Tube Miniaturization

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I. INTRODUCTION

As indicated in the accompanying article, electronic components of minimum dimensions are attaining wide use and great importance. It may be stated confidently that the rapid acceptance of tiny tubes in recent years is but a token of enormously increased acceptance in the near future, as excellent performance is recognized and still better performance achieved.

The "miniature" tube first appeared in 1939; by the end of World War II, over 50 million of these tubes had been used.[1] These "miniatures" are reduced to 1.9 cm maximum diameter from 3.3 cm for equivalent GT's;** and to 5.4 cm maximum length from 8.4 cm for GT's. The

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* Present address: General Electric Co., Schenectady, New York.

** GT, for "Glass Tube," is a designation adopted for the standard radio receiving tube with glass envelope to distinguish from the MT, or "Metal-Envelope Tube."

trend now is to go still farther, to the so-called subminiature sizes, whose largest version uses the T-3* bulb.

It is the purpose of this paper to give an indication of the functional variety now available in highly miniaturized tubes, to point out operational and physical difficulties and limitations encountered as size is reduced, and to describe technological methods being employed to overcome the difficulties.

Since there are now over one hundred types of subminiature tubes commercially available, those mentioned below are merely indicative of the scope covered by this new tool.

No part of the paper is devoted to cataloguing the "advantages" of subminiatures, although some space is given to their limitations. This is because, in general, the user wants just one advantage, which is small size; he is willing to accept certain disadvantages to gain this end.

Actually, however, very small tubes do have certain advantages intrinsic in their size. One of these advantages is a generally higher frequency limit of operation obtainable with scaled-down dimensions, due to transit time and inductive effects. Another not inconsiderable advantage is the increased ruggedness provided by small structures. It is easier to make subminiature tubes to withstand high shock and vibration forces without damage than to make larger tubes for the same service.

II. LIMITATIONS IN MINIATURIZATION OF TUBES

Before giving way to enthusiastic plans for reducing all types of tubes to minimum dimensions, stock should be taken of the drawbacks to be encountered and the extent to which these are fundamental or can easily be overcome. From the standpoint of the user, such drawbacks are essentially operational or economic, whereas the designer and the student of physical processes are more concerned with reasons why there are limitations. The three viewpoints are considered separately in subheadings of this chapter.

1. *Expected Operational Shortcomings*

a. Short Life. Relatively high ratings per unit volume are the rule in subminiatures and early lots were very short lived. Improved processing, cathode studies, and quality control methods have now increased subminiature life to where it is competitive with that of other tubes for the same class of service. One manufacturer now claims a

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* The T size indicates *nominal* bulb outside diameter, in eighths of an inch. Thus, a T-1 has a nominal OD of ⅛ inch, or nearly ⅓ cm; a T-3 bulb is nominally just under 1 cm in outside diameter, etc.

life expectancy of 2500 hours for most of his subminiatures and 5000 hours for premium tubes.

A life expectancy of *t* hours does not, of course, imply that all tubes with that expectancy will hold their characteristics that long. A standard finding acceptance in the United States calls for any "lot" (or batch) of tubes of a given type to have an average life not less than 80% of that specified for the type. End of life for any tube occurs when its characteristics deviate the maximum permissible amount from their specified values.

Statistical studies of tube life and causes of failure are still in their very early stages, even for conventional tubes, so that an accurate picture of life in actual service is not possible at present. This unsatisfactory state of affairs has arisen because the cost of shipment, study of service conditions, and fault isolation in tubes which have failed while performing their duties would in general exceed the cost of original manufacture.

b. Microphony. Subminiature tubes are frequently forced to operate under conditions of shock and vibration; the electrical output caused by such mechanical stress on a tube is called microphony. Although, as mentioned earlier, small tubes will in general withstand higher acceleration than the large ones without permanent damage, smallness does not give any advantage microphonically. This is because the mechanical displacement of internal parts which are already crowded together produces a larger electrical effect than the same displacement when spacings are larger.

