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NBS CIRCULAR 587

Electroforming of Waveguide Components for the Millimeter-Wavelength Range

UNITED STATES DEPARTMENT OF COMMERCE

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Electroforming of Waveguide Components for the Millimeter-Wavelength Range

Albert A. Feldmann

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Albert A. Feldmann

The technique of electroforming has become very important in the production of precision waveguide components. In the millimeter-wavelength range it represents almost the sole method of construction for precision components. Given machine-shop facilities, normal laboratory facilities, and a few auxiliary items, electroforming of the best quality can be done without much difficulty. This is of particular importance to research workers in university or Government laboratories. Simple techniques are outlined that permit the production of high-quality millimeter components with a minimum of equipment, time, or specialized knowledge of electrodeposition.

1. Introduction

The technique of electroforming is increasingly being employed for the production of precision waveguide components at all microwave frequencies. In the frequencies up to 25,000 Mc, corresponding to the so-called K-band size, certain alternate techniques of construction are available. These include the soldering together of assemblies made from straight sections of waveguide, or precision casting of components [1].[1] With increasing frequencies the mechanical tolerances required exclude the other methods, leaving electroforming, at present, as the only suitable manufacturing technique.

Although the process of electroforming is well known and has been employed for making electrotypes and record masters, very few commercial electroplaters offer such services. Demand for electroforming, except for special applications, is small, and the cleanliness and close supervision required are more trouble than it is worth to the average electroplater. The need for machining facilities for mandrels is another deterrent. As a result, there are only a few companies in the United States of America that will electroform waveguide components.

Most of the work at millimeter wavelengths is still carried on by university laboratories or Government research laboratories, such as the National Bureau of Standards or the Naval Research Laboratory in Washington, D. C. The number of components required in the individual case may be small, but requirements of accuracy are often quite stringent. The reason for these requirements will easily be recognized from table 1.

Mechanical accuracy of inside waveguide dimensions in electroformed components is a direct function of the dimensional accuracy of the mandrel over which they are formed, because there is no separating medium between them. The tolerances listed in table 1 are those permitted by the Armed Forces. Far stricter tolerances apply in many research projects, and particularly in National Bureau of Standards work. In other words, means for producing accurate mandrels, i. e., machine-shop facilities, are indispensable. It has been the author's experience that, even where the actual electroforming was done commercially, it proved more reliable to provide completed mandrels whose dimensional accuracy

TABLE 1. *Rigid rectangular waveguide sizes in the millimeter range*

				DIMENSIONS IN INCHES						RECOMMENDED OPERATING RANGE FOR TE$_{1,0}$ MODE		CUT-OFF FOR TE$_{1,0}$ MODE	
				INSIDE			OUTSIDE						
		JAN TYPE	MAT'L	WIDTH	HEIGHT	TOL	WIDTH	HEIGHT	TOL	FREQUENCY	WAVELENGTH	FREQUENCY	WAVELENGTH
▭	K	RG-66/U	SILVER	0.420	0.170	±0.002	0.500	0.250	±0.003	kMc 18.00-26.50	cm 1.67 - 1.13	kMc 14.080	cm 2.13
▭	K		COPPER	0.420	0.170	±0.002	0.500	0.250	±0.003	18.00-26.50	1.67 - 1.13	14.080	2.13
▭	V	RG-96/U	SILVER	0.280	0.140	±0.0015	0.360	0.220	±0.002	26.50-40.00	1.13-0.75	21.100	1.423
▭	J	RG-97/U	SILVER	0.224	0.112	±0.0010	0.304	0.192	±0.002	33.00-50.00	0.909-0.600	26.350	1.138
▭		RG-98/U	SILVER	0.148	0.074	±0.0010	0.228	0.154	±0.002	50.00-75.00	0.600-0.400	39.900	0.752
▭		RG-99/U	SILVER	0.122	0.061	±0.0005	0.202	0.141	±0.002	60.00-90.00	0.500-0.330	48.400	0.620
●		RG-138/U	SILVER	0.080	0.040	±0.0003	0.156 DIA.		±0.001	90.00-140.00	0.330 - 0.214	73.840	0.406

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[1] Figures in brackets indicate the literature references at the end of this Circular.

had been checked than to rely on the electroforming company for their construction. Even then, the various delays involved in shipping and necessary correspondence fix the completion time for a component anywhere from 1 to 3 months. This contrasts with the actual time of electrodeposition for the average component of from 15 to 25 hr.

Given the machine-shop facilities, normal laboratory facilities, and a few auxiliary items, electroforming of the best quality can be done without much difficulty. The following is an outline of the procedures and materials required, from a small beaker operation to a small-scale production facility.

2. Metals To Be Deposited

Some 20 or more pure metals have been successfully electrodeposited. However, there is a definite dividing line in electrodeposition, between electroplating and electroforming. By definition, "electroforming is the production or reproduction of articles by electrodesposition" [2]. Only a few metals lend themselves to the heavy metal deposits (0.015 to ¼ in.) applied in the process. Four of them are of significance in the construction of waveguide components. They are silver, copper, nickel, and aluminum. Of these four metals, silver and copper are by far the most important because of their high electrical conductivity. Nickel is used where components might be exposed to very high temperatures or chemical attack. Aluminum would be considered for lightness in aircraft installations. This is presently not a consideration in millimeter-wavelength components, although it applies at lower microwave frequencies [3]. Therefore, aluminum as a forming metal will not be discussed. Prime consideration will be given to silver and copper, which account for perhaps 95 percent of all millimeter waveguide components.

Silver is used mainly because of its superior electrical conductivity. Because the physical dimensions of millimeter components rarely exceed 2 to 3 in. in any direction, the cost of the metal (about $1.10 an ounce) is small as compared to the cost of labor involved. The electrical conductivity of copper is slightly inferior to that of silver (1.67 microhm-cm resistivity for copper as against 1.62 microhm-cm resistivity for silver) [4]. But because electrodeposited metals may have a somewhat porous structure that is influenced by a number of variables during the process of deposition, data taken from conductivity measurements on solid metal specimens are not properly applicable. Certain investigations indicate that the maximum conductivity to be expected approaches 95 percent of IAC value [5]. Therefore, from the consideration of conductivity, the preference of silver over copper as an electroforming material may not be fully justified. Whatever metal is used, it is best to obtain it in the highest purity available as anode material.

