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The Design of Electronic Equipment Using Subminiature Components*

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Summary—This article discusses briefly the advantages and disadvantages of subminiature design, and indicates the amount of space that can be saved by such design. It discusses in greater detail the major problems of design, and presents some practical suggestions concerning the methods and materials found most useful.

For several years there has been an ever-increasing interest in the construction of electronic equipment using subminiature tubes and exceptionally small components. Various laboratories and development groups have collectively constructed nearly every type of applicable circuit using such components. Since the method of design using small components is somewhat different than the regular design procedure, it is felt that a review of some of the more pertinent facts is in order. The information presented here, although probably applicable in part to all subminiature tubes, is based upon experience with high-performance tubes of the heater-cathode type used in circuits where ten or more such tubes are in a single piece of equipment. Many of the data are, of course, applicable to design of compact equipment using any tube type.

I. Advantages of Subminiature Design

THE USE OF subminiature components, in general, is undertaken only because a saving of size and weight or a more rugged construction can be achieved. There are certain applications where such tubes are useful because of their better high-frequency characteristics, but such will not be treated specifically.

1. Space Saving

The use of small lightweight components results directly in a weight savings, but, as will be pointed out later, it is not always possible to save as much space as seems at first possible. Since the amount of space savings achievable depends upon the operating temperature, such will be discussed following the discussion of temperature.

2. Shock Resistance

The susceptibility to damage from shock or vibration of any structure depends, among other things, upon its moment of inertia and the stiffness of the mounting. Thus, the reduction of the mass of the structure improves the ruggedness of components, providing that the stiffness of the mounting does not suffer. Many small components are mounted by their leads. With subminiature components, such leads can be made quite short which further improves the ruggedness of the equipment. In general, the lead stiffness does not reduce in proportion to the mass of the component. For somewhat the same reasons, the components themselves will be more rugged. Thus, improved ruggedness, as well as space and weight savings, can be achieved by simple means, providing subminiature components are used, and it is, in general for these reasons that such components are used.

II. Disadvantages of Subminiature Design

The first difficulties encountered in using subminiature components are generally not those which prove to be of major importance. Lack of familiarity with compact design generally handicaps the early efforts of any group undertaking such work, with the result that there is generally an overemphasis on such activities as deleting terminal strips, using no chassis, and combining components into exceptionally compact structures to save additional space. The major difficulties connected with such design are, in their approximate order of importance, as follows:

1. High temperature resulting in reduced life and reliability.
2. Difficulty of parts replacement.
3. Circuit difficulties at low frequencies.
4. High cost.

1. High Temperature

The high temperatures are a direct result of reducing the size of the equipment without a proportional reduction of the power input. The effect of this on the design of different types of cirucits will be discussed later.

2. Parts Replacement

The difficulty of parts replacement can be greatly relieved by careful design, but, under the best of circumstances, the compact design generally leaves little room for parts removal, and frequently it is necessary to remove several parts to replace a single one. This difficulty becomes greater because the removal of a part in close quarters frequently damages it, and because most subminiature tubes are soldered into the circuit. Troubleshooting by parts replacement is nearly impossible. These difficulties require that consideration be given to the use of small replaceable subassemblies. If this is not done, greater skill of maintenance personnel is required, and, frequently, special test equipment must be devised for the use of maintenance personnel.

3. Difficulties at Low Frequencies

The difficulty of design for low frequencies stems from the desire to minimize the size of the components. At frequencies below about a kilocycle, transformers or chokes become too bulky to be considered except as a last resort. There is an ever-present urge to use large-value resistors as grid leaks, and thus reduce the size of coupling capacitors in resistance-capacity coupled am-

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plifiers. This leads to difficulties with capacitor leakage because of the high ambient temperatures, and requires tubes with exceptionally small grid conductance.