Microphony is being reduced by making parts stiffer and fits snugger and by locating the parts more accurately with respect to each other. A number of very small tubes are now quite adequate microphonically for their intended applications.

c. Unreliability. The recent historical period, which has seen the birth and early growth of the subminiature tube, has also witnessed a more and more insistent demand for tubes of unquestioned reliability. The requirements of electronic computers, aircraft control systems, and instrumentation, for example, are very severe and cannot compromise with tubes prone to frequent failures. It has been necessary in the past for users with highest quality requirements to avoid, sometimes with reluctance, the use of subminiature tubes. One major factor here was questionable life expectancy, discussed in the preceding section. Uniformly high quality assembly is difficult to achieve in very small sizes where parts and aggregates must be inspected under magnification; loose welds and the like are to be anticipated in relatively high proportion. Absolute dimensional tolerances must be tightened considerably in small tubes to achieve even approximately the same degree of reproducibility of electrical characteristics as commonly obtained in the GT sizes.

Despite all this, subminiatures are now being offered for instrument service.[2] More accurate jigging; more thorough inspection; and designs less susceptible to assembly errors will undoubtedly make the subminiature tube the cornerstone of electronic instrumentation someday. At present, however, the quality tube user is safer with larger sizes, unless he has an unusually good record of the performance of the subminiature type he contemplates using.

2. Physical Sources of Limitation

Progress in achieving acceptable performance with minimum size is the result of successfully coping with a number of physically limiting factors. Those of especial significance will be discussed in the paragraphs below as problems, whose solutions will appear, in the main, in Chapter III.

a. Current Density. Oxide-coated cathodes are not usually called on to deliver more than 0.2 amp per square centimeter average in tubes expected to have a reasonably long life. Subminiatures are, of course, subject to this limitation, so that current obtainable depends in part on the cathode area which can be provided in the space available. This area is quite small per unit length when the cathode is a coated wire filament; this type of cathode is preferred in hearing-aid tubes because of low drain required from the batteries used as power supplies.

Current density also restricts the size to which openings may be reduced in gas tubes, such as thyratrons, if current requirements are fixed. Several amperes average per square centimeter is a reasonable design target in ordinary gas tubes, but increased pressures permit relaxation of this figure in subminiatures, where the increased pressures are permissible because of reduced electrode spacings. Existing subminiature gas tubes have not gone as far as possible in this direction.

Figure 1 shows the arrangement of parts in a subminiature thyratron, indicating the degree of constriction imposed on the conducting path by the control grid. The tube of Fig. 1 is rated at 100 ma peak.

b. Cleanup. Gas pressure change during operation is a perennial difficulty in permanent-gas-filled tubes. This problem of cleanup would seem more serious in subminiatures than in large tubes because ratings tend to vary as the square of the linear dimensions while volume varies as the cube. The quantity of gas available varies as the volume, for like pressures. The saving fact here is that higher gas pressures may be used in small-dimension tubes, so that cleanup is really no more difficult to combat in small tubes than in large ones.

c. Anode Dissipation. As in larger tubes, most of the power loss must be radiated from the anode. This electrode is generally operated well below incandescence, largely to avoid the necessity of an economically unfeasible degree of outgassing during manufacture, but also for secondary reasons such as avoidance of evaporation of the anode material, thermal buckling, and excessive heat conduction to seals. The anode radiating area cannot be reduced below that necessary to dissipate rated losses at a permissible temperature.

d. Envelope Dissipation. The envelope of the tube is cooled by both radiation and convection and obviously must not operate at a temperature too close to the exhaust bake-out temperature, which is generally about 350°C for subminiatures with soft glass envelopes. In some applications, high envelope temperatures also result in detrimental glass electrolysis at the leads. About the maximum temperature presently permitted for subminiature envelopes is 250°C.

