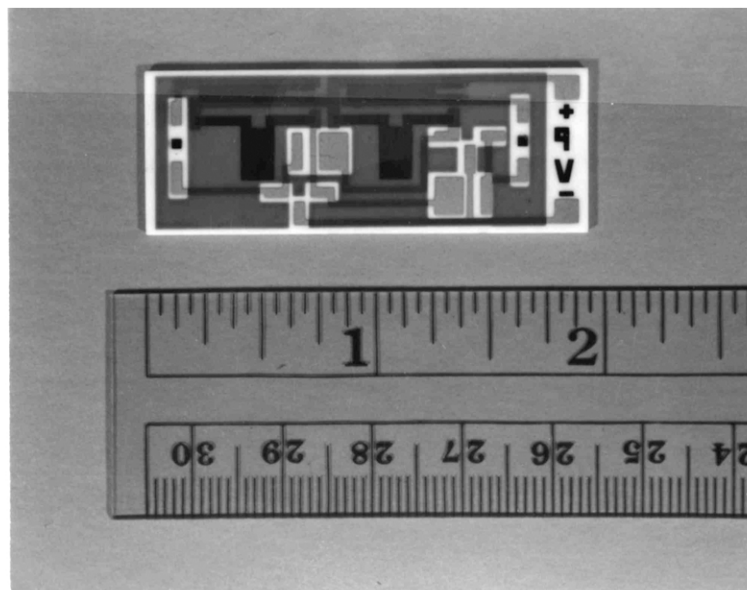


Figure 14. The finished substrate after the overglaze firing.

2.11 TRIMMING THE THICK FILM RESISTORS

Trimming a thick film resistor amounts to physically removing a portion of the resistor until its resistance value is increased to some desired value. There is no successful way to trim a thick film resistor to a lower value of resistance. The only way to go is up.

In the laboratory two successful trimming methods have been used: for the small laboratory a miniature grinding wheel mounted in an electric drill will work; however, a more desirable method is to use a small abrasive trimmer, which is just a sand blasting unit complete with an electronic bridge to monitor the resistor during trimming and to control the abrasive unit.

When the small grinder is used, the resistor's value must be monitored with an ohmmeter during the trimming operation. When the abrasive trimmer is used, the bridge on the trimming unit monitors the resistor's value and stops the process when the desired value is reached. See Figure 15 for a typical abrasive trimmer.

With the abrasive trimmer resistors can be adjusted to tolerances that are in the range of $\pm 0.1\%$, which is much better than is required for most thick film circuits.[8]

After all of the resistors have been trimmed and tested the circuits are ready to have the discrete components attached.

The resistors will appear as shown in Figure 16 after

they have all been properly trimmed.

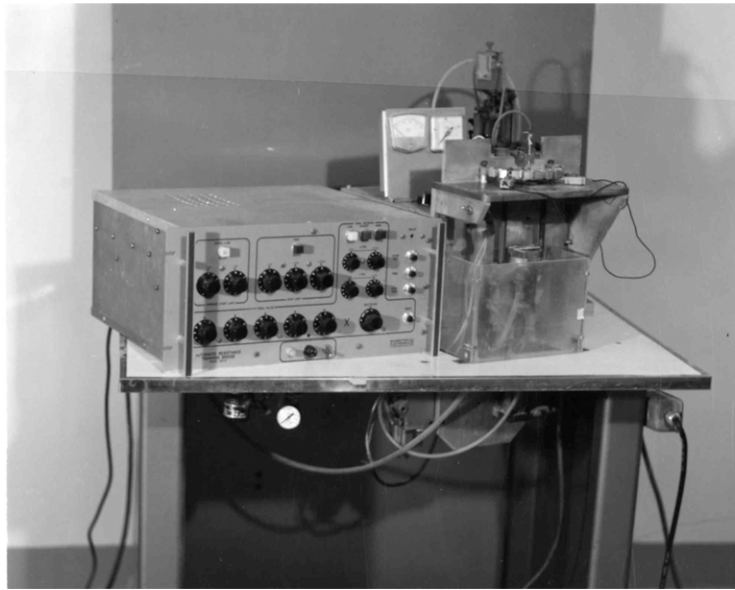


Figure 15. A typical abrasive trimmer.

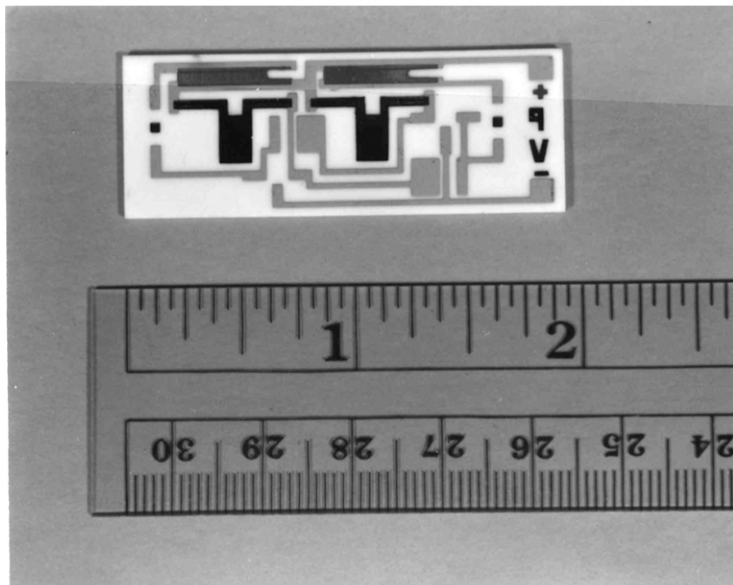


Figure 16. The sample circuit with properly trimmed resistors.

2.12 ATTACHMENT OF COMPONENTS AND LEADS

The discrete components must all be tested and found in good electrical and physical condition before preceeding. The components must then be positioned on the substrate for a trial fit. Some component leads may have to be bent or shortened before everything fits as planned.. The external leads should be placed in position at this time also. Since this is a very delicate part of the fabrication process it is recommended that the work be viewed through a microscope of 10 to 20 power magnification.

After it is seen that all components and leads will fit as planned, the solder paste can be placed on the appropriate solder pads. A layer of solder paste 5 to 6 mils thick should be sufficient. For most work either 60%Sn/40%Pb or 62%Sn/36%Pb/2%Ag solder paste should be used. Both of these solders melt at about 180 C and they work very well with silver bearing conductors.

The components can be placed carefully on the solder paste with the aid of a pair of tweezers. The tacky paste will hold the components in place until the solder is melted. Some external holding fixtures may be needed to keep the leads in place at this time.

The solder can be melted, or "re-flowed" by placing the substrate on a hot plate set at 200 C to 220 C for a period of 10 to 20 seconds. By the end of this time all of the solder paste should have melted and formed good solder fillets

around all of the component leads or solder terminals.

The substrates should then be cooled, cleaned in toluene, and examined closely with the aid of a microscope for any solder defects. Most defects can be patched successfully with a small soldering iron and a bit of rosin core solder. If extra rosin flux is available it should be used generously during the patch-up operation.

As an alternative, more solder paste can be placed on the defective area and it can be re-flowed as before, but the addition of heat to the whole substrate will tarnish the other solder joints unless they are protected by a coating of flux. Also, if the substrate is reheated too many times, or if it is heated for too long a time, the strength of all of the solder connections will be seriously reduced.

After final examination of the completed assembly, it should be cleaned in toluene once more to remove all traces of flux. See Figure 17 for the completed circuit. The circuit is now ready to be packaged and/or tested.

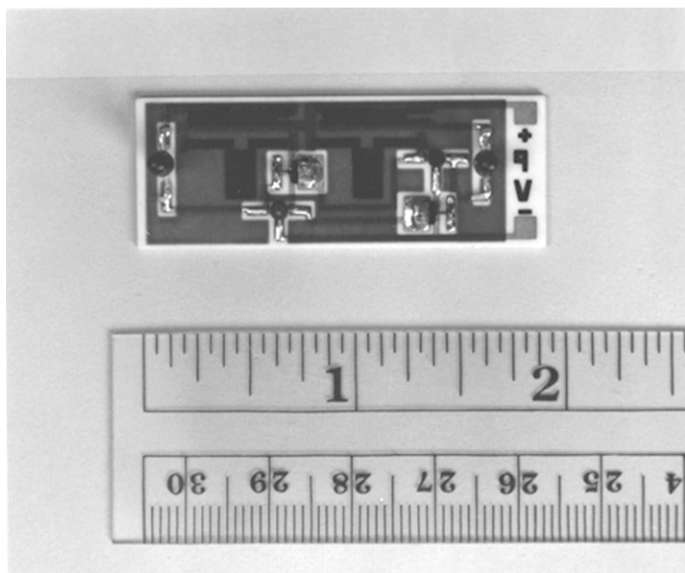


Figure 17. The assembled hybrid circuit before packaging.

2.13 PACKAGING THE HYBRID CIRCUIT

Since the package for the sample circuit was decided upon before the final layout was made we have merely to coat the circuit with the encapsulation material at this time.

In general, one of several package types may be used for a hybrid circuit. Many circuits are packaged by molding a plastic or epoxy case around them. Others are packaged by dipping them in liquid epoxy that coats them evenly on all sides. Still others are placed in previously-prepared cases. In all instances the purpose is to place the circuit in a protective case to exclude dirt and moisture.

The sample circuit, after being coated with the urethane coating, Solithane, appears as shown in Figure 18.

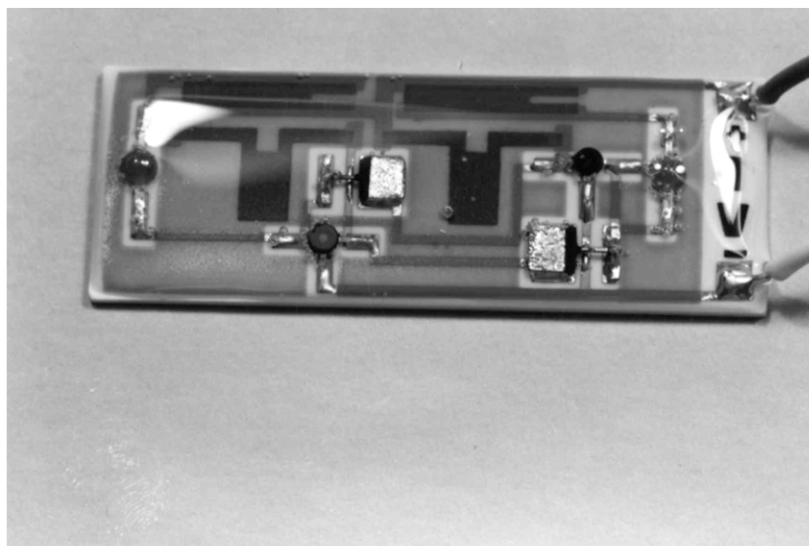


Figure 18. The hybrid circuit after encapsulating.

2.14 TESTING THE FINISHED CIRCUIT

Before a hybrid circuit can be used reliably in any application it must first be subjected to some operational and environmental tests. If possible the unit should be tested for an extended time period so that any defects will show up before it is placed into useful service.

Most tests should subject the circuit to conditions similar to those it will be operating under in its intended installation. Many commercially produced electronic circuits are tested according to specifications put out by military purchasing authorities. These specifications are referred to as Military Standards. MIL-STD-202D is the most common specification under which consumer-grade circuits are tested. MIL-STD-883 is a more rigid specification under which many high reliability microcircuits are tested. These specifications have been generally accepted by industry as being standard procedures with which to test electronic circuits.

Once the hybrid circuit has passed the necessary tests it is ready to be sold or placed in operation, whichever the case may be.

In the case of the sample circuit, the only requirement was that the two LEDs flash alternately off and on. However, if the output waveform shape and frequency of the multivibrator had been specified within certain limits, it could have been observed with an oscilloscope while the resistors were trimmed. This operation is called functional trimming and it is often used on hybrid microcircuits.

III. DETAILED EXPLANATIONS OF SOME OF THE MAJOR THICK FILM HYBRID CIRCUIT PROCESSES

3.1 PACKAGE SELECTION

3.1.1 GENERAL PACKAGE CONSIDERATIONS

Before the thick film circuit can be designed from the circuit's schematic diagram, the package that the finished hybrid circuit will be placed in must be chosen. The selection of a suitable package will depend on many factors, and it is your job, as the design engineer, to weigh each of the factors carefully and then choose the best possible package based on the facts you know about the circuit and its intended application. Some of the factors to consider are:

- A. The amount of room available for the finished circuit in its proposed installation.
- B. The amount of substrate area required for all of the circuit components.
- C. The type of environment that the circuit will be placed in.
- D. The cost of the finished circuit.
- E. The quantity of circuits to be fabricated.

This list can go on and on but you should now have some idea of the factors that must be considered before choosing the best package for the hybrid circuit.

The selection of a package can be somewhat simplified if we consider some of the guidelines that will be followed as the circuit is designed and fabricated. They are as follows:

- A. Resistors and conductors will be fabricated with thick film techniques.
- B. Capacitors will be of the miniature "chip" variety that are designed specifically for hybrid circuits, for values of capacitance less than 50 mfd., and will be discrete units for larger values.
- C. All active devices will be in their packaged forms just as they come from the various semiconductor manufacturers.
- D. Other devices will be selected from industry or else built specifically for each individual application.
- E. External leads will either be those that are standards for hybrid circuits, or else they will be made from small gauge tinned copper wire.

With these basic rules in mind we may proceed with the selection of a suitable package for the hybrid circuit.

The package selection problem should now appear a little simpler than it did at first! In most instances it can be simplified to two basic considerations:

1. The substrate area required for the hybrid circuit.
2. The kind of package that the circuit will occupy.

It should be understood that both of the above factors must be considered simultaneously since each one will have some influence on the other.

3.1.2 SELECTION OF THE THICK FILM SUBSTRATE

Since the size and number of circuit components that make up the hybrid circuit will determine the minimum size of the substrate, and hence the package size to be used, the first consideration in the design should be the substrate.

The best substrate materials to use for thick film hybrid circuits, or for any thick film circuits except possibly the lowest grade of consumer circuits, are either 95% or 96% alumina (Al_2O_3). Both of these materials have nearly the same properties necessary to the formation of high quality thick film circuits.

Alumina is used as a substrate material because it can be fired many times at high temperatures without changing its characteristics in any way. Also it has exceptionally good thermal conductivity, it is a very good electrical insulator, and it is relatively inexpensive to use.

One property of alumina substrates that must be watched carefully is the surface finish, which should be in the range of 25 to 50 microinches for thick film circuits. Most pastes are designed to work best on substrates with this surface finish. If substrates with different surface finishes are used, the properties of the circuit elements will not be optimum.

Most substrate manufacturers stock standard sizes of substrates and will usually sell small quantities of them at reasonable prices. Some standard substrate sizes that are

available from stock from most manufacturers are listed below in Table 2, which is repeated from page 12.

LENGTH	X	WIDTH	X	THICKNESS
.500		.500		.025
.750		.750		.025
1.000		1.000		.025
2.000		2.000		.025
(all dimensions in inches)				

Table 2. Standard substrate sizes.

If at all possible try to use a standard size substrate rather than one of your own design because the cost will be much lower.

3.1.3 SELECTION OF THE BEST PACKAGE OR PACKAGING TECHNIQUE

There are three basic package styles that can be used for the thick film hybrid circuit. They are as follows:

1. A prefabricated metal, metal-and-glass, epoxy, or plastic box or container, that the circuit can be soldered or glued into and then sealed from the environment.
2. Solid epoxy or plastic molded packages that are formed around the circuit.
3. Conformal coatings which are formed by dipping the circuit into a liquid coating material that conforms to the surface contour of the components on the substrate.

3.1.3.1 PREFABRICATED PACKAGES

There is a large number and variety of hybrid circuit packages on the market today. Some of the different kinds are as follows:

1. Round, metal cans with separate lids that must be soldered or welded in place after the circuit is placed in the can.
2. Metal and glass packages in the Dual-In-Line configuration, that are designed specifically for good hermetic seals once the circuit is placed in the package and the lid is welded.
3. Molded plastic or epoxy packages that are designed for consumer grade circuits that do not need to have a military grade hermetic seal from the environment.

With any of these packages, the circuit must be soldered or epoxied into the package and then the connections to the external package leads must be made. Sometimes the external leads act as mechanical supports for the circuit (inside the package) and they need only to be soldered directly to the hybrid circuit. The final step is to attach the lid to the package, either with solder, by welding it in place, or by fastening it in place with epoxy.

In addition to the packages mentioned above, there are countless other special packages that are used for hybrid circuits; however, many of them are special packages designed

by hybrid circuit manufacturers and they are not available on the open market. [16]

See Figure 19 for examples of some of the different kinds of prefabricated circuit packages.

3.1.3.2 SOLID MOLDED PACKAGES

On high volume production lines where many circuits of one particular design are built, a standard package is usually chosen for a particular circuit and then a mold is designed for the package. The circuits are then attached to their leads and placed in the mold. Either plastic or epoxy is forced into the mold and the circuits emerge from the mold as completely packaged units. Examples of molded packages are the common plastic transistors (TO-92) and many of the common 14 and 16 pin integrated circuits (TO-114 and TO-116).

Molds are not usually used on low volumes of parts since they are very expensive. However, molded packages have the advantage of being a standard size with very tight dimensional tolerances. Also, they are very eye-appealing with their smooth sides and well formed corners.

One precaution that must be taken when hybrid circuits have packages molded around them is that the molding compound must not have thermal expansion characteristics that vary drastically from the circuit that it encases. If this is the case, then the molded package will usually not pass very many demanding environmental tests and it will often fail in use if it is subjected to a changing environment.

See Figure 19 for examples of some molded packages.

3.1.3.3 CONFORMAL COATINGS

One of the easiest ways to package a hybrid circuit is to dip it in a coating material that will cover the entire circuit with a strong, moistureproof coating. This method of sealing the circuit from the environment is known as conformal coating, because the coating conforms to the contour of the circuit beneath it.

The conformal coating method of packaging is very attractive because it is a very simple process to use; and since it is simple it is also inexpensive. (For instance, a circuit that is 1 inch square can usually be coated for less than 5¢, including labor!)

To conformally coat a hybrid circuit, all you need to do is obtain a container of the desired coating material and dip the circuit into the material while holding it by its leads. Or else you can place a few drops of the coating material on the circuit with a spatula and let it flow evenly over the entire circuit. Once the circuit has been coated the excess material should be allowed to drip off, and then the circuit should be placed out of the way until the coating cures.

Three types of materials that can be used for conformal coatings are:

1. Silicone rubber compounds
2. Urethane compounds
3. Epoxy compounds

The silicon rubber compounds are usually very flexible but not very tough or durable. Many of them are clear in color and the circuit can be easily seen through them.

The urethane compounds are similar to the silicone rubber compounds in flexibility, but they are much tougher. Also, they adhere to most substrate materials and to the circuit components much better than the silicone rubber compounds. Most urethanes are straw coloured but transparent so that the circuit can be easily seen through them.

Epoxies come in a wide range of hardnesses, varying from very flexible to very brittle, and in a wide range of colours, from clear to black. Epoxies adhere exceptionally well to just about anything and they form a very tough, moistureproof coating for all kinds of things, including hybrid circuits.

Most of the above coating compounds come from the manufacturer as two-part systems, the resin and the catalyst, and they must be mixed together in certain proportions before they will cure to their final form. Once the catalyst has been added to the resin, the mixture will begin to slowly harden. The curing process usually takes several hours at room temperature but at elevated temperatures it can be greatly speeded up. The manufacturer will usually provide a chart of time versus temperature for the curing of the coating material that you want to use.

See Figure 19 for examples of some circuits that have been packaged with a conformal coating.

3.1.4 STANDARDIZATION OF THE PACKAGE

With any package style, you should first try to fit the hybrid circuit into a package whose dimensions are considered standard in the electronics industry. You can find examples of standard packages for electronic circuits in most of the semiconductor data books published by semiconductor manufacturers, such as Motorola and Signetics.

Although some manufacturers place their own number designations on the packages they use, most of them fall within the dimensional outlines for the packages as they have been established by the Electronics Industry Association (EIA). The EIA is one of the organizations that has been instrumental in the establishment of standard dimensions for many commonly used electronic circuit packages. See Figure 19.