4. *High Cost*

The high cost of the equipment stems from three sources. The components themselves are generally rather special and thus are expensive. This cost may go down with increased use, but at the present time component costs can be expected to be from two to twenty times as expensive as larger components that would serve the same purpose. The cost of design for most circuits can be expected to be somewhat greater because the final layout must be made by exceptionally skilled personnel after careful planning, and frequently after the construction of several prototype units to study the design. The final cost differential results from the cost of replacing any parts found to be defective or of improper value. To reduce this cost of replacement it will be found economically desirable to increase the expenditures for incoming inspection.

III. EFFECT OF HIGH TEMPERATURES

With octal-base tubes and orthodox construction, it is seldom found necessary to use special means of heat dissipation of electronics equipment. With subminiature components, heat dissipation can become one of the major considerations of design.

There has been set up an empirical relationship between the number of watts to be dissipated and the area of the case capable of dissipating such wattage into still air at room temperature. The range of values of interest are from 6 square inches per watt to 1½ square inches per watt. With reasonable care in construction and component selection, almost any electronic circuit can be made to operate continuously with 6 or more square inches per watt, and almost no piece of electronic equipment can be expected to operate continuously with less than 1½ square inches per watt. Between these two limits the frequency of operation, the band pass, the case material, the thermal bonding between dissipative elements and the case, the required stability of the equipment, and the presence or absence of automatic control or compensation circuits all enter into the maximum workable dissipation per square inch. Fig. 1 shows the relationship between case temperature and square inches of aluminum case per watt.

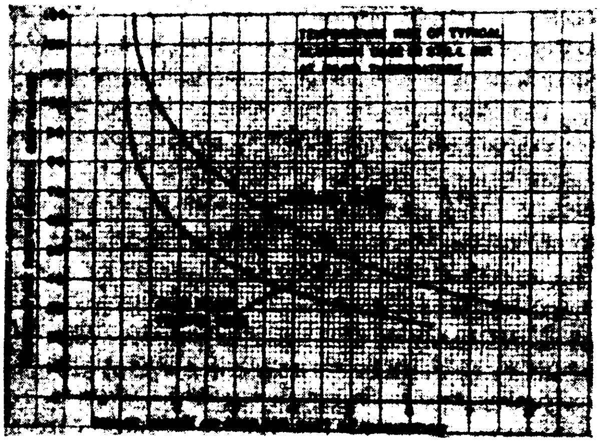

Fig. 1—Plot of temperature rise above ambient of a typical aluminum box having about 150 square inches of surface.

1. *Broad-Band High-Frequency Amplifiers*

Broad-band high-frequency amplifiers whose gain and frequency stability requirements are average can be built having case areas of 2 to 2½ square inches per watt. Such units operate satisfactorily with case temperatures approaching 100°C, providing components are picked carefully. Such high dissipations per square inch are possible because the circuit Q's are low, the capacitors small, the tuning not exceptionally critical, and most of the dissipation is in the tubes where it is easily conducted directly to the case or outside of the unit. Because such amplifiers must be constructed "in line," it is very difficult to reduce the case area below the figures given. Thus, the maximum dissipation per square inch is unknown, but is probably close to the above.

2. *Other Alternating Current Amplifiers*

Low-frequency or narrow-band amplifiers whose frequency or gain characteristics are critical must be allotted larger case areas, generally of the order of 3 to 5 square inches per watt. This is true, in part, because paper capacitors are necessary, effective circuit Q's may be high, or narrow tolerances must be held during operation.

3. *Direct-Current Amplifiers*

High-gain dc amplifiers or low-gain dc amplifiers having exceptional stability requirements may require cases having over 5 square inches per watt.

IV. SIZE OF EQUIPMENT

In general, a reasonable measure of the complexity and power consumption of electronic equipment is the number of tubes. Heater-cathode subminiature circuits generally consume on the average of 2 watts per tube.

1. *Smallest Size*

To estimate the smallest possible size units, it can be assumed that the equipment is to be contained in a long flat box ½×2 inches and that there should be a surface of 1½ square inches per watt. The spacing between tube centers would be 0.6 inch resulting in 0.6 cubic inch per tube. This probably is a more compact design than can be achieved with any very useful circuit. About 0.9 cubic inch per tube is the most compact practical design achieved to date. It is a 60-Mc intermediate-frequency amplifier using printed circuits.