3. Required Equipment

3.1. Power Source

A low-voltage d-c source is required. This may be an available d-c filament supply, a storage or automobile battery, or similar source. Variable voltage from 1 to 6 v and current capacity of about 10 to 20 amp are required. Each bath supplied from the power source requires an ammeter with a series-connected rheostat of suitable capacity for control of current density. If several beakers or tanks will be operated regularly at the same time, the use of bus bars will be found very convenient (fig. 1).

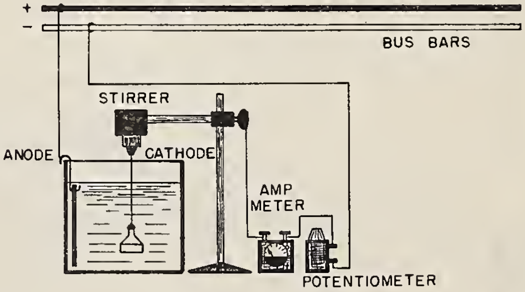

Figure 1. *Bus bars.*

3.2. Tanks

The size of the bath may vary from 500 ml to 10 gal or more, depending on the size and number of components it is to accommodate. On an average, a 1,000-ml beaker will suffice for most strike baths, whereas the size of the electroforming tank may vary. Up to a gallon, Pyrex beakers or battery jars are the best tanks. They can be washed easily, are not attacked by acids or alkalis, and permit observations of the article during the electroforming process. In the larger sizes, transparent plastic tanks with welded seams are recommended. It is important that well-fitting covers be provided for all types of tanks to minimize evaporation during periods when the bath is not in use.

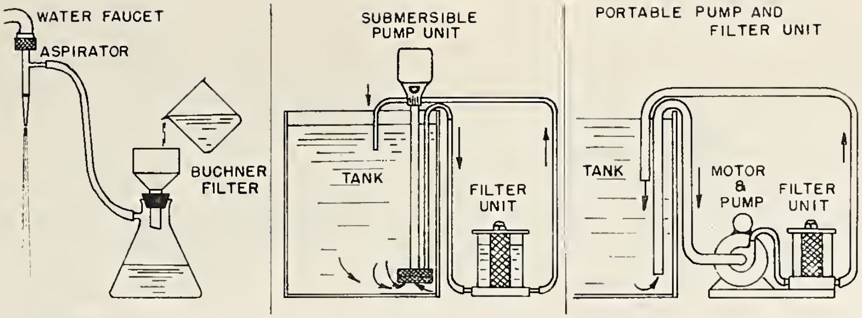

FIGURE 2. *Arrangements of filtering units.*

3.3. Filters

Periodic filtering of solutions and occasional treatment with activated carbon will remove most accumulated impurities and metal particles. The appearance of the deposit will be greatly improved along with its quality, and troubles will remain at a minimum. An aspirator, to be attached to the water faucet, a filtering flask of 1-liter capacity, a Buchner funnel, and some filtering paper of the right size to fit the funnel are all that is required for a tank up to a 1-gal capacity. For larger tanks it will be more practical to use a small combination pump and filter. It can be portable and, if thoroughly cleaned after each use, may be used to filter any number of different solutions. For ease and cleanliness of operation, it is important that the pump be self-priming and leakproof. The latter condition is not easily met, particularly after a pump has been in use for a while. Where filtering is done periodically this represents only a small nuisance. If it is decided to provide continuous filtering in a heavily used large bath, the best solution is a submerged centrifugal pump with the filter unit outside the bath. Figure 2 shows the different arrangements. The material of the pump and the filter is important, and the recommendations of the manufacturer should be followed with regard to corrosion resistance.

3.4. Auxiliary Equipment

Stirrers, heaters, *p*H indicators, masking materials, cleaning brushes, calibrated graduates, funnels, a few spare tanks, and a balance are required.

a. Stirrers

A laboratory stirrer should be available for each bath to provide agitation of the bath, and a means for rotating of the work. A more elaborate arrangement is shown in figure 3, providing a drive for multiple spindle operation. Variable speed control is important.

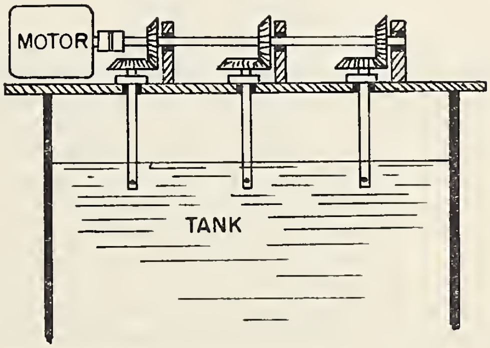

FIGURE 3. *Multiple spindle operations.*

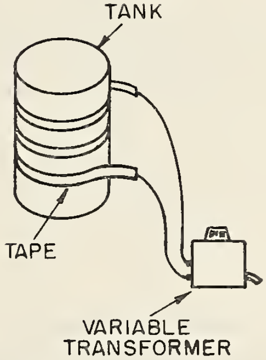

FIGURE 4. *Use of heating tape.*

b. Heaters

At least one electric hotplate should be available. Although most plating solutions will be operated at room temperature, cleaning and pickling solutions should be used hot, for best results. For this purpose, heating tapes can be used. These are resistance wires that are insulated by layers of knitted glass yarn and arranged in the form of tapes. They can easily be wrapped around a beaker or small tank. A variable transformer (fig. 4) provides close temperature control.

c. Thermometers

Several thermometers of the dial type with long stems will be useful.

d. Control of *p*H

Maintenance of the correct *p*H (acidity or alkalinity) of the solution is very important. The *p*H can be most easily measured by the colorimetric method. A strip of paper containing a number of standard color bands and covering a certain range of *p*H values is immersed in the bath. In the middle of the strip is the "indicator" band, which changes color according to the *p*H of the solution. By matching the "indicator" color with one of the standard color bands, the *p*H of the solution is found. The strips can be obtained for a variety of *p*H ranges.

e. Masking Material

It is generally necessary to mask the ends of a mandrel to retain reference surfaces for subsequent machining and mounting of connecting flanges. The masking can be done with plastic tape made specifically for this purpose, by painting the area with protective paint or by dipping it into a hot plastic material that solidifies at room temperature within a few seconds. All three of the above methods are used. The last mentioned is the easiest to apply and provides the most protection. The hot-dip method calls for an additional piece of equipment, i. e., a small melting pot with a built-in temperature control.

f. Brushes

A few small brushes, preferably hard bristled, are needed for cleaning. It is well to get one small enough to fit the inside of the smaller-sized guides. For the very smallest, pipe cleaners can be used.

g. Glassware

One or two graduates calibrated in milliliters and ounces are needed for measuring solutions. Some funnels and a few extra beakers of various sizes, for transferring solutions, are also needed.

h. Balance

A balance for weighing chemicals is required. It need not be accurate to more than ½ g.