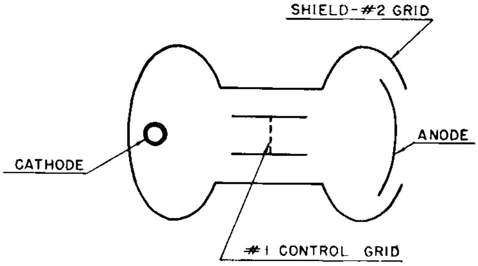

FIG. 1. Electrode arrangement in a subminiature thyratron with 1-cm outside envelope diameter. (*Courtesy Sylvania Electric Products, Inc.*)

e. Grid Emission. Close spacings and high operating temperatures make grid emission a serious problem in some of the very small tubes. Emission coating evaporates from the cathode in all tubes with activation and operating temperatures generally used, and small tubes generally do not have the space required to shield the grid from this material. A grid coated with emission compounds will release enough thermionic electrons to trouble many circuits at quite moderate temperatures. Exposure of the grid to radiation from the cathode increases the thermal problem, while cooling is not effective with the limited-area side rods used to support the grid. Evaporation from the cathode is accentuated in applications where the cathode heater voltage varies over a considerable range. It is clear that reduced ratings, low cathode temperatures, and narrow tolerances on cathode heater voltages will ease the grid emission problem; but it is also clear that design considerations are in order. These will be taken up in Chapter III.

f. Mechanics of Fabrication. Most subminiature tubes are designed and manufactured like their larger counterparts. Cathode coating, grid winding, bulb sealing, and exhaust processing are generally carried out on automatic machinery; but assembly or mounting operations are done by hand, frequently without benefit of magnification. It may be that the ultimate has not yet been reached in this type of fabrication. But the prediction that production costs will become prohibitive in this "watchmaker's art" before sizes have been farther reduced seems reasonable.

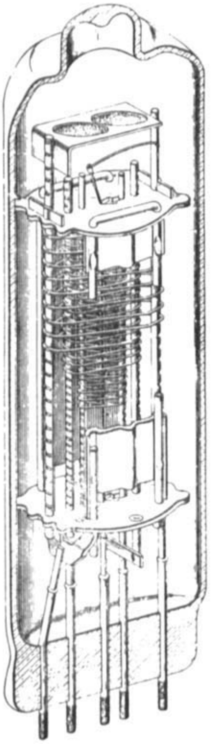

FIG. 2. Cutaway view of a subminiature pentode. The bulb cross-section dimensions are approximately ⅔ × 1 cm (T2 × 3), outside. (*Courtesy Raytheon Manufacturing Co.*)

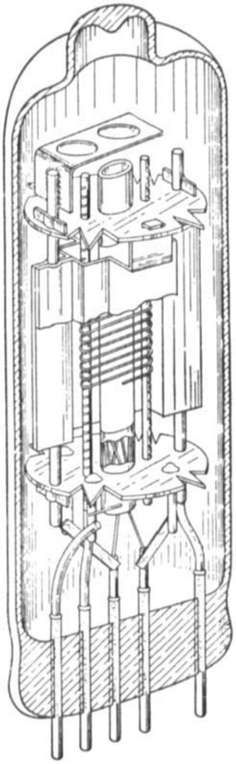

FIG. 3. Subminiature UHF triode. (*Courtesy Raytheon Manufacturing Co.*)

A remarkable fact is that low-cost, high-production fabricated and stamped parts are held in close-spaced, mutually insulated positions with an accuracy of location closer than usual machining tolerances. Some fixtures are used, but not on all tubes. The basic jigs are really the mica wafers built into the tube at each end of its structure, with accurately placed holes to locate the parts. A serious size and complexity limitation is, in fact, the minimum spacing attainable between mica holes without breakthrough, this being about 0.03 cm for usual mica thickness.

Figure 2 is worth a thousand words in showing the complexity contrived into a typical subminiature pentode. Coaxial elements include a filament, three grids, and a plate. The filament is held taut by a cantilever spring shown near the top and is centered by an arrow cut through the mica. Dark circles in the "flag" at the top are getter compound.

Figure 3 is another tube of the same bulb size as shown in Fig. 2; it illustrates the use of an indirectly heated cathode in this size tube.