Some advantages of using industry standard packages are that they will fit standard circuit board patterns, they can be plugged into standard sockets and connectors, and they can be handled by standardized parts-handling equipment.

If you cannot fit the circuit into one of the standard packages then you must design your own package, while trying to use as many industry standard features as possible. It should be obvious to you that it will be less costly to use standardized parts in your design whenever possible, rather than having everything made exactly to your own specifications, since standard parts are nearly always cheaper and easier to obtain than are special parts.

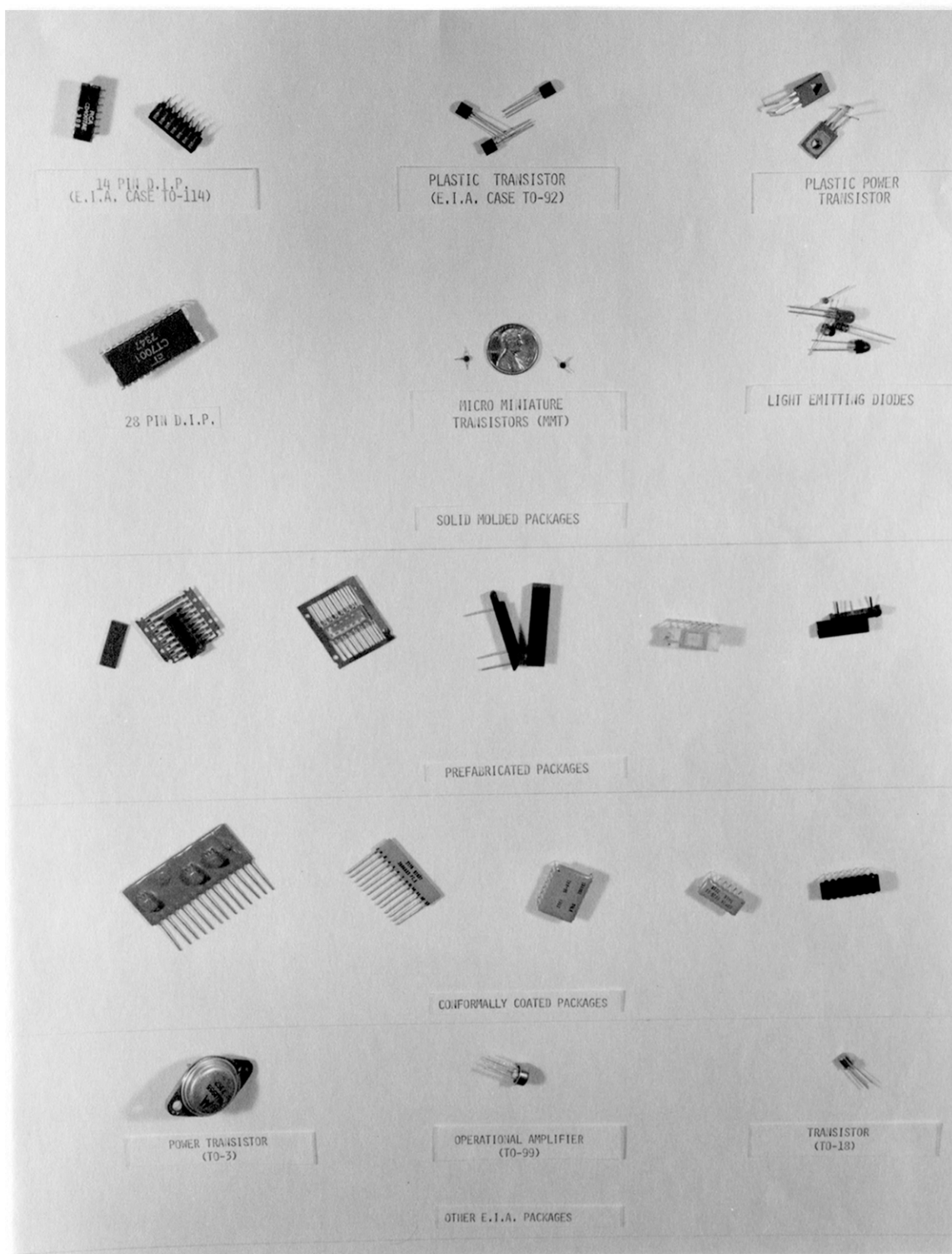


Figure 19. Examples of different packages for hybrid circuits, including some industry standard packages.

3.2 CIRCUIT LAYOUT AND DESIGN GUIDELINES

3.2.1 THE CIRCUIT LAYOUT IN GENERAL

In the normal thick film fabrication process the circuits are usually drawn on sheets of drawing paper and they must be transferred to the printing screens before they can be fabricated using the process of screen printing.

On the drawing paper, the circuits are usually drawn to a size that is larger than the final circuit. The large size of these layout drawings allows the designer to make patterns of considerable complexity and of high accuracy. (The accuracy of the layout drawings should be on the order of ten times better than the desired accuracy of the finished circuit, for typical circuits.) Typically, the more complex the circuit, the larger the drawings should be, so that the accuracy of the drawings can be retained.

For most thick film circuits a layout size of 5 to 10 times the normal size is usually sufficient. Larger sizes can be used but since the thick film process can only yield component tolerances on the order of $\pm 10\%$ under normal processing conditions, more accuracy for the layout (as would be obtained with a larger layout) is usually not necessary.

The following design guidelines list general steps to follow in the design of typical low frequency (generally less than 10 MHz) thick film hybrid circuits.

3.2.2 GUIDELINES FOR THE DESIGN OF THICK FILM HYBRID CIRCUITS

Make some preliminary sketches of the proposed circuit layout. Many items, such as component sizes, resistor sizes, and conductor sizes must be considered before the final layout is completed. You should not expect to make a perfect layout on the first attempt!

3.2.3 DESIGN AND LAYOUT OF CONDUCTOR PATTERNS

The following items are the general ideas that must be considered during the layout of conductor patterns.

1. Selection of a conductor composition depends on many things, including the intended use of the proposed hybrid circuit, the metal used in the conductor composition, the performance characteristics of the composition, and even the price of the composition. The manufacturer's specification sheet must be studied carefully before the proper conductor composition is chosen for each application.
2. Do not design conductors that are either larger than necessary or smaller than practical. Line widths in the range of 15 to 20 mils can be printed with little or no difficulty. Finer lines will be harder to print since lint and dust will collect on the screen during printing and cause incomplete prints on the substrate. Larger lines are usually not necessary because the magnitudes of the currents and voltages encountered in most hybrid circuits are quite small. Also, larger lines require more material than do smaller lines and hence they cost more.

3. Conductor paths should be designed as straight lines that are parallel to the X or Y axis. Also, all corners should be designed as right angle corners. In general, angled lines and round corners require the designer to spend more time than would otherwise be necessary on the final layout. See Figure 20.

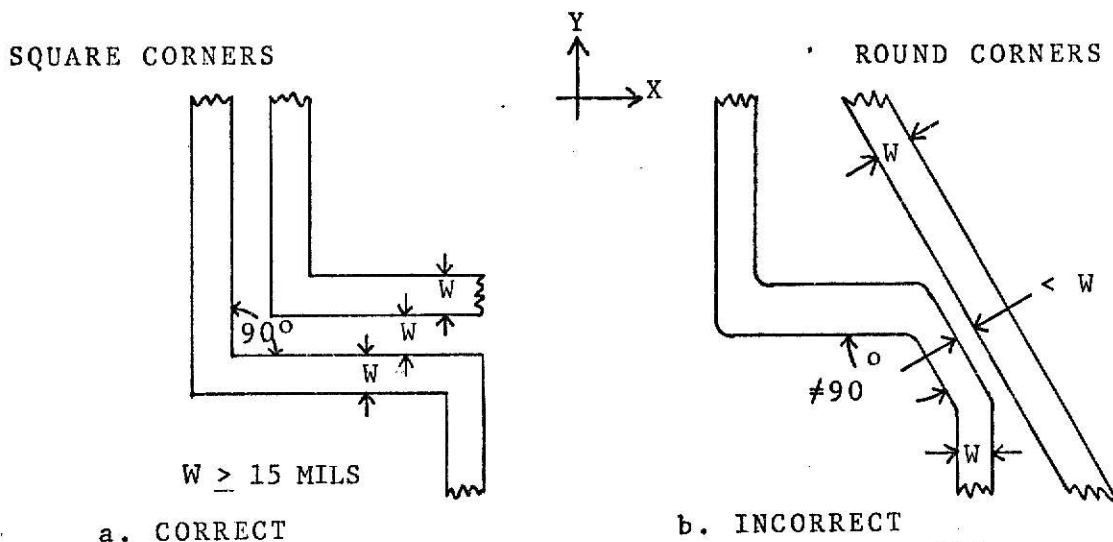


Figure 20. Conductor orientation and size.

4. Do not place conductors too close to the edges of the substrate. Substrates are not all the same size and the designer must take this into consideration. Also, substrates are often very irregular along their edges and a conductor printed there would not always be acceptable. If conductors are placed at least 5 mils from each edge of the substrate (assuming the nominal substrate size as the standard size to be encountered) the resulting prints will usually be acceptable.

5. Conductors that connect to resistors must be larger than the resistors at the point of overlap. Otherwise, when the resistors are printed they will sometimes not touch both conductors and they will then appear as open circuits. At the overlap area the conductors should be 20 mils wider than the resistors and the resistors should lap over the conductors by 10 mils on each end. See Figure 21.

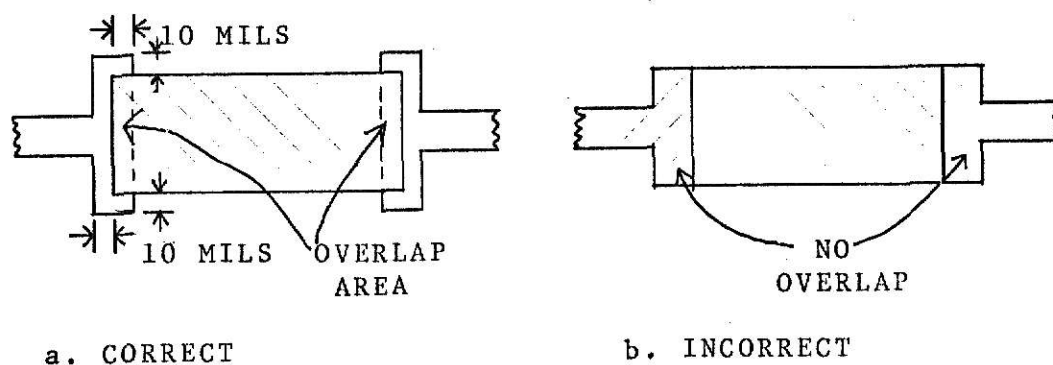


Figure 21. Proper conductor-resistor overlap.

6. Conductor pads for mounting discrete components must be designed slightly larger than the component leads or solder tabs that will be attached to them. A good rule of thumb is to design the pads 20 mils wider and longer than the lead or tab to be mounted to them. Also, as in the case of chip capacitors, the pads must be designed to accept the full range of possible capacitor electrode sizes. See Figure 22.
7. Solder pads for external leads must be designed to provide adequate lead strength for the hybrid circuit. As a general rule thick film conductors have a strength of 5 to 10 pounds

for a pad that measures 80 mils on a side, when subjected to a peeling force perpendicular to the solder pad. In general the pads should be at least 20 mils wider than the lead (if it is flat) and at least 50 mils long. For round leads the pads should be two to three times the lead diameter, in width, and again at least 50 mils long.

The most common error that the novice designer makes is to design the external lead attachment pads too small. Always design the external lead attachment pads a little larger than what appears adequate if you are not sure just how much strength the conductor composition has. See Figure 23.

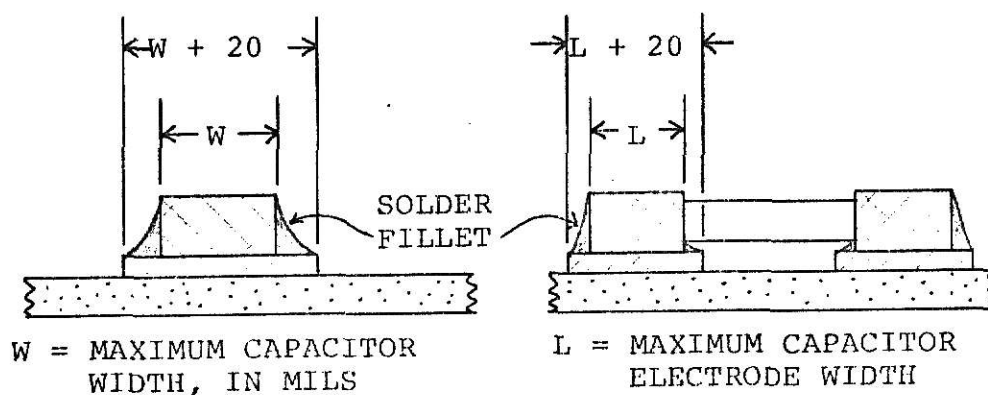


Figure 22. Discrete component solder pads.

(DIMENSIONS IN MILS)

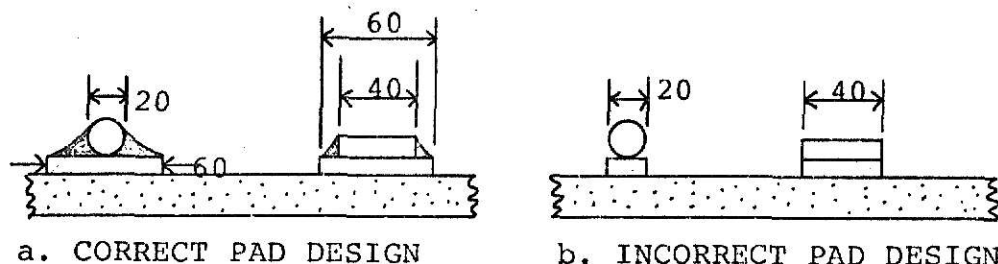


Figure 23. Lead attachment solder pads.

8. Place at least two alignment dots or other distinguishing marks on the conductor pattern at opposite ends of the layout. These will be common to every pattern printed on the hybrid circuit and will be used for the precise alignment of the pattern during printing.

3.2.4 DESIGN AND LAYOUT OF RESISTOR PATTERNS

1. The selection of a suitable thick film resistor composition is probably the most important step in the design of a thick film hybrid circuit! The manufacturer's specification sheet is a valuable source of information but one must be very careful not to misinterpret the data. The information on the data sheets should not be assumed to be absolutely correct in every case, but rather one should assume that the data sheets indicate general trends and typical performance characteristics of the resistor compositions.

Some desirable properties of a good resistor composition are relative insensitivity to processing variables, a wide range of available sheet resistivities, low TCR, and moderate price.

2. Resistors should be designed so that their power dissipation is limited to 20 watts per square inch of resistor area.
3. Resistors should be designed so that their sides parallel the X or Y axis. Zigzag or serpentine resistor patterns should be avoided if possible. See Figure 24.

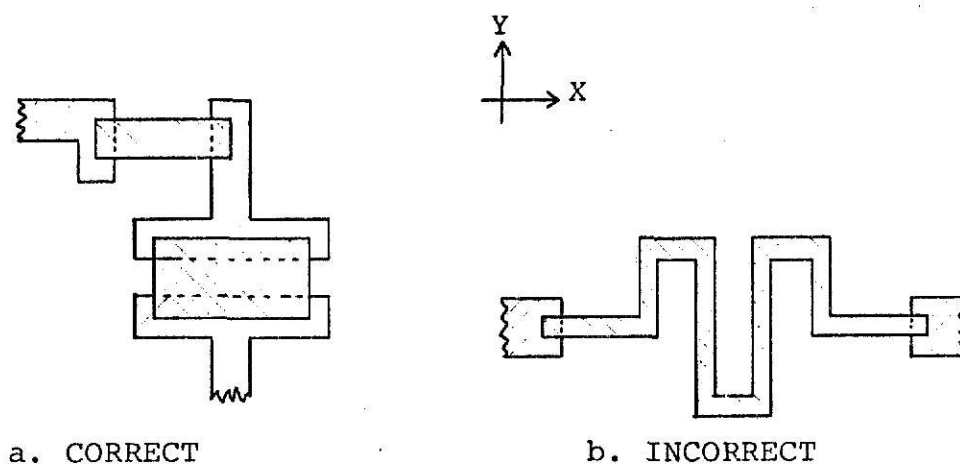


Figure 24. Resistor geometry and orientation.

4. Most resistor patterns are classified according to their geometry into one of the following three groups:
 - a) The Forward Ratio design, in which case the resistor's length is equal-to or greater-than its width. The typical range of values for the aspect ratio of this design is $1.0 \leq L/W \leq 5.0$. See Figure 25.
 - b) The Inverse Ratio design, in which case the resistor's length is less than its width. The typical range of values

for the aspect ratio of this design is $0.2 \leq L/W < 1.0$.
See Figure 26.

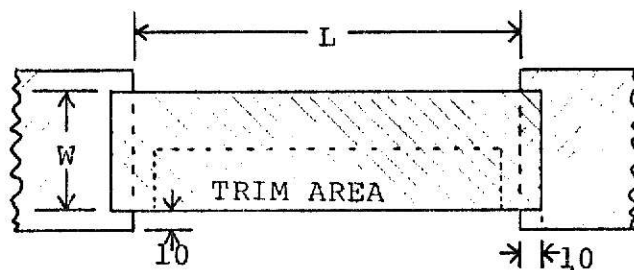


Figure 25. Design of the Forward Ratio resistor.

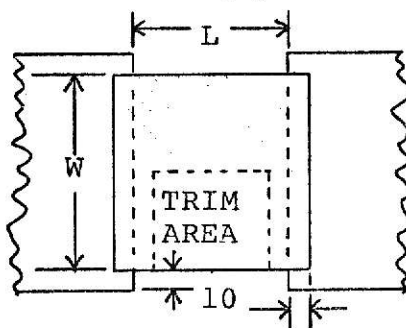


Figure 26. Design of the Inverse Ratio resistor.

Note: When design (a) or (b) is used the value of the resistor is calculated from the formula: $R(\Omega) = \rho(\Omega/\square) \times L/W(\square)$. In words this formula reads: Resistance (in ohms) equals the ink sheet resistivity (in ohms-per-square) times the resistor's aspect ratio (L/W) in the unitless quantity "square".

c) The High Gain design, in which case the resistor resembles a "Top-Hat". This design is used when an aspect ratio much greater than 5 is required. There are two similar "Top-Hat" designs, as shown in Figure 27.

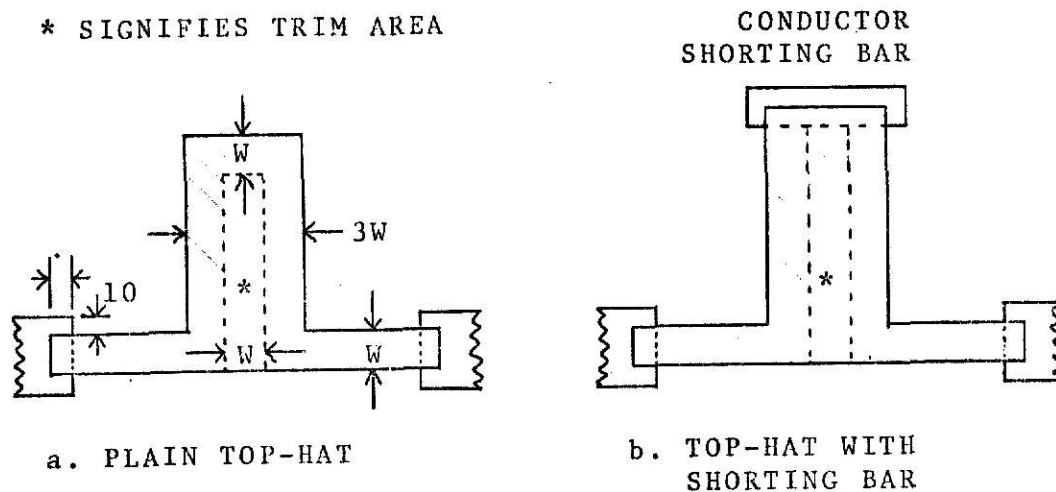


Figure 27. Design of the High-Gain or "Top-Hat" resistor.