3.5. Chemicals

a. For Cleaning

Soda ash (Na_2CO_3),
Sodium hydroxide (Na OH),
Trisodium phosphate (Na_3PO_4),
Pumice of several grades,
A good liquid detergent,
Hydrochloric acid (HCl),
Sulfuric acid (H_2SO_4),
Nitric acid (HNO_3),
Chromic acid (Cr_2O_3),
Magnesium oxide (MgO).

b. For Bath Solutions

1. *Copper baths:* Copper sulfate ($CuSO_4{\cdot}5H_2O$),
Copper cyanide (CuCN),
Sodium cyanide (NaCN),
Copper addition agent: Wes–X–303.[2]

2. *Silver baths:* Silver cyanide (AgCN),
Potassium cyanide (KCN),
Potassium carbonate ($K'CO_3$),
Potassium nitrate (KNO_3),
Potassium hydroxide (KOH),
Silver addition agent: Ammonium thiosulfate $(NH_4)_2\ S_2O_3$.

3. *Nickel baths:* Nickelous sulfate ($NiSO_4{\cdot}6H_2O$),
Nickel chloride ($NiCl_2{\cdot}6H_2O$),
Boric acid (H_3BO_3).

4. Mandrels

The form or mandrel over which the millimeter waveguide component is electroformed is expendable. Nevertheless, careful consideration must be given to its design and construction to achieve satisfactory results. Many mandrels used for larger waveguide sizes are of the permanent type. That means they can be withdrawn after the forming process, by one way or another, and be used over again almost indefinitely. This applies, of course, only to components such as straight sections, tapered adapters, and horns, which permit the removal of the mandrel. In other cases such as bends, hybrid junctions, and directional couplers, expendable mandrels or combinations of permanent and expendable mandrels are used.

The ratio of length to cross-sectional dimensions of a millimeter waveguide mandrel is such as to render it quite fragile even if made of steel. To remove such a mandrel, even from a straight section of guide, will almost always cause it to twist or bend, thus making it useless for further application.

The first qualification for the mandrel material will then be that it be easily removable from the electroform. This can be accomplished by melting it out, or by chemically removing it. Several alloys with low melting points could be used for this purpose. However, because their constituents are lead, tin, and bismuth, they are quite soft and cannot be machined to accuracies of the order of 0.0002 in. Chemical removal calls for a metal which can be dissolved at a relatively fast rate in a solution that will not attack the waveguide metal.

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[2] Wes–X–303 is an addition agent for electroforming in an acid-copper bath. It is available from suppliers of plating chemicals. Among several addition agents tried, Wes–X–303 was found to give the best results in providing smooth, fine-grained deposits of high quality.

Aluminum fills that requirement because it can be dissolved quite readily in a concentrated caustic solution which will not attack copper, silver, or nickel. But pure aluminum of the 2S or 3S commercial grade is still too soft, making accurate machining difficult. However, there are a number of aluminum alloys which are of suitable quality. Those containing a high percentage of copper cannot be used because the copper of the mandrel may bond to the deposit and leave either pits or raised spots on the surface. The most suitable alloy was found to be No. 61S–T with No. 52S–O also acceptable.

In machining the mandrel, care must be taken not to use any kind of cutting oil. Since a thorough scrubbing of the mandrel is usually impossible because of its fragility, grease and dirt removal depend almost entirely on the alkaline cleaning and pickling cycle. Cutting oils often penetrate into the surface layers of the metal. They may be the cause of blistering of the deposit on what appeared to be a chemically clean surface. Although thin deposits can be stripped, the surface finish will suffer, often leaving the mandrel surface too rough and etched for further use.

The machining of straight sections is best done on a milling machine. The operation known as fly-cutting gives a good surface finish. Subsequent lapping can be done but is not usually necessary. Holding the mandrel on the chuck during the machining presents a problem. A simple, but very effective procedure is to mount the parts by means of double coated, pressure-sensitive tape (see fig. 5).

Among the most frequent types of components encountered are H-plane and E-plane T-junctions, hybrid junctions and bends. In the larger waveguide sizes such mandrels were generally assembled from several pieces (fig. 6). The maintenance of perfect symmetry and avoidance of cracks at the joining surface always requires much time of a highly skilled instrument maker. As the waveguide sizes reach the millimeter region, even this laborious method becomes unfeasible because of the flimsiness of the mandrel. Some components have been constructed by machining from solid stock and bolting the several parts together (fig. 7).

A new approach to the design of mandrels permits the electroforming of millimeter components with the same techniques as applied with larger size waveguides. By using this design also for the larger size mandrels, machining time can be reduced and the mechanical strength of the electroformed components greatly increased. By starting with 61S–T aluminum alloy in angle shape, a hybrid T-junction mandrel can be machined as indicated in figure 8. A new feature is the provision for filleted corners which provides advantages which are important enough to be discussed further.[3]

Initially, waveguide components were constructed by soldering straight sections of guide together into an assembly (fig. 9). This method is still widely used in large waveguide sizes where mechanical tolerances are not very close, such as for components of some communication systems. In making up mandrels for electroforming, the same method was used for assembly, the waveguide being replaced by straight sections of mandrel that were screwed, rather than soldered, into an assembly. The sharp corners formed by the apices of the angles between the sides of the waveguide arms, permit a close check for symmetry of the mandrel. These same sharp corners, though, are detrimental to the mechanical strength of the electroformed component.

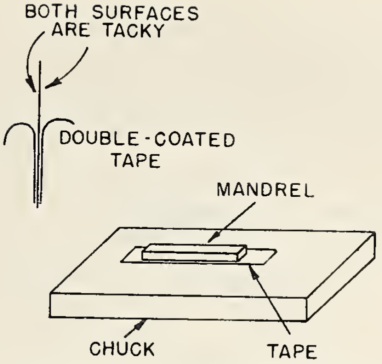

Figure 5. *Use of double coated tape.*

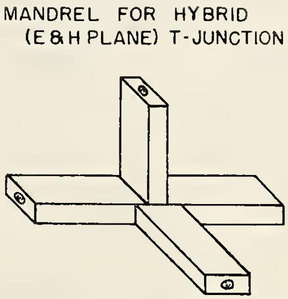

Figure 6. *Mandrel for hybrid (E&H plane) T-junction.*

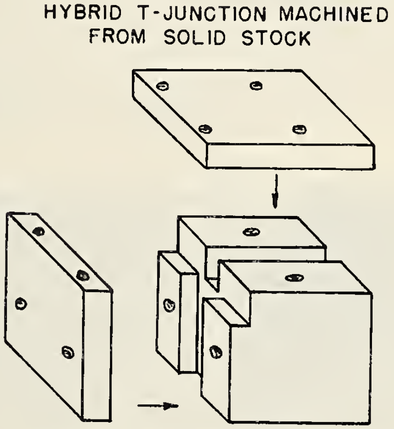

Figure 7. *Hybrid T-junction machined from solid stock.*

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[3] The possibility of this use of fillets was suggested by David M. Kerns.