2. *Larger Units*

If the shape of the elongated box is changed to 2 inches by 2 inches in cross section to permit the use of larger components and a surface of 3 square inches per watt is allowed, the tube centers will be 0.75 inch and the resulting volume will be 3 cubic inches per tube. This is about the minimum size that can be achieved with diversified circuits using separate components.

If twenty tubes consuming 40 watts are to be packaged in a cube so that the area of the container is 120 square inches (3 square inches per watt), the sides of the box will be about 4.5 inches. The volume of the box will be about 90 cubic inches or about 4½ cubic inches per tube.

Even this is a "small" container for a twenty-tube circuit, but it might contain considerable unused space if designed using subminiature components.

From the above it can be seen that size, although dictated by case area, can be reduced to a value far below that possible with larger components.

V. SOME THERMAL DESIGN CONSIDERATIONS

The amount of space that must be used to provide the necessary case area, and at the same time just enclose all of the parts, is at once the first, and essentially the only, problem in design after a workable schematic diagram is completed. All other design problems only contribute to this solution. However, a knowledge of the required case area, the dimensions of the largest parts, and the desired shape and size of the finished product will generally lead directly to the first trial solution.

1. *Thermal Bonding*

The first consideration of design must be good thermal bonding between the major heat sources and the case. In most designs it will be found very helpful to bond the chassis to the case as well as possible. The tubes should be contained within close-fitting metal sleeves which are in contact with the chassis over a reasonable area. Whenever possible, the bonding should consist of a metal-to-metal contact of at least ¼ square inch of surface per tube. Because of their good thermal conductivity, aluminum or copper is recommended as a material for the sleeves.

2. *Chassis Material*

Aluminum chassis material is recommended wherever possible. Where such metal is not sufficiently strong in thin sheets, thick aluminum chassis plates (¼ inch thick) are recommended because they offer good stiffness, light weight, good thermal conductivity, and can be tapped, thus eliminating nuts.

3. *Case Material*

All of the dissipation figures given in III above were based upon experience with equipment dissipating from 15 to 150 watts and having aluminum and/or steel cases. The temperature gradient in the steel sheet may be so large as to reduce the effective case area unless carefully distributed thermal bonds between heat sources and case are provided. Thus, steel cases are somewhat inferior to aluminum cases where there is only a small bonding area between chassis and case.

4. *Forced Air Cooling*

Where the wattage dissipation per square inch exceeds the values given above, it is necessary to use forced air cooling or some other suitable means of heat dissipation. Where such is feasible, the compactness of the equipment is dictated by the size of the components and the space required to ventilate them.

VI. SELECTION OF COMPONENTS

The selection of components for use in subminiature electronic design consists, in general, of finding small components that will stand the high temperatures.

1. *Tubes*

Considerable has been written about subminiature tubes and their application. There are now available tubes of almost every type necessary to design any electronic circuit, excepting those which require tubes with large plate dissipations. For the majority of applications tube size is of secondary importance, providing the tube is in a T-3 (or smaller) envelope. If it were possible to reduce the power consumption of the tube in proportion to its size, then any reduction of size and dissipation would be advantageous.

2. *Resistors*

Standard half-watt insulated carbon resistors will supply substantially all resistor needs. The insulation is important, and the use of narrow tolerance parts will be found advantageous because somewhat larger changes (of all parts) due to temperature changes can be expected than with less compact equipment. Other resistor requirements can also be met with standard parts. Small variable resistors are available, but there remains a need for a subminiature locking-type potentiometer. For units that are to operate with case temperatures approaching 100°C, it may be necessary to use resistors at less than their full rating. The manufacturers' recommendations should be followed in this regard.