The aspect ratio of the "Top-Hat" resistor can be increased by 5 times or more by trimming, if the resistor is designed properly. This is not possible with the other two designs, in which the aspect ratios should not be increased by more than a factor of 2 by trimming. For those designs the power dissipation will be increased to 40 watts per square inch if the aspect ratio is doubled by trimming and this is considered to be the maximum limit for typical thick film resistor materials if long time stability is important. For the "Top-Hat" design the designer should again base the size of the resistor on the figure of 20 watts per square inch and realize that the actual surface area of the resistor will never be doubled even when the resistor is trimmed to the maximum.

typical range of resistor values obtained during printing and allow for the maximum number of good parts from a particular printing.

6. Resistors should overlap conductors by at least 10 mils at each termination and they should be 20 mils narrower than the conductor termination pad. See Figures 21, 25, 26, and 28.
7. The minimum dimension for a resistor, whether it be length or width, should be 50 mils. Smaller sizes create reproduceability, target value, and other problems.
8. Closed resistor loops should be avoided since the resistors in the loop will be difficult to trim without expensive trimming equipment. Instead, the loop should be designed with a break in it. The break can later be closed with a small solder bridge. See Figure 29.

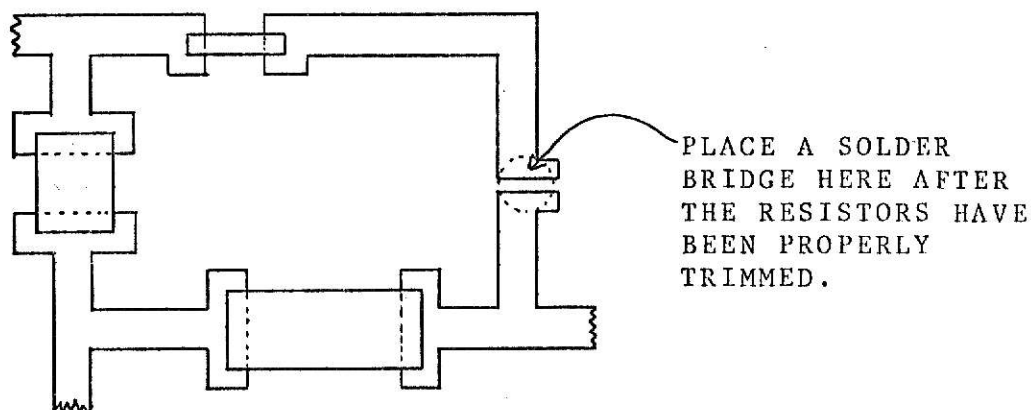


Figure 29. A properly designed resistor loop.

3.2.5 PROTECTIVE RESISTOR OVERGLAZES

1. Resistor overglazes are usually used to provide a transparent, air tight seal over the resistors and even over some conductors on the thick film substrate. Resistor overglazes come in a variety of colors and can also be used for color coding various circuits. The manufacturer's specification sheet will supply all of the important information about the overglaze selected.
2. The resistor pattern can be used for the overglaze print if desired, or a separate pattern can be designed to cover as much of the substrate as desired.

3.2.6 CROSSOVER DIELECTRICS AND MULTI-LAYER PRINTS

1. Select a dielectric that is compatible with the conductor composition being used and also be sure it will work for the kind and number of crossover layers required. The manufacturer's specification sheet will tell exactly what the dielectric can be used for.
2. For single layer crossovers the dielectric layer should be 40 mils greater in length and width (if possible) than the conductors. See Figure 30.
3. For multi-layer prints, each successive layer should have openings, or windows, wherever connections from layer to layer are required. Openings should be as large as possible for printing ease, but not so large that conductors on adjacent layers can short together. Since multi-layer

prints are usually very compact it is hard to specify exact line widths and spacings. In general though, the same line widths and spacings should be used on multi-layer prints as are used on regular prints. A good rule of thumb is to keep conductor lines on upper layers at least 10 mils from the edge of the dielectric layer underneath.

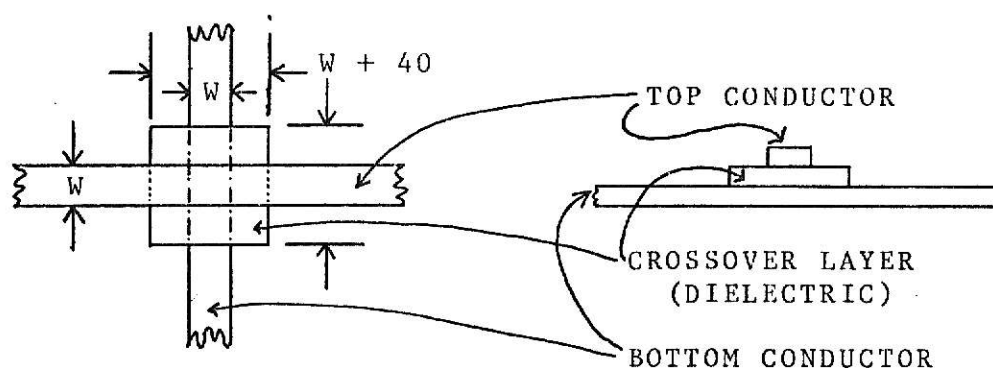


Figure 30. A typical crossover layout.

3.2.7 SUMMARY OF THICK FILM HYBRID CIRCUIT LAYOUT GUIDELINES

1. Check the manufacturer's specification sheet for each material to be used in the fabrication of the hybrid circuit before starting the design.
2. Develop a plan of attack for the design and then proceed in the most logical manner, using the design guidelines as just that; guidelines. You will probably never be able to design the circuit exactly as the guidelines suggest because they are too general. They are only intended to point you in the right direction.

3. Place alignment dots or other identifying marks on the final layout so that they will be common to each pattern designed.

3.2.8 ADDITIONAL SUGGESTIONS

1. Draw a title block on the layout and place in it as much information as is necessary for future reference.
2. Shade or color all patterns that will be printed with each thick film composition and attach a legend that identifies each pattern, the composition to be used, and when each pattern should be printed.
3. Draw the final layout on good quality graph paper that has some multiple of 5 or 10 divisions to the inch.
4. Somewhere on the layout draw the number signifying the reduction size of the layout, such as 5X.

3.3 GENERATION OF THE MASTER ARTWORK

3.3.1 CUTTING THE MASTER ARTWORK (OR RUBYLITH)

Once the layout drawings have been completed, the circuit patterns must be transferred to some material that can be easily photographed. The master artwork is the medium used to transfer the layout patterns into high contrast pictures that can be easily photographed.

The master artwork is produced on one of two materials; Rubylith* or Amberlith*. These materials both consist of a lamination of two materials, a thick back layer of clear polyester sheeting and a thin top layer of a colored film. The top

*Reg. T.M. of the Ulano Companies.

film is colored red for Rubylith and amber for Amberlith. With either material the thin top film may be easily cut and peeled from the thick back sheet to produce any desired pattern of clear openings on a red (or amber) field or red (or amber) images on a clear field. From now on the reader may assume either Rubylith or Amberlith whenever Rubylith is mentioned since for most work they are equivalent. Rubylith is advertised as being slightly more light-safe than Amberlith while Amberlith is advertised as being slightly easier to see through than Rubylith.[11]

The equipment required for the production (or "cutting") of top quality artwork is quite minimal! A smooth desk or table top, a good ruler or straight edge, a good cutting tool, and a pair of fine pointed tweezers are all that is needed.

It has been found that a clear plastic ruler or straight edge works better than an opaque one since the layout can be viewed through the clear plastic. For a cutting tool, any kind of X-Acto* knife can be used but a steel needle, such as a dissecting needle, an old fashioned phonograph needle, or a straight hat pin works exceptionally well. The needle can be placed in a wooden holder or it can be loaded into a mechanical pencil, such as a Pentel** writing pencil or an Alvin***drafting pencil. In any case, the resulting cutting tool is excellent for cutting Rubylith and it represents a small monetary investment to the user. Replacement needles are seldom needed since

*Reg. T.M.

**Reg. T.M.

*** Reg. T.M.

the needle can be easily resharpened on a small whetstone or even on an alumina substrate.

The process of cutting the Rubylith is as follows:

Locate a suitable desk or table and place a thick sheet of white paper on the flat surface. The paper should be a little smaller than the layout drawing. Use masking tape to secure the layout drawing to the surface, with the white paper centered under the drawing. The white paper will add contrast to the lines on the layout and make them easier to see through the Rubylith. Tape a sheet of Rubylith down over the layout drawing with the red film up. (You may have to scratch a corner of the sheet to see which side is the red side.) In general, the Rubylith sheet should be 1 to 2 inches larger than the layout drawing so that an ample boarder will remain beyond the patterns cut out. Usually it is most convenient to use sheets of Rubylith that are all the same size. They are then easy to handle and to file away without losing.

Starting with the conductor pattern, place the ruler on the Rubylith and line it up with the line to be cut. If a good desk lamp is available you should adjust it so that the lines on the layout are clearly visible and shadows from the ruler are minimized.

Place the cutting tool against the ruler and with firm pressure on the tool make a smooth cut the full length of the line to be cut out. The cutting edge of the tool should have an angle-of-attack in the direction of the cut of about 30 degrees to make a good cut. If the tool is held nearly

perpendicular it will not cut very well, and in the case of a needle, it will tend to tear the Rubylith film and make a ragged cut. See Figure 31.

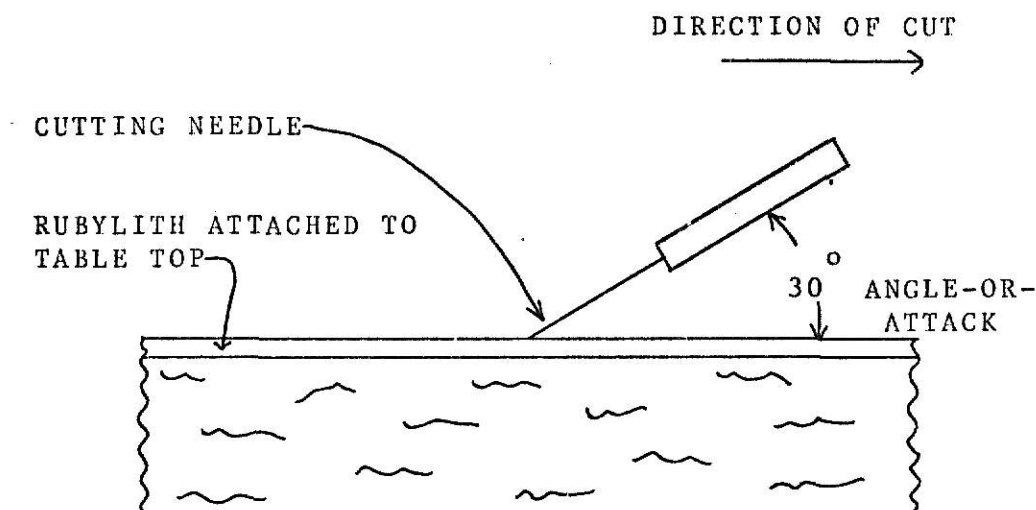


Figure 31. Proper angle-of-attack of the cutting tool.

Once each line is cut it can be removed from the sheet by peeling it off with a pair of tweezers. However, be sure that you want to end up with a sheet of artwork which has clear openings on a red field before you hastily peel the patterns off. In some cases you will need a clear field with red patterns left on the sheet and you must be familiar with the rest of the photographic processes involved in the thick film fabrication process before you proceed with confidence.

If a line is over-cut you can usually rub it with your finger and push the red film back together, or you can place a small scrap of red film over the cut and press it firmly down until it stays in place. You can also easily replace lines that were cut and removed by accident in the same manner.

The red film has a mild adhesive on it and it will usually stick to the clean polyester or even to itself quite easily.

Each succeeding pattern to be printed on the final thick film circuit must be cut in the same way. After each pattern has been cut out and all of the cut pieces of film have been peeled off, you should place the patterns, one at a time, on the circuit layout and check to make sure that all of them fit properly. If any errors are evident they must be corrected.

As a final note you should be sure that each Rubylith pattern contains alignment dots that are common to all patterns, and that all of the alignment dots coincide when the patterns are lined up properly over the layout drawing. Also, each Rubylith pattern should contain a cut-out stating the size of the pattern with respect to the final size of the circuit, and the part number or name of the circuit.

After the Rubylith patterns have all been cut and checked for accuracy you should obtain a large envelope and place the finished artwork in the envelope. The envelope will protect the artwork from being scratched or otherwise damaged. The envelope should be marked to identify the contents and then it should be filed in a safe place until the photographs are to be taken of the artwork.

3.3.2 RUBYLITH PATTERNS-----POSITIVES OR NEGATIVES

The choice of whether to produce Rubylith patterns that are positives of the circuit layout (red images on a clear

field) or negative (clear openings on a red field) will depend on several things. The determining factors are:

- A. The type of photo emulsion used on the printing screen (i.e., negative or positive emulsion).
- B. The type of film used in the photographic process (i.e., negative or positive film).
- C. The maximum reduction capability of the photographic system.
- D. The size of the artwork to be photographed.

The emulsion used on the printing screens will be a negative emulsion; that is, the image obtained on the emulsion will be the opposite (the negative) of the pattern used to produce the image. The emulsions to be used are Blue Poly*, Ulanocron RX200*, which are both indirect emulsions, and Azocol R**, which is a direct emulsion. These are all negative emulsions. Other positive and negative emulsions are also available but they will not be discussed here. These emulsions have been found to give excellent results when used properly.

The Film, from Kodak, is a negative, high contrast, graphic arts film.

The maximum reduction capability of the photographic system will depend on the camera used and the size of the darkroom. For the sake of argument the maximum reduction capability will be assumed to be 10X.

After considering the above factors you can easily determine which Rubylith pattern to produce; negative or positive.

*Reg. T.M. of the Ulano Companies.

**Reg. T.M. of Colonial Printing Ink Co.

For example, if the artwork is cut 10X, the reduction can be done in one photographic step and the Rubylith patterns must therefore consist of clear openings on a red field.

If the artwork is cut 20X the reduction must be done in two steps, since the maximum possible reduction in one step is 10X. To get a 20X reduction the common procedure is to take a 5X reduction and then take a 4X reduction of the first reduction. In this example the Rubylith patterns would have to be red images on a clear field. In both examples it must be realized that the final photograph (often called a negative) must consist of a black image on a clear field.

3.3.3 MORE SOPHISTICATED ARTWORK CUTTING METHODS

The preceding method for cutting the master artwork is the simplest method that can be used. Other methods also exist but usually additional equipment is needed, which often costs a lot of money.

A big improvement can be made in the Rubylith cutting operation if a light table is available. A light table consists of a translucent glass top, a sturdy frame, and a light source below the glass top. The layout drawing and the Rubylith are taped to the glass top, as explained earlier for the table or desk top. However, the light coming through the glass top greatly improves the legibility of the lines on the layout so that the Rubylith can be cut with much less eye-strain.

The next step up in the Rubylith cutting operation is to use a coordinatograph to cut the patterns. The coordinatograph is a light table with a cutting blade suspended over the table top on a precision X-Y track. The blade can be operated manually or by remote computer control (in the case of the real expensive models) to cut extremely long, parallel lines of very exact widths on the Rubylith film. For thick film hybrid circuits this kind of a device is usually not required since extreme pattern accuracy is not of paramount importance. A coordinatograph is also an expensive device and therefore gives way to a less expensive cutting method, such as that mentioned earlier. The coordinatograph is usually used mostly for cutting the master artwork for silicon integrated circuits.

3.4 THE THICK FILM PHOTOGRAPHIC SYSTEM

3.4.1 GENERAL REQUIREMENTS FOR THE PHOTOGRAPHIC SYSTEM

The photographic system used for the reduction of the master artwork must be capable of producing a high contrast negative (or positive) of the original artwork without distorting it. However, the system does not have to be extremely expensive if the system components are selected carefully.

The heart of the photographic system is the camera lens. It must be designed for copying high contrast artwork. This type of lens is often referred to as a "flat copy" lens since it is designed for copying two dimensional images.

The camera is also an important part of the system but it does not have to be very expensive so long as it provides the necessary focus and alignment adjustments. It should also have a translucent viewing plate in the back so that the pattern size and focus can be checked before the film is exposed.

The film used for artwork reduction must be a high contrast stable base film that has a wide exposure latitude and essentially no gray scale. Quite a variety of graphic arts film is available for just this kind of photography, from Eastman Kodak Company.

The other darkroom facilities will vary depending on the sophistication of the darkroom but most of them may be obtained from any photographic store. Literature is also available from Eastman Kodak concerning just about any application of photography to electronics that a person might be interested in.

3.4.2 A SIMPLE PHOTO REDUCTION SYSTEM

For the beginning thick film laboratory almost any kind of camera can be used if it will produce negatives that are large enough for the desired thick film circuits and if it does not distort the artwork too badly.

A 35mm camera will work very well for artwork reduction in most cases but because the film is small the negatives must usually be enlarged to the desired size after the reduction is made. (Notice that this method produces a positive of the

original artwork because of the two photographic steps involved, so the master artwork must be cut accordingly.)

Some people have even experimented with a Polaroid camera but negative film for the camera is hard to find and usually a 4" x 5" film holder (an extra attachment) must be purchased before the camera can be used successfully.

3.4.3 A MORE SOPHISTICATED PHOTO REDUCTION SYSTEM

For the more professional thick film hybrid circuit builder more sophisticated photographic equipment is needed. This equipment does not need to be extremely expensive though, if it is selected carefully.

The camera lens is probably the most important part of the entire photographic system since it must be capable of reproducing the original artwork without producing any distortions or irregularities in the pictures. A lens that has been found to give excellent results for the photography of thick film artwork is the Schneider-Kreuznach Repro-Claron 1:9/210 flat-copy lens.

The camera is also an important item but it doesn't have to be really expensive, just so it has focus and alignment adjustments and a translucent image viewing plate for focus and pattern size measurement. The Calumet Photographic Company manufactures a very good 4" x 5" camera which is ideally suited to this type of work. The camera should be mounted on a heavy base or tripod for optimum stability.

A back lighted copy board is also essential for good artwork photography. The best contrast for this kind of photography is obtained when the master artwork is photographed with light originating from behind the copy board. The copy board usually consists of a translucent glass sheet held in a rigid frame which is attached to the wall of the darkroom. Fluorescent lights mounted behind the glass provide a good light source.

Other items needed in the darkroom, such as a safelight, developing tanks or pans, film drying clamps, and developing and fixing solutions are available at all camera shops and can be selected as needed.

See Figure 32 for a picture of the photographic system discussed above.

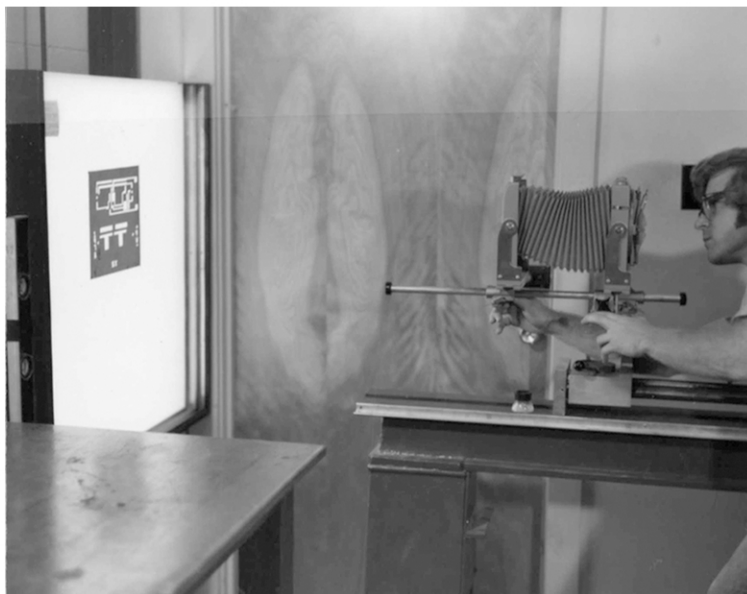


Figure 32. A typical thick film photo reduction system.

3.4.4 FILM REQUIREMENTS FOR THE THICK FILM ARTWORK

Many different kinds of film are available for this type of photography, depending on what you need and want. In general, the film must provide a high contrast image, have a wide exposure and development latitude, and have a relatively stable backing.