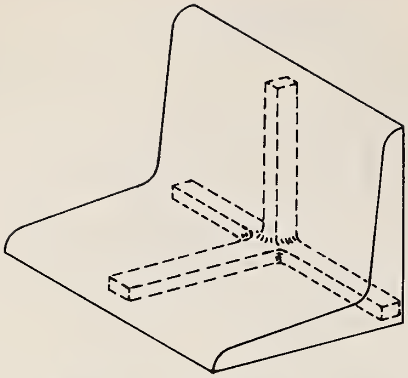


Figure 8. *Method of milling hybrid T-junction mondrel from aluminum angle.*

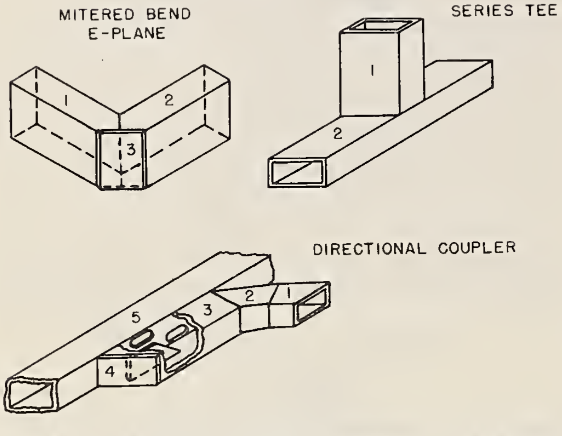


Figure 9. *Method of joining waveguide components by soldering.*

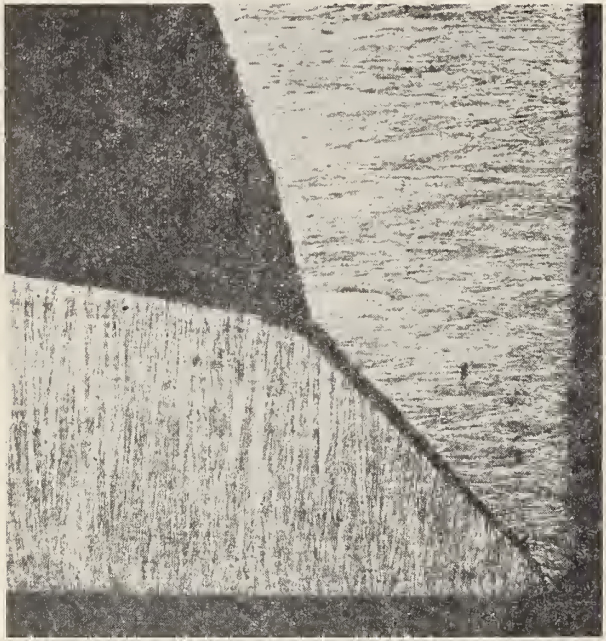


Figure 10. *Photomicrograph of acid copper deposit inside sharp angle.*

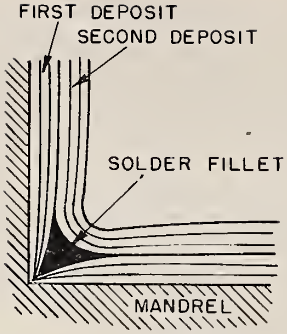


Figure 11. *Use of solder fillets.*

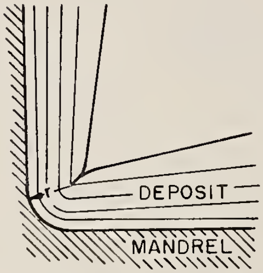


Figure 12. *Reappearance of cleavage plane.*

It is in the nature of electrodeposition on an irregularly shaped mandrel that the deposit will be thicker on projecting areas than it is in recesses. This is a progressive phenomenon in which the deposits on the projecting areas become heavier and heavier, and those in recesses thinner until they stop altogether. In theory, no metal will deposit in the apex of an acute angle. Actually, deposits do form here, particularly with the help of auxiliary anodes. However, the deposit forms in a peculiar way. A photomicrograph taken of an acid copper deposit inside a sharp angle furnishes the explanation (fig. 10). Crystals grow out from both legs of the angle until they meet in the middle, forming a clearly defined straight cleavage plane. As a result, the mechanical strength of the joint is negligible. One method for overcoming this weakness consists in forming a fillet of solder over the cleavage, after which more metal is deposited over the fillet to build a reinforcement. This method is effective, but requires great skill in application and makes the whole operation much more complicated. Sometimes the solder will run through the cleavage plane and distort the inside surface of the waveguide junction (fig. 11).

By providing mandrels with fillets in recessed corners, continuous electrodeposition can take place. A sound metal deposit is formed and the need for the above-mentioned method of reinforcement is eliminated. The mechanical advantages of fillets are thus quite evident. Metzger and Lamb have reported [6], and the author has confirmed, that a minimum radius equal to the desired thickness of deposit is necessary to prevent the forming of a cleavage plane in an internal angle. If deposition continues, the cleavage plane will start forming again (fig. 12).

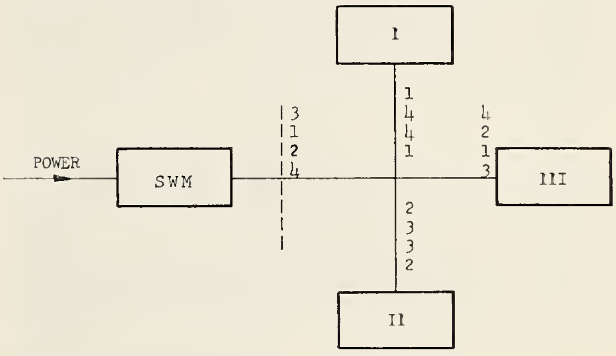
The electroformed components, being negatives of the mandrel, will have the filleted corners on their inside, or working surfaces. In many cases this will not affect the electrical properties in an essential way, as might be expected where the ratio of wavelength to fillet radius is large. In the smaller waveguide sizes, where the ratio approaches 2 to 1 (as at 3 mm), one might expect the effect from the use of fillets to be more pronounced. In order to get factual information on this condition, a series of measurements was taken on three hybrid T-junctions of RG 98/U, or 6-mm waveguide.