3. *Capacitors*

Electronic circuit designers have long considered a capacitor as a device drawing only reactive current and serving as an open circuit for dc. At temperatures above 100°C, this idea must be modified greatly unless capacitors of exceptional physical size or small capacitance are used. For capacitors of the size range of 0.01 to 1 μf operating at 150°C, a dissipation factor of 10 per cent is above average. In this size range, the dc leakage at 150°C is less than 10 megohm-microfarads for any known capacitor suitable for use in subminiature equipment. Most manufacturers of small capacitors do not recommend that they be operated above about 100°C and promise very little for their performance at higher temperatures. Some of the lowest leakage capacitors found to date are the new metalized paper capacitors, but these generally have leakages of about 1 megohm-microfarad at 150°C. Molded mica and ceramic capaci-

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tors are generally not much superior as far as leakage is concerned, probably because of case leakage. A few samples of uncased mica capacitors showed leakages of nearly 10 megohm-microfarads at 150°C. In general, no satisfactorily high leakage resistance capacitors are available for high temperatures. The circuits must be so designed as to permit considerable capacitor leakage.

Electrolytic capacitors will operate for a considerable period at 100°C or slightly above.

Variable capacitors are generally to be avoided whenever possible because of their size. However, compression mica trimmers generally are satisfactory for circuits that are not excessively critical. Cycling in temperature a few times sometimes improves the stability of such trimmers.

4. *Inductances*

Small high-quality inductances are available from many component manufacturers. Although such units are generally not recommended for use at high temperatures, no difficulty has been encountered with them in subminiature equipment. No undue reduction of life has been noted, and the increase of the copper loss at high temperatures is generally not sufficient to cause difficulty. Wherever the shielding can be dispensed with, iron core units should be selected without cases to save space.

5. *Transformers*

The size of iron-core audio transformers is dictated by the same considerations as inductances. Thus, the above applies to them. With power transformers it is possible, by use of silicon and glass insulation, to operate the transformers at high flux and current densities with remarkable savings of space and weight. Such operation is permissible only if the life requirement of the unit is reduced, because the interturn insulation must remain the ordinary wire enamel to save space. An example of such a unit is a 350 VA, 11-winding, 3-phase, 400-cycle power transformer that occupies 15 cubic inches and weighs 21 ounces.

6. *Miscellaneous*

Other components sometimes require greater care in their selection than the major ones, but space does not justify detailed discussions of such equipment. Briefly, wire must be the highest quality available (glass-insulated wire is nearly essential); the smallest relays available are quite suitable for most applications, although melted wax from other components can cause fouling of the contacts; terminal lugs and mounting strips are generally too large, but specially constructed ones are excessively expensive. Suitable small connectors are difficult to find. Doubtless there will be available at some time in the future a connector having most of the good points of the many now proposed or available.

VII. SPECIFIC CIRCUIT DESIGN

In general, the use of subminiature components does not alter the circuit design but creates a new emphasis upon certain circuit problems. The major design problems generally are mechanical. However, certain electrical considerations are of importance.

1. *Radio-Frequency and Intermediate-Frequency Design*

After the smallest available components have been found, the only design problem is that of providing the increased shielding required because of the reduction of the size of the amplifiers. Exceptional care in the placement of the components must be used.

2. *Audio and Video Design*

Because the size of transformers and inductors is not subject to much reduction, selective-frequency circuits in the low audio band require the use of filters or tuned circuits using only resistors and capacitors. The capabilities and limitations of *R-C* filters (including twin-tee filters) are well documented. Therefore, it is only necessary to adapt such circuits to the problems at hand.

The *R-C* type of filter generally requires greater gains in the associated amplifiers, but even the size of an additional gain stage is small in comparison to the size of an inductor.

For broad-band audio or video amplifiers resistance-capacity interstage coupling is essential, and the problems of capacitor leakage become important. The cathode follower will be found to be the standard impedance-matching device in subminiature design. In general, transformers will be found useful as a last resort.

Power at audio or video frequencies is limited by the plate dissipation of subminiature tubes with the result that one or two watts is the upper limit. At any frequency, the number of subminiature tubes that can be paralleled successfully is an interesting engineering problem. Because the tubes are soldered into the circuit, it is frequently difficult to find a defective tube, and it is sometimes difficult to remove the tube without breaking the leads on one or more other tubes or parts. The result is that the cost of finding and replacing a single defective tube may be quite large in comparison to the cost of replacement of a miniature tube which would have had greater plate dissipation and occupied at most only a small additional space.