Kodak's Kodalith Ortho Film, Type 3, Number 2556, with a 4 mil ester base (a graphic arts film) has been found to give excellent results when used for thick film hybrid circuit negatives.

Some experimentation must be done before the proper camera settings and development times are determined but once this is done you should be able to produce very professional negatives with little difficulty.

This film works very well for artwork with line widths and spaces down to 5 mils. For finer work extra care must be taken in focusing, exposing, and developing the film but in general it is relatively insensitive to small changes in exposure time and development time and temperature.

3.5 PRINTING (SILK) SCREENS AND THEIR FABRICATION

3.5.1 THE PRINTING (SILK) SCREEN

The printing screen used in modern screen printing operations consists of a rigid frame, a fabric stretched over the frame, and a photographic emulsion placed on the fabric. The pattern to be printed is retained by the photo emulsion.

The printing screen is usually referred to as a "silk screen" in most facilities. This is because some of the first printing fabrics were made of silk. In recent times the silk fabrics have been replaced by newer and better fabrics but the screens themselves are still referred to as "silk screens" by many people.

In the thick film industry the fabrics most commonly used today are woven either from stainless steel or polyester fibers. Stainless steel fabric is the one that has been used the most in the thick film industry. Polyester fabric is a relatively new fabric in the thick film industry and has not yet achieved the high acceptance that stainless steel fabric enjoys. It does however offer certain advantages over stainless steel fabric which should be considered by the thick film manufacturer.

3.5.2 THE SCREEN FRAME

Two kinds of screen frames are available, either wooden or metal. Wooden frames are often used in small scale screen printing operations, such as in a student laboratory project or in a hobbyist's basement workshop. Wooden frames do not offer exceptional dimensional stability or long life and are therefore not recommended for the serious thick film screen printing enthusiast. For any serious work, the metal frame is a necessity, especially if large volumes of parts are to be printed. Most metal frames are made of cast aluminum and are very rigid. They offer the dimensional stability necessary

for the printing of electronic circuits and they can be used many times before they have to be replaced. In fact, usually just the fabric needs to be periodically replaced while the frame itself never deteriorates.

3.5.3 THE SCREEN FABRIC

Many screen fabrics are available today in the screen printing industry. Three fabrics, all woven with monofilament threads, that can be used for thick film screen printing are nylon, stainless steel, and polyester. Nylon is seldom used in the thick film industry because it absorbs a high percentage of moisture [1] and does not retain a uniform screen tension. The two leading fabrics in the industry are stainless steel and polyester. Stainless steel fabric has been used for many years and most of the printing information available is based on it. Polyester fabric is a fairly new material and has not yet gained widespread acceptance in the electronics field even though it is gaining in popularity.

For thick film printing either of two fabric weaves may be used; plain weave or twill weave. A plain weave fabric is formed by passing every thread alternately over and then under each thread running perpendicular to it. A twill weave fabric is formed by passing every thread alternately over and then under every two threads that run perpendicular to it. See Figure 33 for a cross section of each of these two types of fabric weaves. Of these two weaves the plain weave is the most popular even though both weaves seem to give similar prints.

PLAIN WEAVE FABRIC



TWILL WEAVE FABRIC



Figure 33. Cross sections of plain weave and twill weave fabrics.

Many different mesh sizes are available in either polyester or stainless steel fabric. The sizes run from about 25 mesh to 420 mesh, with 25 mesh being very coarse and 420 mesh being very fine. The mesh size refers to the number of threads per inch in the fabric weave.

The mesh size is usually chosen to give a certain print thickness and a certain pattern definition. In general, the coarsest mesh size should be used whenever possible since it will not plug with lint and dirt as easily as a finer mesh. See Table 3 for a list of stainless steel and polyester fabrics, the different sizes of each fabric available, and their relation to one another in terms of interchangeability.

MONOFILAMENT STAINLESS STEEL	THREAD DIA. (inches)	CLOSEST MONOFILAMENT POLYESTER EQUIVALENT	THREAD DIA. (inches)
105	.0030	86	.0039
120	.0026	110	.0031
145	.0022	125	.0027
165	.0020	139	.0026
180	.0018	157	.0026
200	.0021	---	-----
200	.0016	175	.0022
230	.0014	200	.0022
250	.0016	225	.0016
270	.0014	260	.0016
325	.0011	330	.0013

(Information from Majestic Bolting Cloth Corp.)

Table 3. Stainless steel and equivalent polyester fabrics.

There is much controversy in the thick film screen printing profession concerning which kind of screen fabric is the best to use. Since the old standby is stainless steel, many people use it without question. However, recent work has shown that polyester fabrics offer several advantages over stainless steel fabrics for most applications.[1,2]

Stainless steel fabric is well known for its exceptional dimensional stability, unless it is stretched beyond its elastic limit; and since it has a finer thread size than a comparable polyester fabric, it can print a finer line than its polyester equivalent. Stainless steel fabric is very

unforgiving of minor abuse whereas polyester fabric is quite forgiving of even major abuse. This is because of the much higher elastic limit of polyester fibers, for similar thread sizes. Stainless steel fabric costs about three times as much as its polyester equivalent also. Finally, it has been shown that polyester fabric can produce prints with the same quality as a comparable stainless steel fabric. Therefore, stainless steel fabric should only be used when line widths and spaces become so small that polyester fabric can no longer be used to produce acceptable prints; usually in the range of 3 mils or less.

It is suggested that polyester fabrics be seriously considered for any thick film screen printing operation since material costs will be lower, screen life will be longer, and print quality will be comparable with that obtained with stainless steel fabrics, in most instances.

3.5.4 THE PHOTO EMULSION

Many different kinds of photo emulsions are available for making thick film printing screens, and each of them has its advantages and disadvantages over the others. Three materials that have been found to give excellent results in the laboratory are Blue Poly, Ulanocron RX, and Azocol R. The first two materials are classified as indirect emulsions, and the third is a direct emulsion.

An indirect emulsion is a thin layer of light sensitive material laminated to a clear polyester backing. The emulsion

sheet is cut to the desired size, exposed, developed, washed out, placed on the screen fabric, and dried. The polyester backing is then removed and the screen is ready to be used.

A direct emulsion is a liquid containing a light sensitive ingredient. It is poured onto the printing screen and carefully spread around with a squeegee until a uniform thickness of emulsion over the entire center of the screen surface is obtained. It is then dried and measured to determine its thickness. Additional coats of emulsion are then applied to the screen (if needed) until the desired thickness is obtained. It is then exposed, developed, washed out, and dried again. The screen is then ready to be used.

The advantage of an indirect emulsion is that it is easy to handle and process. The disadvantages are that, in most cases, it cannot be used to obtain fine pattern detail (line widths and spaces of 7 mils or less) and it is not very durable, since it usually begins to deteriorate after a few hundred prints.

The disadvantage of a direct emulsion is that it is hard to place on the screen in a uniform thickness. However, its advantages are that it can be used for extremely fine pattern detail and it will usually last for thousands of prints without deteriorating. For a thick film production line, or even an engineering prototype line, a direct emulsion (Azocol R, in particular) is recommended since it will give exceptionally good pattern detail and extremely long pattern life.

3.5.5 SELECTING THE PROPER FABRIC SIZE AND EMULSION THICKNESS

The purpose of the printing screen is to provide a means of printing a thick film paste of constant thickness throughout the printing process, other things being held constant. Sometimes it is necessary to vary the print thickness for one reason or another. One method is to use one mesh size for all printing screens and vary only the emulsion thickness to vary the print thickness. Another method is to vary the mesh size for different print thicknesses while using the same emulsion thickness for all screens. However, depending on the type of emulsion used, the fabric sizes available, and even the size of the lines to be printed, you may or may not be able to use either method successfully by itself. In practice, it has been found that a combination of the two methods mentioned above gives the best results.

In actual fact, it is necessary to use a certain mesh size and a certain emulsion thickness for a specific print thickness in order to obtain the optimum results. Unfortunately this is not always possible, and some kind of compromise must usually be made. The general rule is that a mesh size must be used that will give the desired print thickness when a certain emulsion thickness is used and that for a thinner print, or for a finer pattern, the mesh size must be finer and the emulsion must be thinner.

Most thick film paste manufacturers recommend that their resistor pastes be printed with 200 mesh stainless steel fabric

with a 1 mil emulsion buildup on the printing side of the screen. From Table 4 notice that 175 mesh polyester fabric could also be used, with a 1 mil emulsion buildup. Some manufacturers list only the recommended print thickness for their pastes and then it is up to the user to figure out what fabric size and emulsion thickness to use.

As shown in Table 4, finer meshes with 1 mil emulsions will produce correspondingly thinner prints, and if the emulsion thickness is reduced the prints will be even thinner. On a production line the best approach is to make several screens with different fabric sizes and emulsion thicknesses and then print enough parts so that you can correlate the print thickness with the mesh size and the emulsion thickness.

If you plan to use an indirect emulsion you will not be able to change the emulsion thickness very easily and you will have to vary the fabric size instead. However, with a direct emulsion you can make it any desired thickness. In any case you must do some experimenting with different fabric sizes and different emulsion thicknesses before you know just what will work the best in your particular operation.

3.5.6 SCREEN FABRICATION USING A WOODEN FRAME AND AN INDIRECT EMULSION

The printing screen explained in this article is a low cost screen that can be used in a student laboratory project or in any other low budget operation. It can be fabricated with very few sophisticated materials and will provide excel-

THICK FILM PASTE	FABRIC SIZE		RECOMMENDED EMULSION THICKNESS	APPROXIMATE FIRED PRINT THICKNESS
	STAINLESS STEEL	POLY- ESTER		
Conductor	200	175	1.0 mil	1.0 mil
Conductor	325	330	.8 mil	.5 mil
Resistor	200	175	1.0 mil	1.0 mil
Overglaze	200	175-225	1.0 mil	1.0-0.8 mil
Dielectric	200	157-175	1.0 mil	1.2-1.0 mil

Table 4. Suggested fabric sizes and emulsion thicknesses.

lent results for the beginning thick film operation.

The printing frame is made of wood and looks like a picture frame when assembled. The frame is held together with heavy staples or corrugated fasteners.

The screen fabric to be used will be a plain weave monofilament polyester fabric. The mesh size will be 175 since this size is the most commonly used for thick film circuits.

The emulsion to be used will be an indirect emulsion. Either Blue Poly or Ulanocron RX indirect emulsion may be used since both materials are processed similarly. The Ulanocron RX will however, give slightly better pattern detail and slightly longer screen life than will the Blue Poly.[3]

The fabrication of the screen will now be covered by listing the process steps, as follows:

A. FRAME ASSEMBLY AND FABRIC STRETCHING

1. Obtain the frame sides and fasteners and assemble the frame.

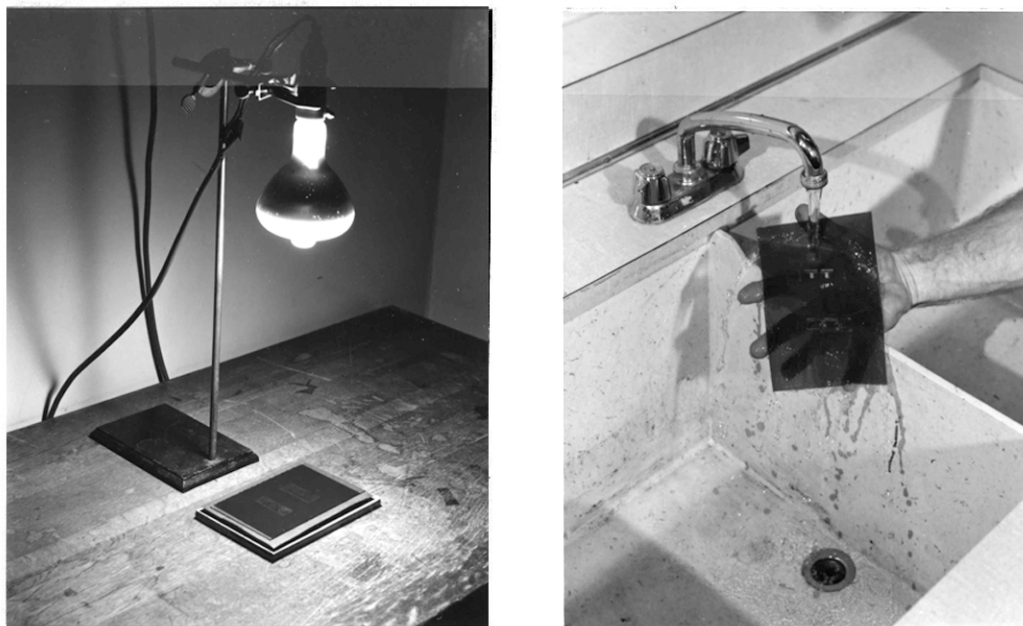
2. Place the frame on a table with the groove up.
3. Obtain a sheet of fabric and place it over the frame.
The sheet of fabric should be 1 to 2 inches larger than the frame.
4. Obtain a cord or stiff rope and force it into the groove with a large screw driver or knife blade, with the screen fabric under the cord. Work around the frame until the whole groove is filled with the cord.
5. Adjust the depth of the cord in the groove until a uniform tension is obtained on the entire surface of the fabric.
6. Trim off the excess fabric.
7. Scrub the surface of the screen with 500 mesh silicon carbide powder and water. This will roughen the mesh fibers and help the emulsion adhere better. Rinse the silicone carbide powder off the screen with water.
8. Pour a small quantity of screen cleaning and degreasing solution (such as Screen Prep 72*, or any liquid organic cleaner) onto the screen fabric.
9. Scrub the screen thoroughly with a stiff nylon-bristled brush and then rinse away all traces of the cleaner with hot water.
10. Dry the screen thoroughly.

B. EXPOSURE AND DEVELOPMENT OF THE INDIRECT EMULSION

1. Work in a room with subdued light, or yellow light, so that the emulsion will not be ruined.

* A product of Colonial Printing Ink Co.

2. On a smooth, flat surface, or on a flat board, place a sheet of black construction paper.
3. Place a 6 inch square sheet of emulsion on top of the black paper, with the clear backing facing up.
4. Position the desired negative on top of the emulsion, with the pattern on the negative upside down.
5. Place a sheet of glass on top of the negative to hold it flat. The glass should be at least 6 inches square.
6. Obtain an ultraviolet light source (a Sears 275 watt sun lamp works very well) and position it 10 to 12 inches above the center of the negative.
7. Expose the emulsion for a period of 7 to 8 minutes.
(See Figure 34.)
8. Mix the developer for the emulsion by adding first 26 grams of Part A and then 35 grams of Part B to 1 pint (500ml) of warm (65° to 75° F) water. (The developer must be purchased with the emulsion.)
9. Place the exposed emulsion in a flat pan with the developer with the clear backing facing down.
10. Gently agitate the developer for about 2 minutes.
11. Rinse the emulsion under a stream of warm (100° F) water until all of the pattern areas are washed out.
12. Rinse the emulsion under cold water for a few seconds. This will make the emulsion firm but it will remain sticky.



a. Exposing the emulsion. b. Washing the emulsion.

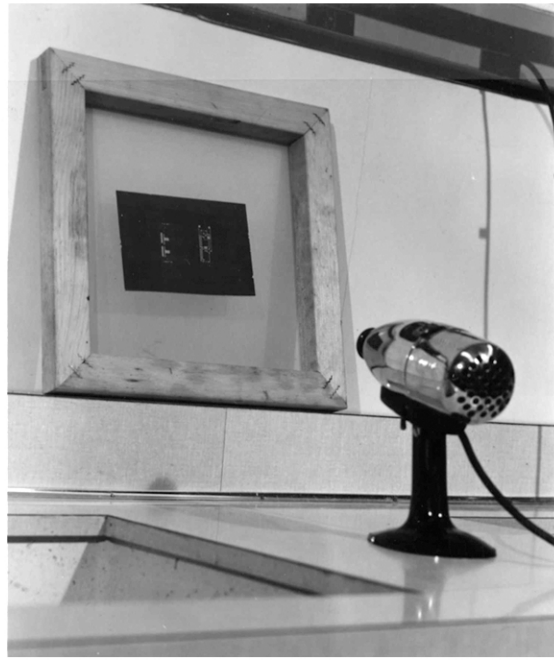
Figure 34. Exposing and washing the indirect emulsion.

C. ATTACHMENT OF THE EMULSION TO THE SCREEN FABRIC

1. Place the wet emulsion on a glass sheet with the clear backing facing down. See Figure 35-a.
2. Gently lower the screen onto the emulsion until the entire sheet of emulsion is in contact with the screen fabric. See Figure 35-a.
3. Blot the inside of the screen with lint free paper to remove the excess water from the fabric. Do not press down very hard on the fabric in the pattern area since excess pressure on the soft emulsion can distort the image in the emulsion.
4. Direct a cool air blast at the inside of the screen until the emulsion is completely dry and begins to release itself from the clear plastic backing. See Figure 35-b.



a. Placing the screen on the emulsion.



b. Drying the emulsion.



c. Removing the backing from the emulsion.



d. The finished screen.

Figure 35. Attaching the indirect emulsion to the screen.

5. Peel the clear plastic backing off of the emulsion very carefully.

6. Wipe the pattern gently with a kimwipe* and some toluene to remove the adhesive that was holding the emulsion to the backing material. The screen is now ready to use and may be stored in a lint free container until then.[38]

3.5.7 SCREEN FABRICATION USING A METAL FRAME AND A DIRECT PHOTO EMULSION

The printing screen explained in this article is typical of the kind used in most thick film screen printing operations. It provides the best dimensional stability and the longest screen life possible for a reasonably priced thick film printing screen.

The screen frames are made of metal and have very good dimensional stability. They may be either cast or machined and they are usually made of aluminum.

The screen fabric to be used is a plain weave monofilament polyester, but monofilament stainless steel fabric may also be used. Any desired mesh size may be used depending on the type of printing to be done. (Refer to Table 4.) The screen fabric will be fastened to the frame with epoxy.

The emulsion to be used will be a direct emulsion. Many kinds of direct emulsions are available but the one that has been found to give excellent results is Azocol R. The fabrication of the screen will now be covered by listing the process steps, as follows:

*Reg. T.M. of The Kimberly-Clark Corp.

A. STRETCHING THE SCREEN FABRIC

1. Obtain a mechanical fabric stretcher, such as a CAM-LOK* model EL-303 stretcher.
2. Obtain a piece of fabric of the desired mesh size and fasten it in the stretcher.
3. Stretch the fabric to a uniform tension. A screen tension gauge should be used to check the fabric tension, but usually it is sufficient to just press on the fabric with your hand and estimate whether it is tight enough or not. See Figure 36-a.
4. Clean the fabric with a kimwipe and some toluene to remove any grease and dirt that has collected on it.

B. ATTACHING THE STRETCHED FABRIC TO THE METAL FRAME

1. Obtain a metal frame and remove the old screen fabric.
2. Scrape the bonding surface (the bottom surface) of the frame with a file to remove old paste and epoxy and to bare the metal.
3. Clean the bonding surface with toluene to remove all grease and dirt.
4. Apply a uniform layer of epoxy (such as 5 minute epoxy) to the entire bonding surface of the frame. See Figure 36-b.
5. Pick up the fabric stretcher, turn it upside down, align the fabric threads as desired with the sides of the frame, and gently lower the stretcher until the fabric is resting on the epoxy covered bottom side of the

*Available at Advance Process Supply Co.

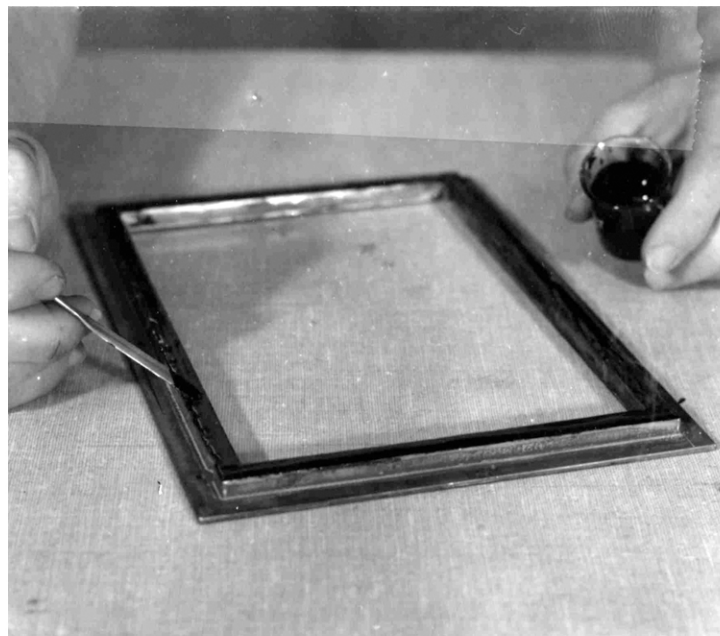
printing frame. See Figure 36-c.