The three junctions were electroformed and are referred to as HT 101, HT 102, HT 103. HT 101 had sharp corners, HT 102 had 0.040-in. fillets, and HT 103 had 0.080-in. fillets. The purpose of using 0.080-in. fillets was to establish a condition scaled to that of 3-mm guide with 0.040-in. fillets, there being no equipment on hand to make measurements at 3-mm.

The voltage standing wave ratio of all four arms was measured as shown in table 2. It appears from the table that the effect of fillets is electrically of no great significance at the frequency at which measurements were made. These measurements, at a single frequency, give no information on the broad-bandedness of the junctions. There are reasons to believe that the existence of fillets affects broad-bandedness adversely.

Thus, through the use of special shapes and filleted corners, construction of mandrels from a solid piece is possible down to the smallest waveguide sizes. This permits the electroforming of these components by conventional methods.

Table 2. *Input VSWR of hybrid T-junctions RG–98/U*



I, II, & III are loads

	Termination	*Run A*	*Run B*	*Average A & B*
HT–101 (Orig. 'T'):				
VSWR arm 3	1–I, 2–II, 4–III	2. 64	2. 48	2. 56
VSWR arm 1	2–II, 3–I, 4–III	1. 34	1. 36	1. 35
VSWR arm 2	1–II, 3–I, 4–III	1. 35	1. 39	1. 37
VSWR arm 4	1–II, 2–III, 3–I	1. 83	1. 82	1. 83
HT–102 (0. 040 in. fillets):				
VSWR arm 3	Same	2. 41	2. 42	2. 42
VSWR arm 1	Same	1. 37	1. 39	1. 38
VSWR arm 2	Same	1. 33	1. 38	1. 36
VSWR arm 4	Same	1. 56	1. 51	1. 54
HT–103 (0. 080 in. fillets):				
VSWR arm 3	Same	2. 08	2. 09	2. 09
VSWR arm 1	Same	1. 22	1. 30	1. 26
VSWR arm 2	Same	1. 27	1. 26	1. 27
VSWR arm 4	Same	1. 65	1. 58	1. 62

5. Cleaning Process

Like the proper design of the mandrel, the proper cleaning procedure will insure the best results from electroforming. It is of great importance that the surfaces to be plated be chemically clean. A fairly good indication of that condition, though not absolutely reliable, is the test for "waterbreaks." If water will flow over the surface in a continuous unbroken stream, then it is sufficiently wetted and clean. If, however, the water separates and breaks in one or more spots, re-cycling through one or more steps of the cleaning process will be necessary until no more breaks appear [7]. This is often the most tedious step in electroforming, but success or failure depends on its conscientious performance. The cleaning procedure involves the following steps:

1. Scrub. The first step is the scrubbing of the surfaces with pumice and hot water. On fragile mandrels, not much of this can be done safely.
2. Water rinse.
3. Alkaline clean. Cleaners are commercially available. However, it is easy to make a very effective one. A solution containing 30 g of sodium carbonate, 15 g of trisodium phosphate, and 8 g of sodium hydroxide per liter of water is maintained at 140° F. A 1-min soak of the articles to be cleaned will generally be sufficient. The solution can also be used at room temperature, but 5 to 10 min will be required for sufficient cleaning, and it is not always reliable. Care should be taken not to leave the mandrel in the cleaner too long. Excessive etching of the surface area can result.
4. Water rinse.
5. Immerse in a pickling bath. It will remove traces of grease and will also brighten the mandrel surface. It contains

38g/liter	Chromic acid
200g/liter	Sulfuric acid

and is operated at 140° F. A 1-min soak will be effective.

6. Water rinse.
7. Acid dip in nitric acid (50% by volume).
8. Water rinse.
9. Zincate. Bath composition

525g/liter	Sodium hydroxide
100g/liter	Zinc oxide.

Perform operation at room temperature.

All aluminum products have an ever-present natural oxide film, which prevents the surface from responding to the normal plating procedures used for deposition on other metals. Cleaning in certain alkali or acid solutions will remove the film, but it reforms immediately after rinsing. However, this new film will be thin and quite uniform. Thus, it provides a suitable surface for zincating. This is a zinc-immersion step during which the thin oxide film is removed from the surface to be plated and is replaced by a thin adherent film of metallic zinc. This layer provides a base on which other metals may be deposited.

The cleaning and preplating procedures suggested were found to be very suitable for the recommended alloys 61S–T and 52S–O. Because of their different metallurgical structures, various types and tempers of aluminum alloys may show different chemical and electrochemical reactions, and their surfaces may not respond uniformly to the same preplating procedures. Sometimes a nonuniform response has been observed even with different lots of the same alloy, due to a difference in microstructures. A procedure that works very well in surface conditioning is called the double-immersion treatment. In it the first layer of zinc is removed by a dip in nitric acid (see step 7). A rinse and a second immersion for deposition of the final zinc layer follow.

A slight etching action occurs in the solution that contains zinc oxide and sodium hydroxide. If the immersion is not prolonged beyond 10 to 15 sec, the etching is insignificant. Microscopic examinations of waveguide surfaces plated over etched mandrels indicated no discernible difference in quality from those plated by copper immersion or other methods. It is good practice to transfer the work quickly from bath to bath. Otherwise, drying stains may form, which influence the appearance of the deposit.

6. Masking of Mandrels (Stopping Off)

A minimum amount of machining has to be done on every electroformed waveguide component to provide seats for the connecting flanges or couplings. These seats have to be machined concentric with the inside of the waveguide. For the purpose of providing an easy reference, short sections at each end of the mandrel are left unplated. To accomplish this, ¼ to ½ in. is masked with a protective covering. This covering is easily peeled off after the electroforming process is completed, leaving the unplated mandrel ends as reference surfaces for machining.