3. *Direct-Current Amplifiers*

Only the warm-up characteristics of subminiature dc amplifiers can be expected to differ from ones having larger components. Since the amplifier will operate at higher temperature, special care must be used in selecting and placing components to minimize the temperature drift of the amplifier. If this is done, and special care is used to insure good thermal bonding, the warm-up characteristics of the subminiature amplifier may be superior to one of orthodox design. The good thermal bonding will result in rapid approach of all components to the stability temperature, and thus shorten the warm-up period. This improved warm-up characteristic can be achieved at any frequency by careful design.

4. *General*

With tubes that are soldered into the circuit it is feasible to adjust some circuit parameters by parts replacement. Since the operation of tube replacement requires the use of a soldering iron, if the necessary parameter adjustment can be made by substitution of one or two standard RMA resistors, most of the space required for a potentiometer or rheostat can be saved by simple parts replacement. Such adjustments require more time, but, if the layout is so made that the required part is easily accessible, the time used for adjustment can be made short in comparison to that of tube replacement.

VIII. LAYOUT

Various laboratories have produced differing solutions to the problem of layout of subminiature equipment. Each of these solutions is based upon the particular requirements of the laboratory making the equipment. At the present time there is no means of passing comparative judgment upon the various solutions. A few of the important considerations will be outlined here.

1. *Layout Using Components*

To save the maximum amount of space it is necessary to group the tubes into clusters of three or four so that common terminals can be used as much as possible. This, of course, applies only to the frequency bands where parallel (or series) operation of heaters and close proximity of parts are permissible. As previously mentioned, the tubes should be supported in the clusters by metal sleeves which offer good thermal bonding to the chassis. Fig. 2 shows tube clusters before mounting. Terminal lugs can be arranged in a rectangle around the tube clusters and the parts supported on the lugs with the shortest possible leads. With this type of construction, capacitors can generally be placed so that they are not adjacent to resistors or tubes having high dissipation, which results in less capacitor leakage.

Fig. 2—Typical tube clusters for T3 tubes ($\frac{3}{8}$-inch diameter) used in compact equipment to take advantage of common terminals to save space.

The most compact design generally requires that components and/or wiring appear on both sides of a chassis while the tubes protrude through the chassis. By orienting tubes properly, it is possible to have wiring on both sides of the chassis, but it is frequently advantageous to mount potentiometers, chokes, trimmers, and transformers with pigtail leads on one side of the chassis between tube clusters while retaining the major portion of the wiring all on one side. Fig. 3 shows an if strip using this type of construction.

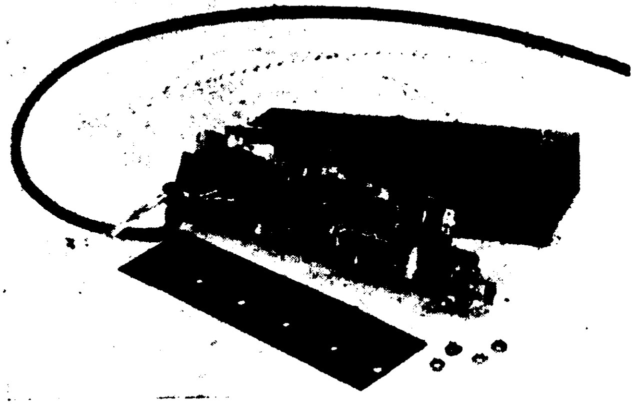

Fig. 3—Typical 5-stage intermediate-frequency amplifier using subminiature components. This amplifier chassis is 6[illegible] inches long by 1[illegible] inches wide.

2. *Printed Circuits*

Printed circuits appear as a final means of further compacting equipment where the space saved by such means can be used. The space limitations set up by the heat generated are generally of such a nature that more orthodox components can be used. In general the cost of printed circuits cannot be justified for development or small production work unless full advantage can be taken of the space saved. At least one laboratory has demonstrated the remarkable space savings that can be achieved by using printed circuits on high-gain intermediate-frequency amplifiers where nearly all components can be printed on glass or ceramic, and thus withstand exceptionally high temperatures. Reference should be made to National Bureau of Standards Circular 468 and Miscellaneous Publication 192.