Note: You may elect to have the fabric threads run parallel to the frame sides, or you may want them to run at some angle to the frame sides. If the fabric threads are to run parallel to the frame sides it will be necessary to align all straight lines on the pattern to be printed exactly parallel to the threads on the screen so that the resulting prints will not have rough edges. To avoid this problem the fabric is usually placed at an angle of 30° to 45° with respect to the sides of the printing frame. Then the resulting prints made with the screen will be less likely to have rough edges.

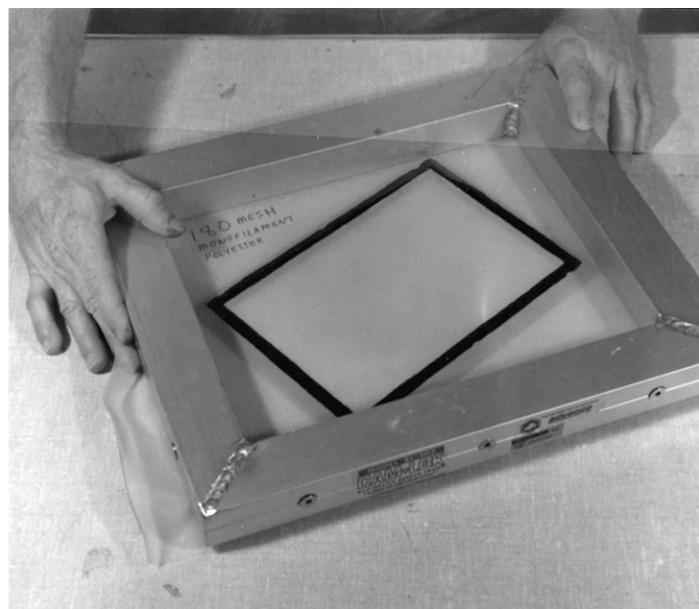
6. Examine the fabric to see if the epoxy has worked through it around the perimeter of the frame. If not, work the fabric up and down with your fingers to draw some extra epoxy up through the fabric. Then scrape the excess epoxy off of the fabric with a small scraper so that there is no epoxy buildup above the fabric surface.
7. Allow the epoxy to cure for the required time.
8. Remove the fabric, with the frame attached, from the fabric stretcher after the epoxy has cured.
9. Cut the excess fabric from the frame with a sharp knife. You now have a screen ready to be coated with emulsion.



a. Stretching the fabric.



b. Applying epoxy to the frame.



c. Placing the fabric on the epoxy coated frame.

Figure 36. Stretching the fabric and attaching it to the metal frame with epoxy.

C. CLEANING THE SCREEN FABRIC

1. Pour a small quantity of screen cleaning and degreasing solution, such as Screen Prep 72, onto the screen fabric.

2. Scrub both sides of the fabric with a moderately stiff nylon-bristled brush and then let the cleaner set on the fabric for a few minutes.
3. Rinse away all traces of the cleaner with hot water.
4. Dry the screen thoroughly.

D. COATING THE SCREEN WITH AZOCOL R DIRECT PHOTO EMULSION

1. Prepare the Azocol R according to the manufacturer's instructions. Once the emulsion has been prepared it will be sensitive to ultraviolet light and it must be handled only in a room illuminated with yellow light. The prepared emulsion must be stored in a refrigerator for maximum shelf life.
2. Pour a generous amount of emulsion onto the outside (printing side) of the clean screen. Make alternate passes across the length of the screen with a squeegee, spreading the emulsion over the screen's surface, until a uniform thickness of emulsion across the whole center of the screen is obtained. Make the final pass of the squeegee on the inside of the screen so that all of the excess emulsion will be forced to the outside of the screen. This is to ensure that all of the emulsion buildup on the screen will be on the outside, or printing side, of the screen.
3. Dry the freshly coated screen immediately with warm air (about 100 F) until the emulsion is dry.

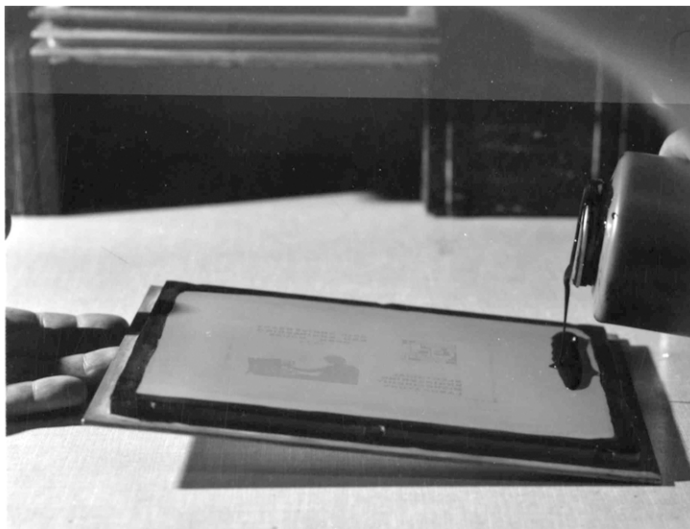
4. One or more additional coats of emulsion may be required on the printing side of the screen before the desired emulsion thickness is obtained. After a few practice screen coating sessions you can usually estimate the proper emulsion thickness quite easily. You may however, have to print some circuits with the screens you coat before you can determine the optimum emulsion thickness for the paste you are using.

An alternate way of determining the emulsion thickness on the screen is to first measure the fabric thickness with a micrometer just prior to coating the screen, and then to measure it again after each emulsion coating has been applied and dried, until the proper emulsion thickness has been obtained. The emulsion must be thoroughly dry before each measurement is made! Emulsion thicknesses can be accurately produced in this way to a tolerance of $\pm .0001$ inch.

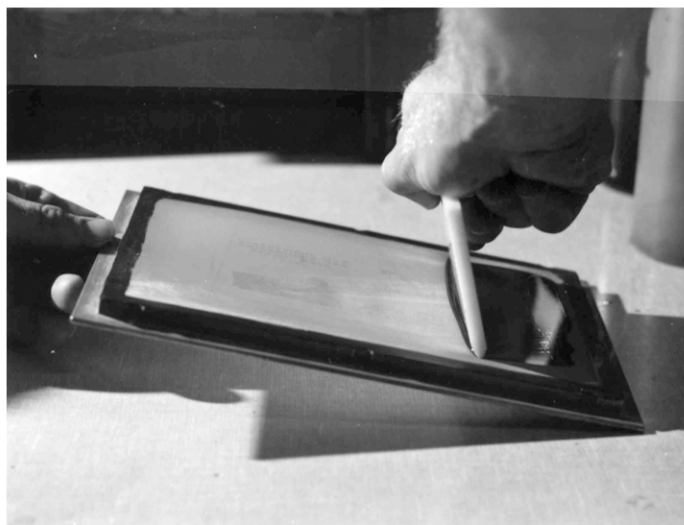
See Figure 37 for the sequence of screen coating steps discussed above.

E. EXPOSING AND DEVELOPING THE AZOCOL R EMULSION

1. Obtain a flat board that is at least $1/8$ inch thick and several inches larger than the screen frame in length and width.
2. Obtain another board, or a book, that is at least as thick as the frame and just a little smaller than the inside of the frame.



a. Pouring the emulsion onto the screen.



b. Spreading the emulsion across the outside of the screen.



c. Spreading the emulsion on the inside of the screen.

Figure 37. Coating a printing screen with Azocol R direct photo emulsion.

3. Place the small board, or the book, on top of the larger board.

4. Place a sheet of soft foam on top of the small board.
The foam should be the same length and width as the small board, or book.
5. Place a piece of black construction paper on top of the sheet of foam. This combination of foam and black paper will form a soft, non-reflective cushion for the inside of the screen fabric during exposure.
6. Place the coated screen on top of the black paper, with the outside of the screen (the emulsion side) facing up.
7. Position the desired negative on the screen with the image upside down and the emulsion side of the negative in contact with the emulsion on the screen.
8. Place a sheet of clean glass on top of the screen to hold the negative in place. The glass should be just slightly larger than the outside dimensions of the screen frame.
9. Press down firmly on the glass to compress the foam as much as possible and then wrap several layers of masking tape completely around the glass sheet and the bottom board. Tape both ends of the glass sheet to the board. An alternative way to hold the glass sheet firmly against the screen is to clamp it with suitable clamps. Either method must hold the negative in intimate contact with the emulsion on the screen so that the exposed pattern will be of the sharpest possible detail.

10. Obtain an ultraviolet light source (a Sears 275 watt sun lamp works very well; however, a 90 amp carbon arc lamp would be better for fine line resolution) and position it 10 to 12 inches above the center of the negative on the screen.
11. Expose the emulsion for a period of 20 minutes (if the Sears sunlamp is used). See Figure 38.

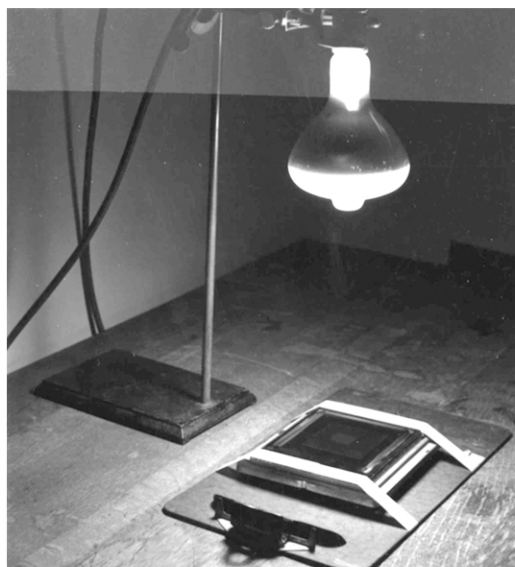


Figure 38. Exposing the Azocol R direct photo emulsion.

12. Remove the screen from the holder and place it in a pan of warm water (100°F), with the outside facing up, for 2 minutes.
13. Remove the screen from the pan of water and rinse it under a gentle stream of warm water (110°F) until all of the unexposed pattern areas are washed out completely. A small stream of water from a hand sprayer may also be used to wash out the patterns. Rinse both sides of the screen until all traces of unexposed emulsion are gone.

14. Blot the screen dry with lint free paper, or kimwipes,
and then dry it with warm air (less than 150 F) for 10
or 15 minutes.
15. Examine the pattern with the aid of a microscope for
any possible defects.
16. If the pattern is acceptable, block out any unwe^d
open areas with Blockout* and dry the screen again.
17. Store the screen in a box or plastic bag until it is
to be used for printing. [4]

3.6 FABRICATING THE THICK FILM CIRCUITS

3.6.1 THE THICK FILM PRINTING PROCESS IN GENERAL

The thick film printing process is just an extension of the process of screen printing that is used to print patterns on such things as draperies, shirts, and pop bottles. The screen printing process is the only printing process that can produce relatively thick prints with a uniform and repeatable thickness. The print thicknesses necessary for thick film circuits are on the order of 1 to 2 mils (wet) and these thicknesses are easy to achieve with the screen printing process.

The pastes used in the printing of thick film circuits are special formulations of precious metal powders, glass powders, and organic vehicles and binders. The pastes are formulated to provide specific characteristics in the printed circuit elements.

*Reg. T.M. of the Ulano Companies.

The individual circuit element values are determined by the geometry of the printed patterns and the particular pastes used. Once the patterns are all printed they are fired in a high temperature furnace to cure the pastes and change them to their final form.

The process of screen printing is a complicated process even though it looks simple to the casual observer. The basic steps in the printing process are as follows:

1. Placing the substrate to be printed in a suitable nest for alignment purposes.
2. Positioning the printing screen over the substrate.
3. Printing the thick film paste.

The above steps will now be looked at in a little more detail. In general they will apply equally well to either manual (hand) printing or machine printing.

3.6.2 CONSTRUCTION OF A NEST FOR THE SUBSTRATE

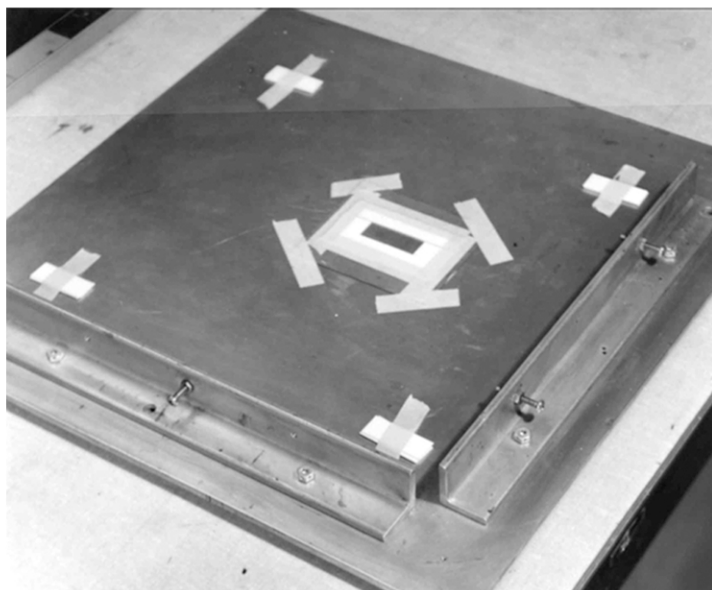
In order for several thick film prints to be placed on a substrate accurately, the substrate must be positioned in a suitable holder with a fixed reference position with respect to the pattern on the printing screen. This is one function performed by the nest.

The nest may be formed by machining a shallow cavity in a metal plate or by gluing or taping several substrates to a flat metal plate. The nest should be 3 to 5 mils shallower than the thickness of the substrate to be printed and it should be 20 to 30 mils longer and wider than the substrate

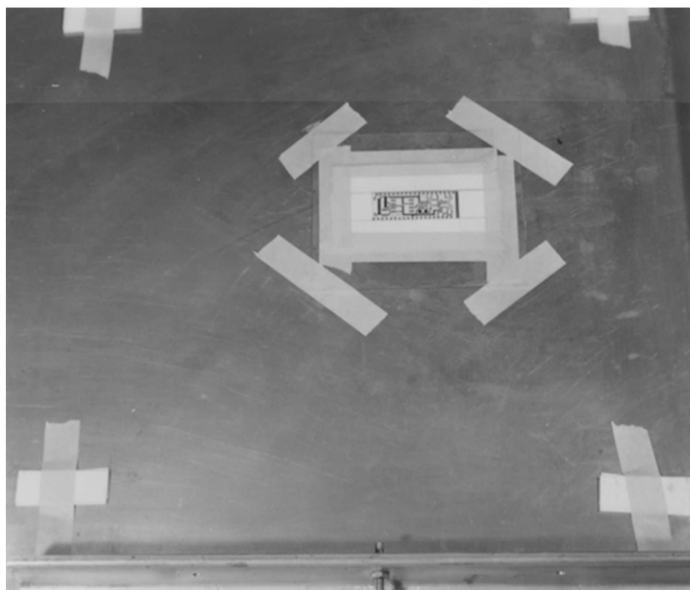
to allow for variations in substrate dimensions and easy removal of the substrate from the nest after printing. See Figure 39 for a typical nest.

Two adjacent sides of the nest are called the reference sides since each substrate will be placed against these two sides prior to printing. All prints will then be located on each substrate with respect to these two sides. See Figure 39.

The nest can be located in any convenient manner but it is customary to locate it with its longest dimension parallel to the direction of squeegee travel. Also, one of the reference sides should be closest to the approaching squeegee. The squeegee will then make a relatively smooth transition from the sides of the nest to the substrate surface and unnecessary wear on the printing screen and the emulsion will be eliminated.



a. Construction of the substrate nest.



b. Location of the substrate in the nest.

Figure 39. Construction of the substrate nest on a manual printing jig.

The nest should have a vacuum hole in its bottom so that a vacuum can be used to hold the substrate in place during printing, or else a piece of double sided tape can be placed in the bottom of the nest to hold the substrate in place.

3.6.3 POSITIONING THE PRINTING SCREEN OVER THE SUBSTRATE

If a printing machine is available it will provide a way to hold the printing screen in the proper position over the substrate. Also it will provide adjustments for the relative position of the screen with respect to the substrate. If a manual printing fixture is being used, it must also provide these adjustments.

The necessary adjustments that must be provided in any printing fixture are the X, Y, and θ positions of the screen with respect to the substrate, and the snap-off distance (the distance from the bottom of the screen to the top of the substrate).

X, Y, and θ adjustments are provided on nearly all printing machines and they are easy to incorporate into manual printing fixtures. The snap-off adjustment is also provided on printing machines. However, on the manual printing fixtures the snap-off may be set by placing several substrates under each of the four corners of the printing screen. See Figure 40 for a typical hand printing alignment jig (fixture), with the screen in place.

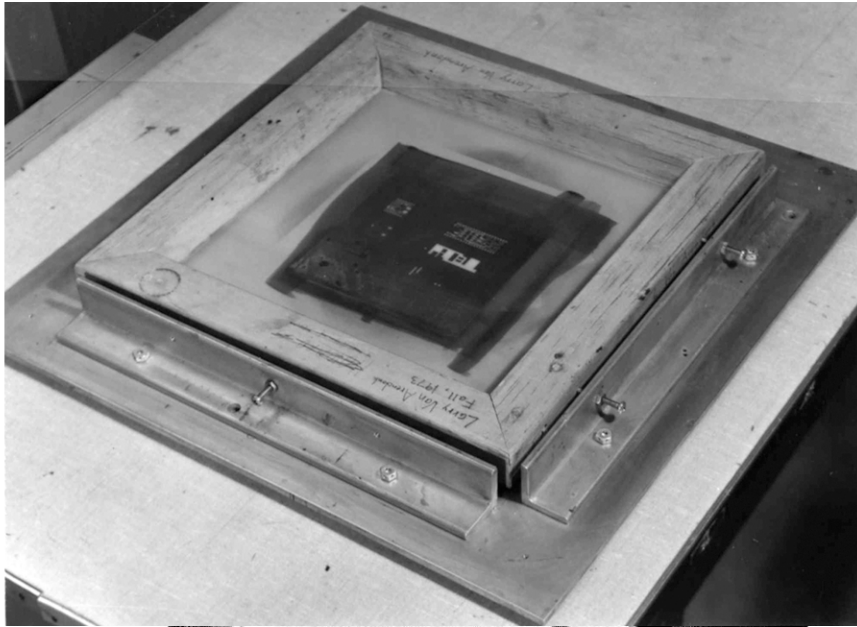


Figure 40. A hand printing alignment jig with the screen in place.

3.6.4 PRINTING THE THICK FILM PASTE

The actual printing of the thick film paste is one of the most delicate parts of the entire thick film fabrication process since, other things being held constant, it is the printing technique that determines the quality of the printed patterns.

There are a number of variables that can be used to change the print quality that do not apply directly to the printing operation, such as fabric size selection and firing temperature changes, but there are also many variables that must be controlled during the printing process if the resulting prints are to be of good quality and of the proper thickness. Some of these variables are the snap-off distance, the squeegee pressure, the angle-of-attack of the squeegee during the print

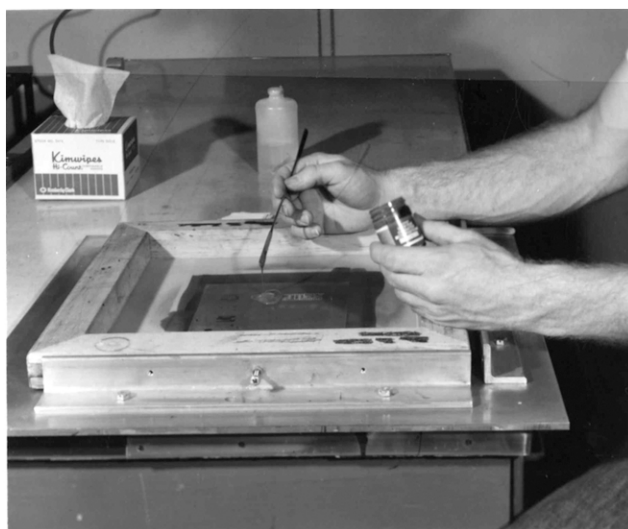
stroke, and the type of material used for the squeegee blade. With the above printing variables in mind, we can now proceed to the actual printing of the paste.