For masking materials, pressure-sensitive tape or a plastic hot dip are best. The tape is made for electroplating purposes, comes in assorted widths, and will seal off any surface if wrapped carefully. After use, it can be peeled off easily. The plastic is a cellulose acetate butyrate compound heated to 350°F. It forms a rubberlike layer that protects the masked-off portion completely, but can be peeled off easily after completion of electroforming. Merely dipping the mandrel in it will seal the surface completely. Repeated dipping will build up a heavy layer. This method offers several advantages. No special skill is required to perform this operation, and the plastic coating can be trimmed with a sharp knife at the exact line where the plating should stop. On the smallest mandrels, where peeling might cause distortion, the plastic need not even be peeled off after electroforming, but can be dissolved in acetone in a few minutes. Thus the handling of the mandrel and potential dangers of distortion are kept to a minimum.

One precaution should be observed. The plastic dipping must be done after all the cleaning cycles have been completed. The hot cleaning or pickling solutions will cause the plastic to soften and contaminate the surface of the mandrel.

7. Electrodeposition

7.1. Discussion

There are numerous factors that govern the character and distribution of electrodeposits. Only those will be discussed here that have direct bearing on the electroforming of waveguide components. Of the various plating baths used for electroforming, only those have been selected that can be handled easily with a minimum of control apparatus and give good results over extended periods and over a range of operating conditions.

Electrodeposition takes place when a direct current is passed through the electrolyte, which in this case is an aqueous solution of a salt of the metal to be deposited. The circuit comprises the power supply, the tank with the electrolyte solution, and positive and negative electrodes (fig. 13). The positive electrode is known as the anode, the negative one as the cathode. The mandrel on which the metal is to be deposited forms the cathode; the anode consists of a bar of the metal to be deposited.

As current is passed through, metal will be deposited from the electrolytic solution onto the mandrel. The plated-out metal is replaced by metal dissolved from the anode. Ideally, the metal dissolved from the anode should replace that deposited on the cathode. This condition is nearly realized because the current cathode

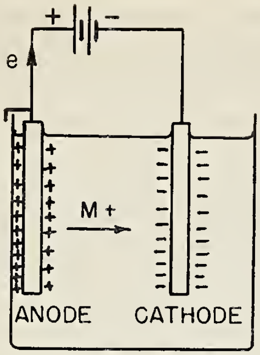


Figure 13. *Electrodeposition process.*

and anode efficiences will be approximately equal under normal conditions. This means that the metal content of the solution will be nearly constant. Any change from this condition of equilibrium will be indicated by a change in the *p*H of the solution. If the anode efficiency increases over that of the cathode, the *p*H will increase. It will decrease if the metal content of the solution becomes poorer because of increased cathode efficiency over that of the anode. The current efficiency of the electrodes is defined as the proportion of the current that is used in a specified reaction (solution or deposition of metal). If all the current flowing is used to deposit or to dissolve metal, current efficiency is 100 percent. Direct calculation of the cathode efficiency can be made from Faraday's law. This is important because the thickness of deposits can be determined from it. Anode efficiency cannot be calculated directly, but may be computed by comparison with the cathode efficiency and from the change in metal concentration in the bath during operation.

One faraday, which is the equivalent of 96,488 coulombs=96,488 amp-sec≅26.8 amp-hr, will deposit 1 g equivalent weight of ions. The equivalent weight equals the atomic weight divided by the valence of the element in the compound.

The above principles and relationships have been used to calculate the factors in table 3, which are useful for estimating the time and current required to produce a desired thickness of deposit. If one wishes to calculate thickness directly rather than by use of the factors in the last two columns in table 3, the following relationship may be used:

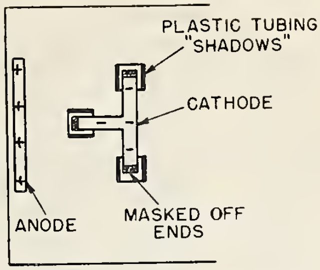


Figure 14. *"Shielding" with plastic tubing.*

$$\text{Thickness of deposit in inch} = \frac{\text{amp-hr/ft}^2 \times \text{efficiency} \times \text{g/amp-hr} \times 0.000425}{\text{density}}.$$

The values for g/amp-hr and density are shown in table 3 for silver, copper, and nickel.

From Faraday's law, 1 coulomb (1 amp-sec) will deposit 1.118 mg of silver. Accordingly, 1 amp-hr will result in a 4.025-g deposit, assuming 100-percent efficiency. By weighing the cathode before and after the deposition of metal, its efficiency can be determined accurately. Owing to a number of factors, the calculated thickness of a deposit cannot be taken at face value. It would be obtained only in the case of uniformly shaped cathodes. Because the current concentrates on corners and along edges, deposits there will be heavier at the expense of other areas. Also, the current does not flow easily around a nonconductor and one conductor steals current from the other.

In electroforming waveguide components, deposits having a thickness of 0.040 in. and upward are required. Variations of several mils mean little. Therefore, the calculation is used merely to estimate the plating time. Actual measurements by micrometer are taken to check the thickness of deposits.

The fact that current does not flow easily around a nonconductor is utilized to counteract the tendency for heavier deposits to form on projecting surfaces. This technique is known as "shadowing." By using pieces of polystyrene tubing as sleeves, the deposit can be equalized. Some experimentation and moving around of the tubes will equired to find the best position for equal deposit (fig. 14). If several articles are plated to-

Table 3. *Electrochemical equivalents and thickness factors*

Metal	Salt	Valence	Equivalent wt= atomic wt ÷valence	Density g/cm³	g/amp-hr [a]	g/mil/sq in.	Thickness in [a] inch for 100 amp-hr/sq in.	Amp-hr/sq ft [a] to deposit 0.001 in.
Silver	AgCN	1	107.9	10.49	4.03	0.172	0.0163	6.2
Copper	CuCN	1	63.54	8.93	2.37	.146	.0113	8.8
	$CuSO_4$	2	31.77	8.93	1.19	.146	.0056	17.7
Nickel	$NiSO_4$ or $NiCl_2$	2	29.35	8.90	1.10	.146	.0053	18.7

[a] These factors are based on 100 percent cathode current efficiency

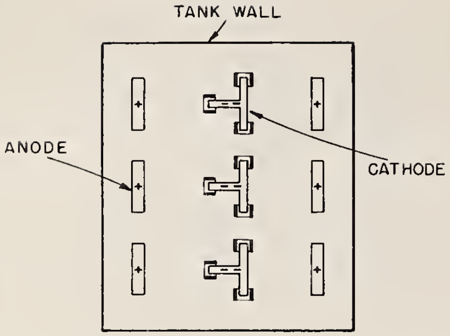


FIGURE 15. *"Robbing" of excess current from projections.*

gether, they can be arranged so that projecting areas are adjacent. They will then rob each other of excess current. An arrangement as in figure 15 shows the essential idea, with the tank walls acting as "shadows" for the two outside edges.