IX. POTTING AND CASTING

Where it is desired to achieve the ultimate in ruggedness, to prevent corona at high altitudes, or minimize the effects of humidity, complete units can be potted in wax or cast into plastic. The potting wax is disadvantageous because most subminiature equipment operates near the melting temperature of suitable waxes.

1. *Casting*

The casting materials, such as polyester-styrene resins, set at room temperature and will withstand high temperatures after setting. Electronic equipment can be cast into such material with the result that the cast unit will withstand more vibration or shock than the tubes contained within it. Of course, moving parts must be excluded from the cast sections.

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2. *Size and Weight of Cast Units*

Once cast into such material, there is no possibility of parts replacement. Thus, such cast units must themselves be considered as replaceable units. This limits the number of parts that can be cast into a single unit, and suitable means for determining the number of parts based upon their reliability must be devised by the design group. The problem of making suitable interconnection between such cast units requires either small plugs or the use of cast-in soldering terminals and/or pigtails.

Cast units are generally somewhat heavier than the equivalent units assembled on an aluminum chassis.

3. *Typical Construction*

One of the best designs found to date is to assemble all parts petween two thin sheets of insulating material in such a manner that the leads protrude through small holes in the material. The connections are made by bending and soldering the leads outside the insulating sheets. With some care in design the resulting assemblage will be sufficiently rigid to test before casting. After test, the unit is supported in a mold and the casting resin poured over it and allowed to set. For most applications the casting resin will function as both support and a heat-conducting medium; thus, no chassis is required. By casting mounting lugs or screws into the assembly it can be fastened to other parts in any manner desired. Fig. 4 illustrates this type of construction before the casting resin is poured.

Fig. 4—Subminiature assembly ready to be cast in polyester-styrene resin, and the mold in which it is to be cast.

X. CONCLUSIONS

The serious application of subminiature components to electronic design is rather recent with the result that a universally applicable layout and design procedure has not yet been found. It is probable that no single solution will satisfy all needs. At the present time, it is hoped to offer only sufficient general information to persons starting new designs so that they will be able to judge the suitability of subminiature design for their specific problems, or so that once started, they will not repeat all the errors of the earlier workers in the field. It is hoped that the information contained in this discussion will provide such minimum guidance.

Electron Beams in Axially Symmetrical Electric and Magnetic Fields*

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***Summary*—The problem considered in this paper is the formulation of the equations governing the motion of an electron beam in axially symmetrical magnetic and electric fields. The equations are obtained for the trajectories of the electrons along the outer edge of the beam for the most general case, in which there are both axial and radial components of the fields. It is shown that, as a result of symmetry, the combined effects of the electric and the magnetic fields can be expressed as a single generalized potential function which depends only on the axial and radial space co-ordinates. This permits one to express the axial and radial force components as the axial and radial components of the gradient of this potential function.**

Numerical solutions have been obtained by numerical integration for the trajectories in a uniform magnetic field. Curves are presented in normalized form, giving the results of these solutions for cases likely to be encountered in practice. It is shown that there exists an equilibrium radius for which the net radial forces acting on the electrons is zero, and that the outer radius of the beam will oscillate about this equilibrium value, the amplitude being nonsymmetrical and depending upon the initial conditions, and the wavelength (distance between successive maxima) depending upon the amplitude.

INTRODUCTION

FOR CERTAIN TYPES of electron tubes, it is desirable to keep an electron beam to a small diameter for a considerable length. It is not very difficult to do this if the electron beam density involved is not large, as in a cathode-ray tube or electron microscope, in which the repulsion forces between electrons are negligible. As a matter of fact, the electron optics used in such kinds of tubes treat the trajectories of individual electrons as if the other electrons do not exist. Usually pure electrostatic means of control are sufficient to control the motion of an electron beam as one desires.

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