Place a substrate that has been cleaned in toluene or trichloroethylene in the nest and position the screen over the substrate. Place a small quantity of paste (about one teaspoonful) on the screen and gently spread it over the pattern with the squeegee. This is known as the flood stroke. Be careful not to force any paste through the pattern on this stroke.

Now grasp the squeegee firmly in your hand, incline it at about 45 degrees in the direction of the print, press down on it until it forces the screen down onto the top of the nest. Then draw the squeegee smoothly and quickly across the surface of the screen. At the end of this stroke (the print stroke) remove the squeegee from the surface of the screen and return it to the starting point. If you work fast enough the excess paste will stay on the squeegee blade. Now flood the pattern again before any of the paste left in the pattern openings begins to dry. See Figure 41 for the sequence of steps discussed above.

This completes the printing of one substrate. Now all that is required is that the printed substrate be removed from the nest and examined for any possible defects. If the print looks good you can place the substrate aside and allow the wet print to level for a few minutes. Then you can proceed with the printing of the next substrate.

If the print has any defects they must be corrected by either cleaning the printed substrate with toluene and re-printing it, or by repairing the defect with a spot of paste applied to the defect with a fine needle or even a a tooth-pick.



a. Placing the paste on the screen.



b. Flooding the pattern with the paste.



c. Printing the pattern.

Figure 41. Printing thick film paste by hand.

When thick film circuits are printed by machines, the results are usually much better than when the printing is done by hand. Figure 42 shows a semi-automatic screen printer which is typical of the kind used on engineering prototype lines and on low and medium volume production lines. Figure 43 shows a fully automatic screen printing system. This equipment is designed for high volume industrial thick film printing and represents some of the latest advances in screen printing equipment for the electronics industry.



Figure 42. A semi-automatic screen printer. (Courtesy of Weltek Division of Wells Electronics, Inc.)

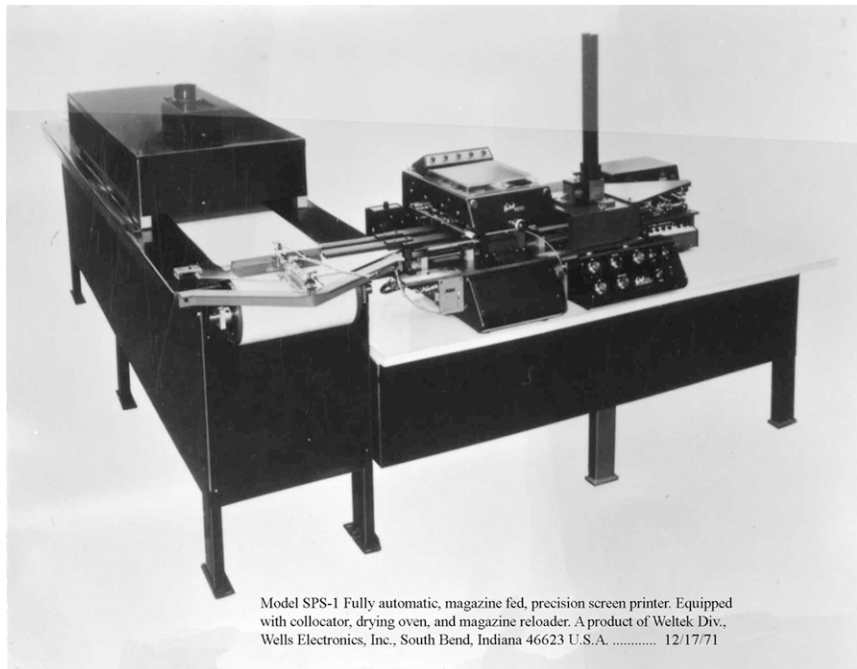


Figure 43. A fully automatic screen printing system. (Photo courtesy of Weltek Division of Wells Electronics, Inc.)

3.6.5 A DISCUSSION OF SOME OF THE PRINTING VARIABLES

Since the quality of the printed thick film patterns can be affected by many factors during the printing operation it is only fair that some of them be discussed so that you can decide how to change the quality of a print if it is not up to your expectations.

1. SNAP-OFF DISTANCE

The snap-off distance is the distance between the bottom of the screen and the top of the substrate being printed when the screen is in its normal position above the substrate. In general, the lower the tension is in a screen the greater the snap-off must be in order to get a good print. Also, the greater the snap-off distance the greater the print thickness. Usually the snap-off must be adjusted for the maximum print quality.

For stainless steel fabric the snap-off is usually set at 10 to 15 mils as a starting point while for polyester fabric it is usually set at 35 to 40 mils. Excessive snap-off must be avoided since the screen can be ruined if it is stretched too much during the printing operation.

2. SQUEEGEE PRESSURE AND ANGLE-OF-ATTACK

The thickness of a print can be varied tremendously if the squeegee pressure or the angle-of-attack of the squeegee during the print stroke is varied. It is therefore necessary to pick a reasonable pressure and angle-of-attack and hold them constant during the printing process.

In general the print thickness can be increased if either the squeegee pressure is increased or the angle-of-attack of the squeegee during the print stroke is decreased. Both actions have the effect of placing more downward pressure on the paste as the squeegee passes over the pattern; thereby forcing more paste through the pattern openings. Conversely reducing the squeegee pressure or increasing the angle-of-attack of the squeegee has the effect of reducing the print thickness, to a degree at least. If the pressure is too low, the pattern will not be printed completely, and in some cases it will not be of uniform thickness. Excessive squeegee pressure must be avoided since it can cause the screen fabric to be coined or stretched out of shape.

3. SQUEEGEE SPEED

The squeegee speed has an effect on the viscosity of the thick film paste; usually the faster the squeegee moves over

the paste the thinner and more uniform the resulting print will be. If the squeegee moves very slowly the paste will not always be removed completely from the pattern during printing. Typical squeegee speeds are in the range of 5 to 10 inches per second for printing machines.

4. SQUEEGEE BLADE MATERIAL AND HARDNESS

The harder a squeegee blade is the less it will deform under the pressure of printing and hence the greater will be its apparent angle-of-attack. Therefore, the resulting print thickness will be somewhat less for a hard squeegee than for a soft one. Also, the squeegee material can affect the print thickness since a material with a low abrasion resistance will wear off fast and develop a round printing edge, which will result in an apparent increase in the angle-of-attack of the squeegee. This will then cause a slight increase in the print thickness of the paste.

One of the most durable squeegee materials is polyurethane. For most printing a squeegee of 60 durometer hardenss works quite well. Harder squeegees can be used but an 80 durometer squeegee is the hardest that should be used for thick film printing.

Other variables could also be discussed but those mentioned above are some of the most important ones and in any event, the main idea during printing any thick film paste is to hold all of the variables constant so that all of the prints will be the same. Then if an adjustment is required, the proper change can be made and the printing can then continue without undue interruption.

3.6.6 DRYING THE THICK FILM CIRCUITS

After the thick film paste has been printed, it must be dried to remove the volatile materials that it contains. If the substrates are fired while the paste is still wet, the fired films will sometimes be rough and pock marked and they will not always have the proper characteristics.

Most paste manufacturers specify the best way to dry their pastes; the methods vary though from one manufacturer to the next. Two drying methods that are very popular in the industry are forced air drying and infrared drying.

Forced air drying works very well for most thick film pastes and is usually used on low volume production lines. The substrates are placed in an oven that is thermostatically controlled and hot air is circulated throughout the oven until the printed pastes are thoroughly dry (usually 10 to 15 minutes at 100° to 125° C is sufficient). In some cases, only room temperature air can be used since the paste viscosity may drop very low when it is heated, and the lines will spread out on the substrate. This can cause poor pattern detail and poor print quality.

Infrared drying is a method used in high volume production facilities because the printed substrates can be automatically removed from the printer and placed on a moving belt that carries them through the drier and on to the firing furnace.

When infrared drying is used, the infrared energy is from the "far" infrared region of the spectrum, typically the 1.2

micron wavelength region. This "long wave" radiation passes through the binders in the paste and is absorbed by the solid particles and in effect dries the paste "from the inside out". [7]

Before you choose one drying method for your particular operation you should test the pastes you plan to use to determine the best drying method to use. It might happen that for fine line printing the paste you are using can only be dried with room temperature air in order to retain the fine line pattern detail on the printed substrate.

3.6.7 FIRING THE THICK FILM CIRCUITS

Another very delicate process in the fabrication of a thick film circuit is the firing process. It is the firing process that melts the glass particles in the paste and causes them to bond the other components in the paste together and adhere them to the substrate to form a dense, hard film. Also, the firing process determines the final electrical characteristics of the various circuit elements, and the firing time and temperature must be controlled very carefully for optimum results.

Firing profiles (so called because they are schedules of temperature versus time that the pastes must be fired at represent the temperature "profile" of the firing furnace) vary from one paste to another, but all profiles, whether for conductors, resistors, or dielectrics, have three critical regions in common. These three regions are:

1. The heating portion of the profile.
2. The peak temperature portion of the profile.
3. The cooling portion of the profile.

In Region I of the firing profile the substrates are slowly heated from room temperature to the maximum temperature in the furnace. Heating rates in this region should not exceed 60°C per minute so that all of the organic materials will be removed from the thick film composition before the glass softens.

In Region II the substrates are maintained at a fairly constant temperature for a specific amount of time. The peak temperature and the time at the peak temperature usually determines the characteristics of the fired films, such as the sheet resistivity, the temperature coefficient, the degree of solderability, and the adhesion of the fired film to the substrate.

Region III, the cooling portion of the profile, must be adjusted so that as the substrates cool off they cool slowly enough so that any residual stresses in the films will be relieved before the films become hard. Cooling rates should be less than 60°C per minute for most materials. High cooling rates can result in erratic temperature coefficients and in instability in resistors. [12]

A typical firing profile is shown in Figure 44 with the three critical regions marked.

Although control of the firing process is very important, modern furnaces are capable of controlling their temperature profiles within $\pm \frac{1}{2}^{\circ}\text{C}$, which is well within the requirements of most thick film pastes.

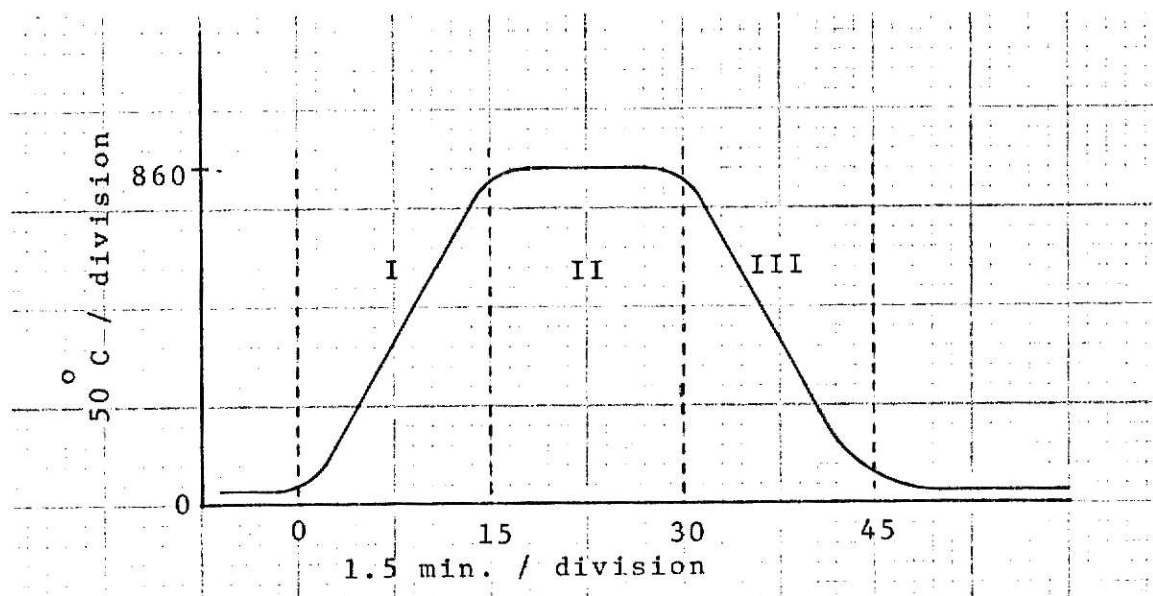


Figure 44. A typical thick film firing profile.

A custom built thick film furnace is shown in Figure 45. For small laboratories a furnace of this type provides an economical solution to the problem of obtaining a good furnace. A modern thick film furnace is shown in Figure 46. This furnace features a variable speed woven metal conveyor belt that runs through the heated zones, four separately controlled heating zones that are individually adjustable, and atmosphere controls for the firing atmosphere and draft through the furnace.

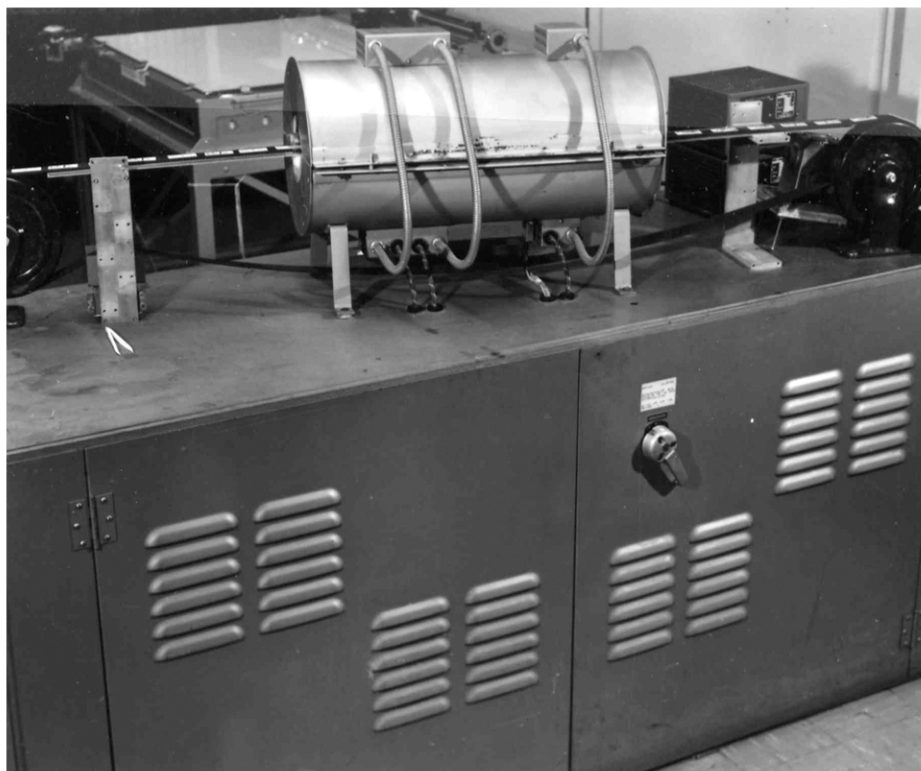


Figure 45. A custom built laboratory thick film furnace.



Figure 46. A modern thick film furnace. (Photo courtesy of BTU Engineering Corp.)

3.6.8 THE PROCESSING ORDER FOR CONDUCTORS AND RESISTORS

There is always some question in people's minds as to what should be printed first; i.e., conductors or resistors. Some people insist that the resistor paste must be printed first, the conductor paste second, and then the whole circuit should be fired. Others believe the conductors should be printed and fired first and then the resistors should be printed and fired.

The whole problem reduces to the fact that there are several ways of processing thick film circuits and the engineer must pick the method that works the best in his installation.

For best results it is wise to follow the paste manufacturer's suggestions but occasionally the manufacturer is not very explicit about the best method to use.

Most manufacturers specify that the best resistor characteristics will be obtained when the resistors are printed and fired first and then the conductors are printed and fired. This method can cause some problems though, since it is difficult to test a fired resistor if it doesn't have a conductor termination, and test samples do have to be evaluated periodically to provide feedback to the printing process. To make matters worse, most manufacturers only list the properties of their resistors after they have been printed and fired once, on substrates with previously printed and fired conductor patterns!

After considering the various ways of processing resistors and conductors we can summarize them as follows:

METHOD 1. Print and dry the conductors, then print and dry the resistors, and finally, fire the entire circuit. This method is one method of co-firing.

METHOD 2. Print and dry the resistors, then print and dry the conductors, and finally, fire the entire circuit. This method also is called co-firing.

METHOD 3. Print, dry, and fire the conductors. Then print and dry the resistors. Finally, fire the entire circuit.

METHOD 4. Print, dry, and fire the resistors. Then print and dry the conductors. Finally, fire the entire circuit.

Of these four methods, 1 and 2 will yield resistors with the widest variations in sheet resistivity and temperature coefficients. [5,6] This is because when the conductors and resistors are fired together (co-fired) for the first time, there is a lot of diffusion of the resistor material into the conductor material, and vice versa, at the conductor/resistor interface and this "contamination" produces some less-than-ideal resistor characteristics.

Method 3 is the method most often used in production line work since it seems to be the most logical way to proceed. It allows the resistors to be printed on substrates that have a fired conductor pattern already on them. The advantages of this method are that the resistors can be easily positioned

on the substrates when the conductor pattern is in place. Then, if any resistors are printed incorrectly and must be washed off, the conductor pattern will not be harmed in the process.

Method 4 is the process to use if you require the resistors to have the lowest possible temperature coefficients. Also, with this method the sheet resistivities of all of the resistor pastes printed will be very close to their theoretical value. This method gives the least spread in resistivity from resistor to resistor, of any of the methods mentioned. When resistors with close tracking characteristics are required this method deserves consideration, although it requires more time during processing.

3.6.9 VARIATIONS IN RESISTOR VALUES AND WHERE THEY COME FROM

Every engineer should be aware of the variables that can affect the results of a process so that he can take the necessary precautions to avoid the fabrication of faulty parts! Such is the case in the thick film process, as well as any other fabrication process.

In the thick film fabrication process, variations in the electrical and physical characteristics of the processed parts come from two main sources: changes in the so-called "fixed" process parameters, and changes in the processed parts due purely to statistical variations.

At the start of the printing process the printing parameters are set so that the printed circuit elements (resistors, in particular) will have an average value, after firing, of 75%

of their nominal value. These adjustments usually result in changes in the thickness of the printed paste until the thickness recommended by the paste manufacturer is obtained.

As the resistors are printed and fired you will notice that there is some variation from part to part in their values. This is the statistical variation mentioned above. When the printing parameters are carefully controlled and the firing profile is set correctly the resistor values will follow a "normal distribution" about their mean (or average) value and the values will typically fall into the following categories:

1. ± 1 standard deviation---67% of the parts will be within a $\pm 10\%$ range about their mean value.
2. ± 2 standard deviations--95% of the parts will be within a $\pm 20\%$ range about their mean value.

See Figure 47 for the plot of a typical normal distribution as it applies to printed and fired thick film resistors.

The normal distribution of resistor values shows up no matter how many resistors are processed. However, if a large number of circuits (more than 100) are printed and fired you will notice that the mean value of the resistors slowly changes. These slow changes are due to slow changes in some of the variable printing parameter that are assumed to be fixed, such as the screen tension, the emulsion thickness, and the ink viscosity. Changes in these variables will result in changes in the thickness of the printed circuit elements which will in turn result in changes in characteristics of the circuit elements.