The hardness of the deposited metal will vary with the composition and operating conditions of the bath. Thus, the hardness of copper ranges from 50 to 150 Brinell, with the lower values produced in acid copper baths. The hardness of silver ranges from 60 to 130 Brinell and of nickel from 125 to 420 Brinell. In microwave applications, the hardness is of little importance, except that, especially with nickel, excessive hardness may be accompanied by high internal stresses, which cause cracks in heavy deposits.

7.2. Plating Solutions

Plating is usually done in two steps, first in a strike bath and then in a regular plating bath. The strike bath is a plating solution with low metal content and high free cyanide. Relatively high current densities are used to prevent the mandrel metal from passing into solution. One minute is the usual time of plating in the strike bath. The strike deposit provides a good bond for subsequent plating, and the mandrel is now ready for the electroforming bath.

a. Copper Solutions

1. *Strike:* CuCN (cuprous cyanide) 30 g/liter; NaCN (sodium cyanide) 45 g/liter. Voltage: 4 to 6. Current density: 15 to 25 amp/ft^2. The bath is operated at room temperature.

2. *Electroforming bath:* $CuSO_4 \cdot 5H_2$ (cupric sulfate) 150 g/liter, $H_2SO_4 \cdot$(sulfuric acid) 50 g/liter, Wes-X-303. Voltage: 2. Current density: 25 to 75 amp/ft^2.

Before adding the addition agent, the bath should be treated with activated carbon and thoroughly filtered. The *p*H should be kept well below 1, between 0.2 and 0.5. This can be checked with *p*H strips. Additions of dilute sulfuric acid will bring the *p*H down if necessary. Rotation of the work will aid in obtaining even distribution of the deposit and promote the formation of dense and smooth deposits.

b. Silver Solutions

1. *Strike:* AgCN (silver cyanide) 7 g/liter, KCN (potassium cyanide) 75 g/liter, KOH (potassium hydroxide) 15 g/liter. Voltage: 4 to 6. The bath is operated at room temperature.

2. *Electroforming bath:* AgCN (silver cyanide) 50 g/liter, KCN (potassium cyanide) 50 g/liter, KOH (potassium hydroxide) 15 g/liter, K_2CO_3 (potassium carbonate) 80 g/liter, KNO_3 (potassium nitrate) 60 g/liter, $(NH_4)_2S_2O_3$ (ammonium thiosulfate) 0.1 g/liter. *p*H: 13.5 to 14. Voltage: 2v. Current density: 20 amp/ft^2 or higher. The bath is operated at room temperature or slightly above (80° to 115° F).

The addition agent, ammonium thiosulfate, may be added to the bath whenever the deposit appears to lose luster or becomes rough. The deposit will be very dense and smooth and very bright up to considerable thickness, when it changes in appearance to semimatte. Rapid rotation of the work is important for best results.

The bath should be treated with activated carbon and thoroughly filtered before operation, and the anodes should be bagged. In many cases it will be desirable to make a sandwich construction, i. e., deposit a substantial layer of silver over the mandrel, and follow it up with copper for bulk. A thickness of 0.015 in. of silver can be considered adequate in every respect.

c. Nickel Solutions

Nickel can be deposited directly on the zincated aluminum mandrel. If a laminated structure is desired, the first deposit of 0.015 to 0.020 in. can be silver or copper and the top layer nickel. Due to the high strength of nickel, that layer can be of a minimum thickness.

1. *Electroforming bath:* $NiSO_4 \cdot 6H_2O$ (nickel sulfate) 180 g/liter, $NiCl_2 \cdot 6H_2O$ (nickel chloride) 25 g/liter, H_3BO_3 (boric acid) 30 g/liter. Voltage: 1 to 2. Current density: 25 to 50 amp/ft^2. The bath is operated at 110° to 140° F.

The bath should be treated with activated carbon, thoroughly filtered, and the anodes bagged. The *p*H range is from 5.4 to 6.2. Inasmuch as the deposit becomes more highly stressed with higher *p*H, it is best to operate the bath at the lower values. This is the only bath in which the maintenance of the *p*H value is critical. Addition of H_2SO_4 will lower it, addition of KOH will raise it. The *p*H will have a tendency to rise with the working of the bath.

7.3. Troubles Frequently Encountered

Certain troubles in electrodeposition are frequently encountered, particularly by inexperienced operators. Following is a list of them and suggestions for their cures.

a. Blistered Deposits or Poor Adhesion

Inadequate cleaning is almost always responsible. Conscientious scrubbing and recycling of the cleaning steps are required. Sometimes the omission of a strike bath will be the cause of poor adhesion.

b. Rough Deposits and Treeing

Solid metal particles or foreign matter contained in the solution will cause roughness. The use of good anodes, bagging of anodes, and frequent filtration of the bath will help greatly. Where addition agents are used in a bath, they should be replenished and proper agitation of bath or cathode provided. High *p*H is also often a factor.

Rolled copper anodes and rolled nickel anodes are best because of their uniform anodic dissolution. Even the purest commercial anodes contain traces of impurities.[4] Some of these form compounds on the anode itself or react with other substances in the bath, resulting in so-called anode sludge. It cannot be prevented, but placing the anodes in bags of cotton or nylon cloth avoids contamination of the bath and resultant rough plating. This precaution, known as "bagging the anodes," helps greatly toward retaining smooth metal surfaces even on heavy deposits.

c. Dark, Burnt Deposits

This can occur at certain spots where an unusually high current density occurs, as on thin protruding parts of a component. Such deposits are best removed mechanically before plating continues. A drop in the operating temperature of the bath can also be responsible because higher current densities are generally permissible at elevated temperatures. Use of nonconducting "shadows" (see fig. 14) will help to bring the current density down in these areas. The bath should be investigated for low metal content.

d. Pitting of Deposits

Pitting happens most frequently with nickel baths. It is somewhat unpredictable, and hydrogen is considered the most common cause. It is objectionable for appearance's sake, as well as for causing weak spots. Remedies include treating the bath with activated carbon and filtering (to remove organic and metallic impurities), and the addition, at frequent intervals, of small quantities of a 3-percent solution of H_2O_2. (In excessive amounts, it will increase the stress of the deposit.) Finally, the addition of boric acid may prove beneficial. A trial-run period under normal operating conditions, which is known as "working" the bath, is good practice and definitely recommended.