A major fabrication problem in the manufacture of small tubes is the sealing of the mount into the bulb. This is more difficult than in large tubes because it is difficult in the limited space available to avoid oxidizing the parts and poisoning the cathode. American practice calls for automatic sealing in a protective gas atmosphere, with preheat, sealing and anneal fires delicately adjusted to give just the heat needed to get vacuum tightness and prevent excessive glass strains with resulting cracks, without overheating the parts. The tubes shown in Figs. 2 and 3 are sealed in by supporting the mount independent of the glass and heating the glass to softness, then quickly pressing the glass around the leads to form a seal. Another American method is to mount the parts on a glass button, prepressed or sintered around the leads. The tube envelope and exhaust tubulation assembly is then dropped over the mount and sealed to the button. Other methods of sealing will be discussed in Chapter III.

3. *Economics*

The cost aspect should be mentioned briefly, for the benefit of those who plan applications. Since the output capabilities of a tube go down with size but its complexity does not, it seems rather fundamental that paralleled subminiatures as now designed cannot compete economically with equivalent rated single tubes of larger size.

III. Noteworthy Features of Subminiatures

Design, materials, and methods now used in subminiatures are mostly adaptations or extensions of the same in larger tubes. This situation may be expected to change as the small types develop out of infancy. Peculiarly adaptable features are already finding broad application in size reduction and new techniques are being explored. Some of the more interesting or newer features will be discussed in this section.

1. *Special Grids*

Wound grids, traditionally of nickel, are generally made of the more refractory materials where small wire diameters are required. Molybdenum, tungsten, and various alloys containing these metals are predominant. In a process finding some application,[3] the desired grid mesh is produced directly by electroplating, instead of using wires.

Under certain conditions, coatings on the grid of gold,[4] silver,[5] or other materials[6] may be expected to reduce grid emission, which has already been mentioned as a problem.

Planar microwave triodes have developed some miniaturization techniques of their own to achieve small electrode spacings and accordingly small electron transit times. Most of these tubes use grids of fine wire wrapped under tension on and brazed to a supporting ring. Ring spacers around the edges of the elements are used to set the required spacings. The most elegant tube of this type yet produced is the Bell Labs 1553,[4] designed to generate up to 4000 megacycles per second. A comparison of the spacings in this tube with those of a planar tube released for production several years ago is shown, to scale, in Fig. 4. The cathode-grid spacing in the 1553 is only 1.5×10^{-3} cm; the grid wires are 7.5×10^{-4} cm in diameter, wound at 395 turns per centimeter.

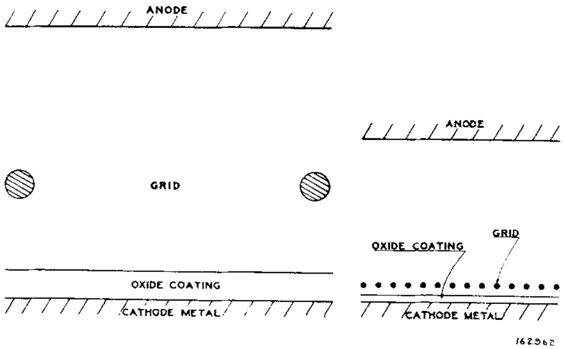

FIG. 4. Comparative size reduction in planar microwave triodes. Lighthouse tube on the left. Grid-cathode spacing in the 1553 is 1.5×10^{-3} cm. (*Courtesy Bell Telephone Laboratories.*)

2. *Cathode Techniques*

The cathode coating on the 1553, just mentioned, is applied by an automatic spray machine, which applies oxide to the metal base in a layer $1.3 \times 10^{-3} \pm 5 \times 10^{-5}$ cm thick.[4]

Accurate control of the cathode coating is sometimes obtained by cataphoretic[7] application.