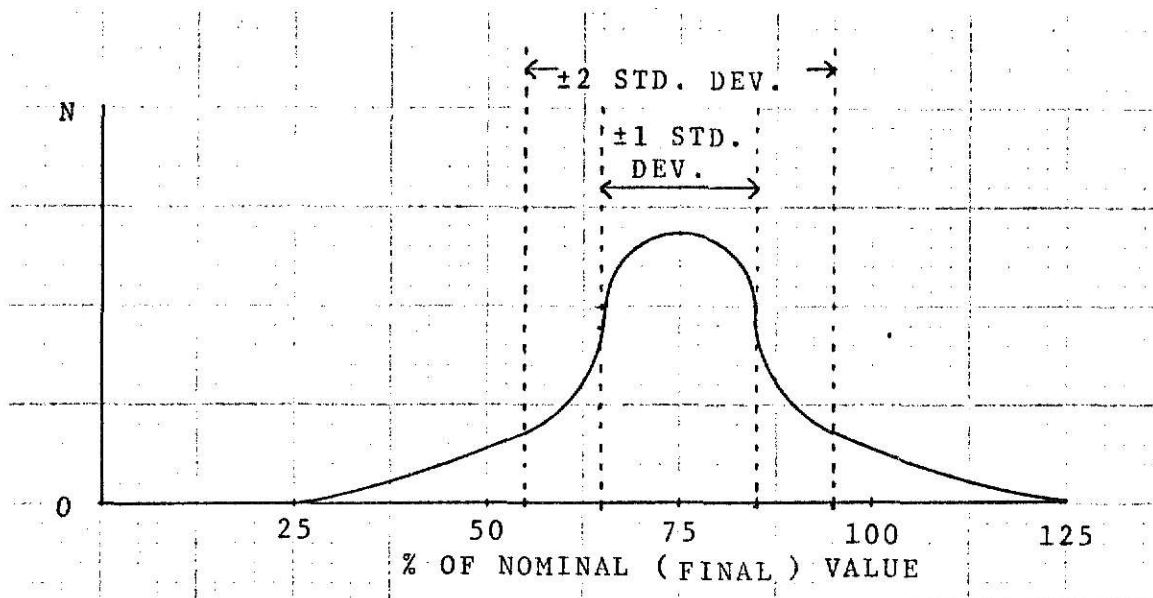


Figure 47. A normal distribution for a typical run of thick film resistors with an average value of 75% of their nominal value.

When large numbers of circuits are processed it is necessary to periodically adjust some of the printing variables to compensate for some of the long term changes in resistor values.

For most thick film circuits, the resistor values should be kept between 50% and 100% of their nominal value. Therefore, considering the fact that most of the resistors will be within the $\pm 10\%$ range about their mean, the printing parameters should be adjusted to bring the mean back to 75% of nominal whenever it gets close to 60% or 90% of nominal. Figure 48 shows what can be expected when the resistor paste slowly dries out during a long printing run, and how readjusting the paste viscosity with some thinner should return the mean value of

the printed resistors to a safe level. You should keep in mind though, that other changing printing variables can also change the mean value of the printed resistors and that you must be aware of all of the possibilities.

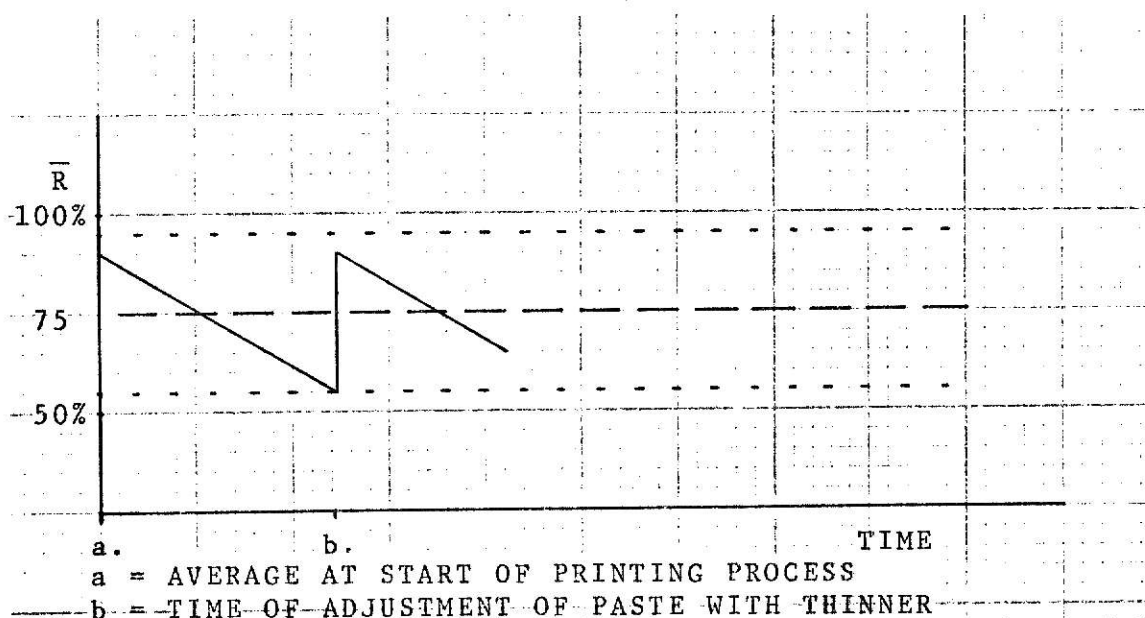


Figure 48. Changes in the mean value of a resistor due to solvent loss during printing, and the return of the mean value to an acceptable level by the addition of fresh solvent to the paste.

3.7 TRIMMING THE THICK FILM CIRCUIT ELEMENTS

3.7.1 THE REASON FOR TRIMMING THICK FILM CIRCUIT ELEMENTS

As was mentioned earlier, the as-fired values of thick film circuit elements processed under normal conditions cannot be expected to fall into a tolerance range of less than $\pm 10\%$ of the average value obtained during a printing run. Therefore, most thick film circuit elements which require working tolerances of less than $\pm 10\%$ are printed to values that are different than their nominal values, and then they

are adjusted to the proper values by a process known as trimming.

The process of trimming (as the name implies) is a process in which material is removed from a circuit element until it reaches some specified value, as determined by its geometry.

The two most common types of circuit elements that are adjusted by trimming are resistors and capacitors. However, capacitor trimming is not nearly as common as resistor trimming because low tolerance capacitors are not as numerous as are low tolerance resistors on thick film hybrid circuits.

When resistors are trimmed their values (and their aspect ratios) are always increased; therefore, they must be printed so that their as-fired values are less than their nominal design values. When capacitors are trimmed their values are always decreased (the effective plate area for a capacitor is decreased during trimming); therefore, they must be printed so that their as-fired values are greater than their nominal design values.

The following methods will discuss resistor trimming in particular; these methods can be used with equal success for trimming capacitors also.

3.7.2 THE ABRASIVE TRIMMING METHOD

One popular method of trimming is known as abrasive trimming. In this method the resistor element is abraided by a high velocity stream of fine abrasive powder. The resistor's

value is electronically monitored with a precision comparison bridge and the abrasion process is terminated when the resistor reaches the desired value.

The abrasive trimming method has proven to be a very good method of adjusting resistors. When special care is exercised by the machine operator, resistors may be adjusted to tolerances on the order of $\pm 0.1\%$. [8] The only major drawbacks to the abrasive trimming method are that it is a dirty process (since an abrasive powder is used) and it is a relatively slow process by today's standards of high volume production. Typical abrasive trimming time for a thick film resistor is on the order of 2 to 5 seconds including pre-trim and post-trim testing. This figure, of course, depends on the initial value of the resistor compared to its final value, the desired tolerance of the resistor, and also many other factors.

However, for a low volume production facility, or an engineering laboratory or prototype production line, an abrasive trimmer is a valuable piece of equipment since it represents a relatively small dollar investment (compared to other trimming methods) and it can do very precise work. See Figure 49 for a typical (home-made) laboratory model of an abrasive trimmer. Although somewhat crude in appearance this trimmer has a bridge with $\pm 0.01\%$ resolution. The system works extremely well! See Figure 50 for a modern factory-built abrasive trimmer. This trimmer has a bridge with $\pm 0.1\%$ resolution. Also it features automatic nozzle movement during trimming for accurate and repeatable trims.

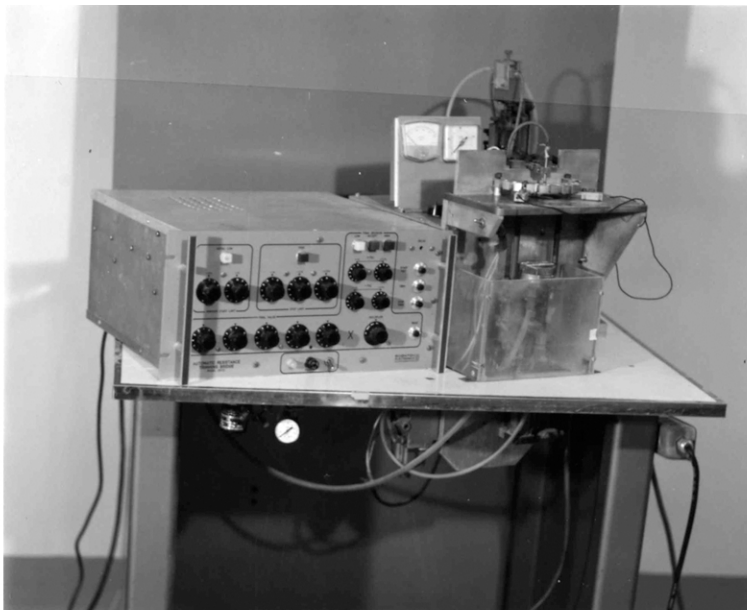
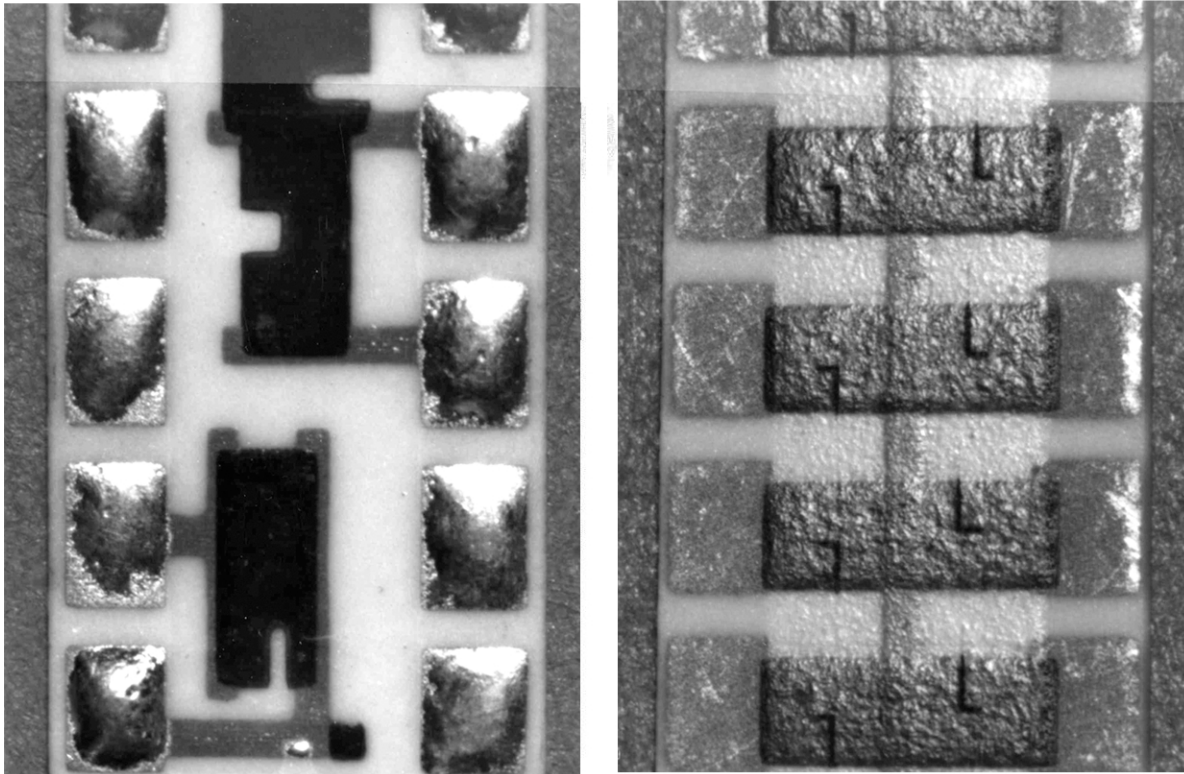


Figure 49. A typical laboratory abrasive trimmer.



Figure 50. A modern abrasive trimming system. (Photo courtesy of S.S.White Division of the Pennwalt Corp.)

Some examples of properly trimmed thick film resistors, using the abrasive trimming method, are shown in Figure 51-a.



a. Abrasive trims.

b. Laser trims.

Figure 51. Examples of abrasive and laser trims on thick film resistors. (10X)

3.7.3 THE LASER TRIMMING METHOD

Another trimming method which is becoming very popular is the method of laser trimming. With this method the resistor is monitored electronically, as before, but the resistor's geometry is changed by burning away a portion of the resistor material with a finely-focused laser beam. The entire process is computer controlled and the time required for the trimming of a typical resistor is much less than for the abrasive method. Typical laser trimming times are on the order of .25 to .50 seconds per resistor, including testing.

The high speed and inherent cleanliness of the laser trimming method make it very attractive for high volume production facilities. However, a laser trimming system represents a large dollar investment (at least \$10,000) and this would be hard to justify for a small production facility. See Figure 51-b for examples of laser trimmed resistors.

3.7.4 A PRECAUTION CONCERNING RESISTOR TRIMMING

With any trimming method, you must be careful not to trim the resistor element so much that it will be operating at a power overload under its normal operating conditions. This means that the maximum amount of adjustment allowable for each resistor must be established at the time of the circuit design. The general rule of thumb for trimming, as stated in the design guidelines (Section 3.2), is not to trim the resistor to more than twice its as-fired value, unless it is a top-hat design. When a top-hat resistor is trimmed, no part of the resistor should be trimmed to a thinner dimension than the width of the part of the resistor that terminates on the conductors at either end of the resistor.

3.8 ATTACHMENT OF COMPONENTS AND LEADS TO THE THICK FILM CIRCUIT

3.8.1 GENERAL COMMENTS ABOUT COMPONENT ATTACHMENT

This step consists of attaching the discrete circuit components and the external leads to the thick film circuit. In this discussion all of the components and leads will be

attached with solder. Conductive epoxy may also be used to attach components and leads to the solder pads on the thick film substrate, but its use will not be explained at this time.

3.8.2 CUTTING AND FORMING THE COMPONENT LEADS

The leads on each of the discrete components must be cut and bent so they touch the proper solder pads while the component stands by itself (if at all possible) with the lowest possible profile. Some components may have to be placed on their sides because they won't stand up by themselves. In any case, you must position each component on its respective solder pads to make sure that it will fit properly.

Component leads and external leads should be formed so they will lay parallel to the substrate over the solder pads. This will allow for the maximum amount of contact between the leads and the solder pads. Leads that are mounted perpendicular to a solder pad do not offer the maximum amount of adhesion possible between the lead and the solder pad and should therefore not be mounted in this way.

Components such as chip capacitors and LID's* need only be positioned on their solder pads to check for the proper orientation, since they should fit their solder pads perfectly if the artwork was cut correctly.

If the external leads that clip onto the substrate are used, you need not clip them on until you are ready to solder them down.

*Reg. T.M. of the Amperex Corp.

3.8.3 APPLICATION OF SOLDER TO THE SOLDER PADS

After all of the components have been fitted to their respective solder pads and it is seen that they fit properly, it is time to apply solder to the solder pads on the circuit.

There are three ways of applying solder that may be used for thick film circuits. They are as follows:

1. Dip soldering--With this method the circuit is submerged in molten solder so that all of the solderable conductors will be coated with solder.
2. Solder plating with a soldering iron--With this method selected portions of the conductors are plated with solder with the aid of a small soldering iron.
3. Application of solder paste--With this method the solder is selectively applied to the conductors as a viscous paste.

METHOD 1

This method is probably the least desirable for two reasons. First, it subjects the thick film circuit to extreme thermal shock, which can cause the resistors to drift off value or it can even cause the substrates to crack. Secondly, a lot of solder is used that is not needed, since all of the solderable conductors will be plated with solder. Despite its shortcomings, this method is often used in industry since it works fairly well on the production line.

When this method is used the circuit is first dipped into a container of rosin flux, and then into the molten solder which is at a temperature of 50 °C to 100 °C above its melting point. The circuit is left in the molten solder just long enough to get a good coating of solder (usually 3 to 5 seconds). If it is left in the solder too long the adhesion of the conductors to the substrate will be reduced and in extreme cases they will be completely removed from the substrate by the dissolving action of the molten solder as it alloys with the conductor material.

METHOD 2

This method is often used when a small number of solder pads need solder plating. It is usually too time consuming to use this method when large volumes of parts are to be processed.

With this method the portion of the conductor to be solder plated is coated with rosin flux and then plated with solder with a small soldering iron. (A Weller 25 watt pencil-tip iron works very well.) The hot iron tip should not be left on the solder pad any longer than it takes to form a smooth, shiny solder coating since the pad can be damaged if it is exposed to molten solder for long periods of time.

METHOD 3

This method is probably the easiest to use since the solder can either be screen printed on the substrate or it can be applied with a small needle or toothpick. The solder

paste must be about 5 mils thick on each solder pad to form a good solder joint. Once the paste is placed on the solder pads it will stay there since it is very viscous; it will also hold circuit components in place during the soldering operation.

3.8.4 SOLDERING DOWN THE COMPONENTS

The next step is to position all of the components and leads on their respective solder pads. If the solder was applied as in methods 1 or 2 the residual flux on the circuit should be tacky enough to hold the components in place. If solder paste was used it will hold the components in place since it is very tacky.

The solder is now ready to be melted (or remelted) so that it can bond to the conductors and the component leads. This process is usually called reflow soldering because, with methods 1 and 2, the solder has already been melted once and when it is heated again it will remelt and flow around the component leads to form a solder fillet. Reflow soldering is actually a misnomer when used to describe the melting of solder paste since it implies that the solder is being melted for the second time on the circuit; however, it is often used this way in the hybrid circuit industry.

To melt (reflow) the solder the circuit must be placed on a hotplate or placed in an infrared heater. When a hotplate is used it is set slightly hotter than the melting

temperature of the solder. When an infrared heater is used its temperature profile is set so that the peak temperature inside the heater is also hotter than the melting temperature of the solder.

Table 5 lists several common solder compositions, their melting temperatures, their suggested reflow temperatures, and their suggested reflow times.

The circuit should be placed on the hotplate, or in the heater, for the suggested time and the solder should be observed to melt and flow around all of the conductors and leads within that time. The soldering operation should not be continued for a long period of time since the conductors can be damaged when molten solder is left on them longer than is necessary. [13, 14, 15]

SOLDER COMPOSITION	MELTING TEMPERATURE	SUGGESTED REFLOW TEMPERATURE	SUGGESTED REFLOW TIME
62%Sn/36%Pb/2%Ag	189 C	200 C-230 C	10-20 sec.
60%Sn/40%Pb	193 C	210 C-240 C	10-20 sec.
95%Sn/5%Ag	235 C	240 C-275 C	10-20 sec.
95%Sn/5%Sb	240 C	260 C-300 C	10-20 sec.
10%Sn/90%Pb	300 C	320 C-350 C	10-20 sec.

Table 5. Popular solders and their suggested reflow times and temperatures. [16]

After the solder has melted and apparently formed good solder fillets around the components and leads the circuit should be allowed to cool to room temperature.

3.8.5 EXAMINATION OF THE SOLDERED CONNECTIONS

The solder fillets should be examined very carefully with the aid of a microscope for any possible defects. Preliminary examination can be done while the soldering flux is still on the circuit. If any defective connections are found they can usually be repaired with a small soldering iron and a small quantity of solder of the same composition as that used on the circuit. The residual flux on the circuit should be sufficient for any repair work that must be done at this time.

A good solder fillet should be very shiny in appearance and the solder should be smooth and free of lumps and partially-melted solder. Also, the solder should have the appearance of wetting the conductors and should actually look as if it has become a part of the conductors, which it should do if it has alloyed properly with the conductor metals.