The general rules given above apply to all baths. However, there are numerous special recommendations for the maintenance and improvement of each bath. They are beyond the scope of this paper, but a list of pertinent literature is given in section 9.2.

7.4. Postforming Operations

After the desired thickness of deposit has been obtained, the formed component is removed from the bath, rinsed, and dried. A compressed airstream is best for quick and efficient drying. It is well to make sure that the compressed air supply is free from grease, oil, or other contaminations. It may be necessary to remove the article from the bath during the plating operation in order to measure the thickness of the deposit. If contaminated air is used for drying, additional cleaning of the article will be required before more metal can be deposited. If no attention is paid to the contamination, subsequent deposits may lack adhesion and be generally poor in quality.

The stop-offs are now removed from the form, exposing the reference surfaces for machining of the connecting flange seats. The types of flanges vary, but certain general considerations apply to all of them. Inasmuch as misalinement of two or more waveguide components in the millimeter-wavelength range is far more serious than at the lower frequencies, special care should be taken in its prevention. This can be done by alining all connecting flanges with the inside surfaces of the waveguide. Using the reference ends, seats for the flanges can be machined to the right thickness. Next, the flanges are placed on the seat and soft-soldered to the waveguide. Although it is best to try to place the flange perfectly perpendicular to the waveguide axis, that is difficult to do. A slight facing cut across the connecting flange surface will establish a perfect right angle with the waveguide axis. The protruding reference ends of the mandrel are also removed at this time. The connecting flanges used are blanks and do not yet contain either screw holes or alining pins (fig. 16).

Next comes the removal of the mandrel. The part is dipped into a boiling caustic solution that will dissolve the aluminum mandrel in a matter of hours. As soon as some heavy sludge forms on

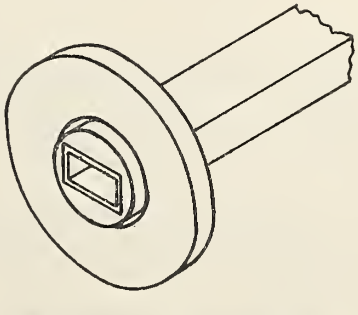


FIGURE 16. *Connecting flange.*

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[4] "Plus 4" copper anodes, made by American Brass Co., Waterbury, Conn., may be the exception. The manufacturer claims that no bagging is required for them.

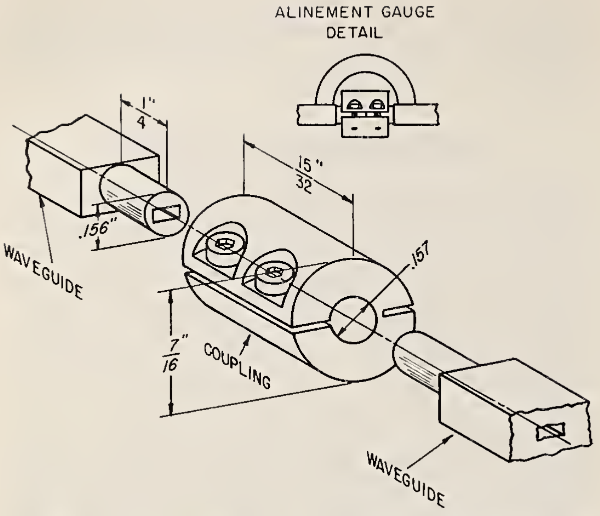

Figure 17. *Alinement of RG–138/U waveguides with coupling.*

the bottom of the solution, it is best to discard it and start with a clean one. The sludge slows up the process of solution and often forms a dark film over the inside and outside surfaces of the waveguide component. This film has to be scrubbed off later and is very difficult to remove from the inside of a waveguide. Thin oxide films on the surface can usually be removed by a quick immersion in a bright dip [5] if the metal is copper, or in a nitric acid dip (50 percent HNO_3) for silver. In cases where the dissolving of some small remainders of aluminum mandrel seems to have slowed up or stopped, immersion in a hydrochloric acid dip (50 percent HCl) will reactivate the process.

The mandrel having been removed, the inside surface can be inspected for flaws. If all is well, holes for connecting screws and alinement pins are drilled and tapped respectively. A special drill jig or template is used which alines all holes from the inside surfaces of the waveguide. Then the pins are inserted and the component is ready for use [8].

For the smallest size of waveguide components, a slightly different procedure has been used successfully [9]. A cylindrical stub is machined on the end of the waveguide and the guides are joined by a clamp coupling (fig. 17). This method has been used with RG–138/U waveguide whose outside shape is circular (see table 1), and on other electroformed components of the same inside dimension where cylindrical outside diameters are machined on the ends.

7.5. Safety Measures

All of the chemical operations should be performed in a well-ventilated room. The larger the size of the tanks the more emphasis must be placed on adequate ventilation. For pilot-plant operation, recommendations such as are contained in the Metal Finishing Guidebook (see section 9.2) should be followed.

The fumes of the cyanide and acid solutions listed will not present a health hazard unless the room is poorly ventilated and the operator is exposed to them for long periods of time. The fumes of the boiling NaOH solution used for dissolving aluminum mandrels are unpleasant as well as unhealthful. Special ventilation should be provided for this solution such as a chemical fume hood.

The usual precautions in handling acids and cyanides must be taken. It is very important to label every container of a solution clearly as to its contents and to change labels if the contents change. This point cannot be overemphasized. Accidental mixing of acid and cyanide solutions will release hydrogen cyanide gas, causing the almost instant death of the operator. Therefore, it is best to dispose of a solution whose identity is in doubt. First-aid measures against acid and alkali burns and cyanide poisoning should be posted in the room.

The author expresses his appreciation to Vernon A. Lamb for his valuable suggestions and to Lawrence W. Miller, Jr., who performed the VSWR measurements on the three hybrid T-junctions and supplied the data for table 2.

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[8] Armed Services Electro Standards Agency (ASESA) drawing No. AS–2072.

[9] E. S. Dayhoff (unpublished data).

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[5] Suggested formula for bright dip:

H_4SO_4	2 gal
HNO_3	1 gal
H_2O	1 qt
HCl	½ floz

9. Appendix

9.1. Suppliers of Equipment

For the benefit of persons who cannot readily determine sources for electrodeposition equipment, sources of supply are listed in the "Metal Finishing Guidebook" published by Finishing Publications, Inc., 381 Broadway, Westwood, N. J.

9.2. Helpful Literature

W. Blum and G. E. Hogaboom, Principles of electroplating and electroforming, 3d ed. (McGraw-Hill Book Co., Inc., New York, N. Y., 1949).

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