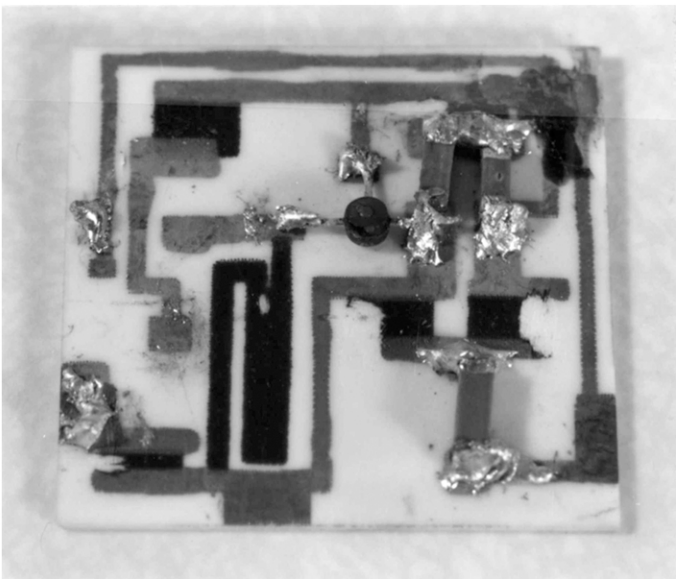
If all of the soldered connections look good the circuit should be cleaned in toluene or trichloroethylene to remove the solder flux. The cleaning should be done in an ultrasonic cleaner if one is available since it will help to remove flux and loose solder from under the components.

After a thorough cleaning the circuit must be examined once more for defective solder connections. With the flux removed a poor solder fillet will be much easier to spot. If too little solder was used or if the soldering time was too long the solder will not appear smooth and shiny; instead

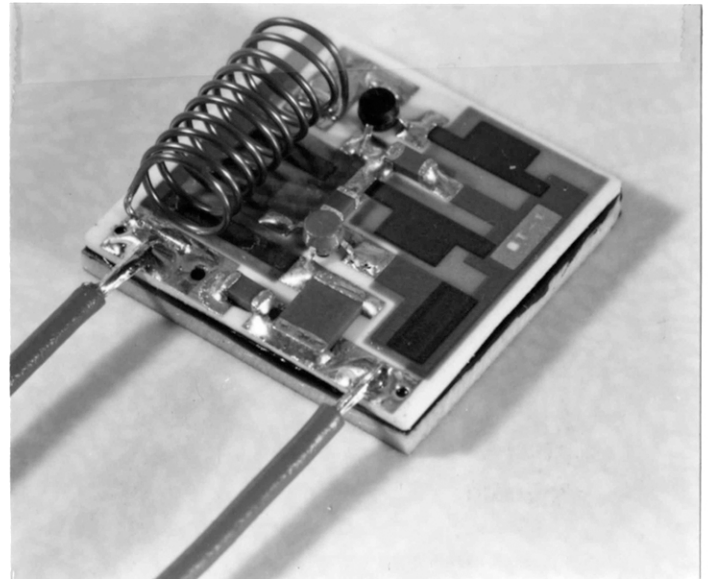
it will be dull gray in color and will often have a rough, granular surface finish. If the soldering operation was performed at too low a temperature the solder will not appear to wet the conductors but rather it will usually just be setting on the conductors in little balls. All defective solder connections must be repaired before the circuit can be considered mechanically sound.

The circuit should be cleaned one final time in toluene or trichloroethylene to remove all traces of residual flux. Several rinses are recommended to remove all of the flux. Each cleaning should be done in an ultrasonic cleaner if possible. If any flux is left on the circuit it may cause shorts or component instability later on. Also, the flux will prevent the coating material from adhering to the circuit properly.

See Figure 52 for examples of both good and bad solder connections.



a. Bad solder connections.



b. Good solder connections.

Figure 52. Examples of good and bad solder connections.

3.9 TESTING THE CIRCUITS ACCORDING TO STANDARD METHODS

3.9.1 THE REASONS FOR TESTING THE CIRCUITS

At various places in the fabrication process, and after the final assembly, each hybrid circuit must be subjected to certain electrical and environmental tests to assure that it will meet all of its design specifications. In order that the consumer and the manufacturer can be in agreement on the types of tests performed on the circuits, certain standard test methods are usually followed. The most widely accepted test methods for electronic circuits are the Military Standards, of which MIL-STD-202D and MIL-STD-883 are the most common. Both of these documents contain standardized test methods and procedures that have been developed by the military for the electronic components that it buys, and they have been generally accepted by most engineers and industrial organizations as standards in the electronics industry.

3.9.2 THE MILITARY STANDARDS

Both of the documents mentioned in section 3.9.1 are divided into three main categories of tests:

1. Environmental tests.
2. Physical-characteristics tests.
3. Electrical-characteristics tests.

Under each of the three main categories many different tests are spelled out. Each test is explained very carefully

so that no mistake concerning interpretation of the test procedure will be made. [9, 10]

Some of the tests that a hybrid circuit might be subjected to, according to the Military Standards, are as follows:

ENVIRONMENTAL TESTS

- a. Temperature cycling
- b. Thermal shock
- c. Moisture resistance
- d. High temperature storage
- e. Package seal

PHYSICAL-CHARACTERISTICS TESTS

- a. Vibration
- b. Mechanical shock
- c. Solderability
- d. Resistance to soldering heat
- e. Resistance to solvents

ELECTRICAL-CHARACTERISTICS TESTS

- a. DC resistance
- b. Resistance-temperature characteristic (TCR)
- c. Capacitance
- d. Current-noise test for fixed resistors
- e. Voltage-coefficient of resistance (VCR)

MIL-STD-202D was written primarily for the testing of individual circuit components such as resistors and capacitors while MIL-STD-883 was written primarily for the testing of

microelectronic circuit components such as transistors and integrated circuits. The test procedures in MIL-STD-202D are in general less involved and less demanding than are those in MIL-STD-883.

For most circuits, only those tests that are the most important and are actually used, since some of the tests were designed for very special purposes. It is up to you, the design engineer, to choose the appropriate tests for the hybrid circuits you design so that you can be sure that they will perform as expected once they are put into service

APPENDIX I

A THICK FILM HYBRID CIRCUIT GLOSSARY

ALUMINA: Aluminum oxide (Al_2O_3). The typical thick film substrate is made from a formulation of 96% Al_2O_3 , with 4% impurities.

AMBERLITH: A registered trade mark of the Ulano Companies. Amberlith is a masking film used in the preparation of artwork patterns. Amberlith consists of a clear polyester backing and a thin, amber colored top film that can be easily cut and peeled off to form any desired pattern.

ANGLE-OF-ATTACK: The angle between the leading edge of the squeegee and the surface of the screen, measured during the printing stroke.

ASPECT RATIO: The ratio of the length to the width, of a thick film resistor.

BREADBOARD: The circuit that is constructed on a piece of perforated circuit board with discrete circuit components so that the performance of the circuit can be determined before the thick film circuit is built.

CHIP CAPACITOR: A miniature capacitor that does not have wire leads extending from its ends but rather has solderable terminals on its ends, and that was designed specifically for use on hybrid microcircuits.

CONDUCTOR: When used in conjunction with thick film hybrid circuits, this term refers to any pattern on the thick film substrate that was printed with a low-resistivity precious metal conductor paste.

CONDUCTOR PASTE: A thick film paste that is composed of a high percentage of metal and a low percentage of glass. Common conductor paste metals are Pt, Pd, Au, and Ag.

CONFORMAL COATING: Any coating on a hybrid circuit that conforms to the surface profile of the components on the substrate. Conformal coatings are usually produced by pouring epoxy onto a circuit or by dipping the circuit into epoxy and then letting the excess drip off.

DIELECTRIC PASTE: A thick film paste that is a special mixture of glass and can be used for making insulating layers on a thick film circuit. There is no conductor metal in a dielectric paste. The glass is usually mixed with a binder of some kind and also some organic solvent.

DIRECT EMULSION: The photographic emulsion that is applied to the printing screen fabric as a liquid. With this type of emulsion the pattern to be printed is transferred to the emulsion after the emulsion has been placed on the screen and dried.

DISCRETE DEVICE: Any electronic device or circuit component that is not fabricated on the thick film substrate, but is attached to the substrate to form a hybrid circuit. Also, any circuit component that is packaged as a single unit, such as a chip capacitor, a round capacitor with axial leads, or even a single transistor in a metal can.

DUROMETER: A measurement of the hardness of a material. Thick film printing squeegees are classified as being of a certain durometer in hardness. Most thick film printing squeegees are between 60 durometer and 80 durometer, with 60 being the most common.

EMULSION: The organic material that is placed on the printing screen to retain the image of the thick film pattern to be printed. It is also sensitive to ultraviolet light.

ENCAPSULATING: The process of covering or sealing a circuit so that it will be protected from the environment. See also "potting".

EPOXY: A packaging and coating material that is applied as a liquid but that hardens to form a tough, moistureproof seal for the component or device that it encases.

FLUX: In soldering, any material that is used to chemically attack oxide and corrosion on a solderable metal so that the solder will alloy properly with the metal when heat is applied. Rosin flux should always be used when soldering to electrical circuits. Acid flux should never be used.

HYBRID MICROCIRCUIT: A microcircuit consisting of elements which are a combination of the film circuit type and the semiconductor types, or combinations of both types with discrete parts (MIL-STD-1313A).

INDIRECT EMULSION: The emulsion that is applied to the printing screen as a sheet of film with the thick film circuit pattern already present in it.

INK: Synonymous with "paste" and "composition" when referring to screen printable thick film materials.

KIMWIPE: A lint-free disposable paper towel that is used in laboratories where dust and lint is not wanted.

LID: Abbreviation for Leadless Inverted Device. A LID is composed of a hollow ceramic shell (alumina) with an active device, such as a transistor, mounted inside the cavity. The LID is designed to be soldered to a thick film circuit to provide a compact and rugged active circuit device.

MONOFILAMENT FABRIC: Fabric that is woven with single-filament threads of material.

NOMINAL VALUE: The final, design value of a circuit component.

OVERGLAZE PASTE: A thick film paste that is a special formulation of glass and organic solvent that can be used to coat resistors and conductors with a transparent layer of glass insulation.

PASTE: The material that is placed on the substrate by the process of screen printing. The paste is a composition of conducting metals, insulating glasses, and organic vehicles and binders that give it its required printing properties. Also synonymous with "ink" and "composition".

POTTING: The process of packaging a circuit by placing it in a container and filling the container with material such as epoxy, so that the circuit is completely encased in the material. See also "encapsulating".

PRINTED CIRCUIT BOARD: A board, either of phenolic and paper, or of fiberglass and epoxy construction, which has been plated with a conductor such as copper, and then has had the conductor selectively etched off to leave a particular pattern of conductors on the board.

PRINTING SCREEN: Synonymous with the term "screen". See also "silk screen".

REFLOW SOLDERING: The process of soldering in which solder is placed on the various component leads and solder pads and then melted and allowed to fasten the component leads to the solder pads.

RESISTOR PASTE: A thick film paste that is composed of a low percentage of metal and a high percentage of glass, and also other materials, which control different properties of the fired resistors.

RUBYLITH: A registered trade mark of the Ulano Companies. Rubylith is a masking film used in the preparation of artwork patterns. Rubylith consists of a clear polyester backing and a thin, red-colored top film that can be easily cut and peeled off to form any desired pattern. Rubylith is equivalent to Amberlith except for its color.

SCREEN: This term refers to the printing screen used in the screen printing process. The screen is composed of a fabric, usually monofilament polyester, stretched over a rigid frame with a pattern retained in an emulsion that is attached to the fabric. See also "silk screen" and "printing screen".

SILICON TECHNOLOGY: The method by which active devices such as transistors and integrated circuits are fabricated. The processes include high temperature diffusions and acid etches in order to form the required devices.

SILK SCREEN: The original name of the screen used in the screen printing process. The silk screen was composed of a silk fabric stretched over a rigid frame with a pattern retained in an emulsion that we attached to the fabric. See also "screen" and "printing screen".

SOLDER PASTE: A composition of finely ground solder, flux, and organic binders. It is designed as a viscous paste so that it can be screen printed.

SQUEEGEE: The tool or instrument that is used to spread the thick film paste across the surface of the printing screen and to force the paste through the openings in the screen and onto the substrate.

SUBSTRATE: (for a microcircuit or an integrated circuit) The supporting material upon or within which the elements of a microcircuit or integrated circuit are fabricated or attached (MIL-STD-1313A). For a thick film circuit the substrate material is alumina while for a semiconductor device such as a transistor or integrated circuit it is silicon.

TARGET VALUE: A value other than the nominal value that a component is processed to in order to allow subsequent adjustment of the component to its nominal value.

TEMPERATURE PROFILE: A graph of the temperature versus distance (or time) through a thick film firing furnace, as seen by a substrate as it is being fired in the furnace.

THICK FILM TECHNOLOGY: The method of producing circuit elements by the process of screen printing of a film and the subsequent firing of the film at a high temperature to cure it to its final form. Thick films are typically 1-2 mils thick.

THIN FILM TECHNOLOGY: A method of producing circuit element by the vacuum evaporation of certain materials to form thin conducting films, usually less than 20,000 Angstroms thick.

THIXOTROPY: The property of thick film pastes whereby they become fluid when they are agitated, as during the printing stroke, and then become very stiff when they are left alone.

TOLERANCE: The allowable variation about the nominal value of a circuit component.

TRIM: The process of removing material from a circuit element in order to change its value to a higher value, in the case of a resistor, or to a lower value, in the case of a capacitor.

VISCOSITY: The resistance of a substance to being fluid, caused by molecular attraction. The unit of viscosity measurement is poise; most thick film pastes have a viscosity in the range of 100,000 to 500,000 centipoise.

THICK FILM HYBRID CIRCUIT COMPONENTS AND MANUFACTURERS

CAPACITORS FOR HYBRID CIRCUITS:

1. UNION CARBIDE CORP., MATERIAL SYSTEMS DIVISION, COMPONENTS DEPT.,
P.O. BOX 5928, GREENVILLE, S.C. 29606
2. USCC/CENTRALAB, ELECTRONICS DIV., GLOBE-UNION, INC., 2151 NORTH
LINCOLN STREET, BURBANK, CALIFORNIA 91504

CIRCUIT BOARDS:

1. KEPRO CIRCUIT SYSTEMS, INC., 3630 SCARLET OAK BLVD.,
ST. LOUIS, MO. 63122
2. VECTOR ELECTRONICS CO., INC., 12460 GLADSTONE AVE.,
SYLMAR, CALIFORNIA 91342

COATING MATERIALS:

1. DOW CORNING CORP., 4825 NORTH SCOTT ST.,
SCHILLER PARK, ILL. 60176
2. EMERSON & CUMING, INC. CANTON, MASS. 02021
3. THIOKOL CHEMICAL CORP., 780 NORTH CLINTON AVE.,
TRENTON, NEW JERSEY 08607
4. TRA-CON, INC., 55 NORTH ST., MEDFORD, MASS. 02155

EMULSIONS FOR THICK FILM PRINTING SCREENS:

1. COLONIAL PRINTING INK CO., 180 EAST UNION AVE.,
EAST RUTHERFORD, NEW JERSEY 07073
2. ULANO PRODUCTS CO., INC., 210 E. 86TH. ST., N.Y., N.Y. 10028

FABRICS FOR THICK FILM PRINTING SCREENS:

1. ADVANCE PROCESS SUPPLY CO., 400 N. NOBLE ST.,
CHICAGO, ILL. 60622
2. MAJESTIC BOLTING CLOTH CORP., 470 PARK AVE. SOUTH,
NEW YORK, NEW YORK 10016

FILMS FOR ARTWORK:

1. EASTMAN KODAK CO., ROCHESTER, NEW YORK 14650
2. ULANO PRODUCTS CO., INC., 210 E. 86TH. ST., N.Y., N.Y. 10028

FRAMES FOR THICK FILM PRINTING SCREENS:

1. ADVANCE PROCESS SUPPLY CO., 400 N. NOBLE ST.,
CHICAGO, ILL. 60622
2. WELTEK DIV., WELLS ELECTRONICS, INC., 1701 S. MAIN ST.,
SOUTH BEND, IND. 46623

FURNACES FOR THICK FILM PROCESSING

1. BTU ENGINEERING CORP., ESQUIRE RD.,
NORTH BILLERICA, MASS. 01862
2. WATKINS-JOHNSON CO., 3333 HILLVIEW AVE., PALO ALTO, CAL. 94304

INKS FOR THICK FILM CIRCUITS:

1. CERMALLOY DIV. OF BALA ELECTRONICS CORP., 14 FAYETTE ST.,
CONSHOHOCKEN, PA. 19428

INKS FOR THICK FILM CIRCUITS (CONT.):

2. E.I.DU PONT DE NEMOURS & CO.(INC.), 1007 MARKET ST.,
WILMINGTON, DEL. 19898
3. ELECTRO SCIENCE LABS, INC., 1601 SHERMAN AVE.,
PENNSAUKEN, NEW JERSEY 08110
4. MATTHEY DISHOP, INC., MALVERN, PENN. 19355

LEADS FOR THICK FILM HYBRID CIRCUITS:

1. ADVALLOY, INC., 844 E. CHARLESTON ROAD, PALO ALTO, CALIF. 94303
2. BERG ELECTRONICS, DIV. E.I.DU PONT DE NEMOURS & CO.(INC.),
YORK EXPRESSWAY, NEW CUMBERLAND, PA. 17070
3. PLESSEY MONTVALE, 20 CRAIG RD., MONTVALE, N.J. 07645

MICROSCOPES

1. AMERICAN OPTICAL CORP., SCIENTIFIC INSTR. DIV., EGGERT RD.,
BUFFALO, N.Y. 14215
2. BAUSCH & LOMB, INC., 61473 BAUSCH ST., ROCHESTER, N.Y. 14602
3. CARL ZEISS, INC., 444 FIFTH AVE., NEW YORK, N.Y. 10018

PRINTERS FOR THICK FILM CIRCUITS:

1. WELTEK DIV., WELLS ELECTRONICS, INC., 1701 S. MAIN ST.,
SOUTH BEND, IND. 46623

SOLDER AND FLUX:

1. KESTER SOLDER CO., 4201 WRIGHTWOOD AVE., CHICAGO, ILL. 60639

SUBSTRATES FOR THICK FILM CIRCUITS:

1. AMERICAN LAVA CORP., MFRS. RD. & CHEROKEE BLVD.,
CHATTANOOGA, TENN. 37405
2. CENTRALAB, DIV. GLOBE-UNION INC., 5757 N. GREEN BAY AVE.,
MILWAUKEE, WIS. 53201
3. COORS PORCELAIN CO., 600 NINTH ST., GOLDEN COLO. 80401

TRANSISTORS (INCLUDING LED'S, DIODES, OP AMPS, ETC.)

1. AMPEREX ELECTRONIC CORP., ELECTRO OPTICAL DEVICES DIV.,
PROVIDENCE PIKE, SLATERSVILLE, R.I. 02876
2. DIALIGHT CORP., 60 STEWART AVE., BROOKLYN, N.Y. 11237
3. MOTOROLA SEMICONDUCTOR PRODUCTS, INC., BOX 20912,
PHOENIX, ARIZ. 85036
4. SIGNETICS CORP., 811 EAST ARQUES AVE., SUNNYVALE, CALIF. 94086

TRIMMERS FOR THICK FILM CIRCUIT ELEMENTS:

1. ELECTRO SCIENTIFIC INDUSTRIES, INC., 13900 N.W. SCIENCE PARK DR.,
PORTLAND, ORE. 97229
2. S.S.WHITE INDUSTRIAL PRODUCTS, 151 OLD NEW BRUNSWICK ROAD,
PISCATAWAY, N.J. 08854

NOTE: ADDITIONAL MANUFACTURER'S ADDRESS CAN BE OBTAINED
FROM THE "ELECTRONICS BUYER'S GUIDE", A PUBLICATION OF
McGRAW-HILL INC.

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A THICK FILM HYBRID CIRCUIT
LABORATORY MANUAL

by

MICHAEL RAYMOND CASEY

B. A., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

This manual was written to provide the student in the Integrated Circuits Engineering laboratory at Kansas State University with the basic information necessary to design and fabricate thick film hybrid circuits. It is intended as a supplement to the material presented in the course lectures and therefore covers many details that are not normally covered in the lectures.

The manual discusses the basic design considerations and fabrication techniques for typical thick film hybrid circuits by first defining a hybrid circuit and then by outlining the steps involved in the fabrication of a typical circuit. Finally, it explains in detail each of the major process steps required in the fabrication of these circuits.

A glossary of the terms common to the thick film hybrid circuit industry is included. Also included is a list of manufacturers and their products.