The base metal of sleeve cathodes is generally nickel, as in larger tubes. In filamentary cathodes, however, nickel is not strong enough in the small sizes required for some applications; especially in hearing-aid tubes where filament drain must be kept low to avoid depleting the small battery used as a source of power. Alloys stronger than nickel at operating temperatures, such as Ni-Cr alloys or refractories such as tungsten, are used as filaments in many tubes, with the conventional alkali-earth oxide coatings. Tungsten filaments only 8×10^{-4} cm in diameter and requiring a heating current of only 12.5 ma are in use.[8]

3. Anode Materials

Carbonized nickel, with its relatively high thermal emissivity, is a common anode material in subminiatures. Operation of the anode at temperatures above the start of incandescence would allow dimensions of the plate to be reduced, with further possible advantages from using plate materials with natural gettering properties such as tantalum or zirconium. Overall size reduction may be accomplished in certain tubes by such increased specific loading of the plate; but in general, plate size reduction will not help until the envelope size may also be reduced. This is also possible, as shown in the next section.

One plate material developed during World War II in Germany is now being applied to some extent in small tubes. This is aluminum-coated iron sheet which, heated in vacuum, takes on a highly emissive black surface with gettering properties.[9]

4. Envelope Facts

As mentioned before, most subminiatures are made with soft-glass envelopes and dumet seals. It would seem possible to reduce the size of such tubes appreciably by using harder glass and higher bake-out temperatures. This would make a more expensive tube, a factor tolerable in some applications. A more fundamental limitation preventing wide adoption of this expedient is that with the small glass thicknesses now existing between leads, further size reduction would in most cases produce excessive electrolysis of the glass or radio-frequency losses with hard glasses just as with soft glasses. Currently used bake-out temperatures could be raised somewhat even for soft glasses, but the limit for hard kovar-sealing glass is only about 100 centigrade degrees higher than for soft glass.

A more hopeful method of achieving high envelope dissipation in small sizes is offered in the use of ceramic envelopes. Ceramics with less electrolysis and radio-frequency losses than glass are readily available. Metals are now being sealed vacuum tight directly to ceramics without the use of glass by several techniques[10] developed during and since World War II.

5. *Solutions of the Sealing Dilemma*

Inasmuch as damage to the cathode and other parts during sealing becomes a more serious problem as size is reduced, it is worth while to mention additional techniques for combating this difficulty.

One such method is the use of a low-melting "solder glass" which matches the envelope and button base material in thermal expansion.[8] This solder glass is sealed at 450°C, as opposed to 800 or 900°C required for the usual soft glass.

Another method finding some application where the final seal is a metal-to-metal joint is the gold diffusion technique.[3] A gold wire is clamped between two copper flanges. The joint is brought to 400°C during exhaust and a vacuum-tight diffusion seal, equivalent to a hard-soldered joint in strength and permissible operating temperatures, is produced.

A glass-to-glass seal may also be produced at normal exhaust temperatures if the surfaces are first optically polished.[11]

IV. SUMMARY STATE OF THE ART

Over a hundred subminiature tube types are already on the market. The varieties which will be produced can be expected to keep up fairly well with expanding requirements since, as demonstrated above, means are at hand for overcoming most of the factors now limiting advancement in this field.

A few more existing types should be mentioned to help orient the reader on the state of the art at the present time.

The 5647 (Sylvania) is a simple diode, but is worth mentioning because it has a 5000-hour life expectancy, with a T-1 (⅓ cm) bulb.

A construction now used by RCA[5] for several types is shown in cross section in Fig. 5. This triode oscillator will deliver over 50 mw at 3000 megacycles per second; the diameter of the body is just that of an ordinary lead pencil.

Voltage regulator tubes are available in subminiature sizes for various ratings. The 5841 (Victoreen) is noteworthy in regulating the relatively high tension of 900 volts, using a corona discharge.

Sylvania's 5642 is remarkable as a rectifier in that it incorporates a 10-kv rating in a T-3 bulb.

Photo tubes are available in subminiature sizes. An example is the RCA 1P42.

A Geiger tube, with No. 2 sewing needle for size comparison,[12] is shown in Fig. 6.

Continuing into somewhat unusual types, we find the RCA 5734 transducer. This is a subminiature triode with one electrode movable through a metal diaphragm. It may be used to convert mechanical vibrations up to 12,000 cycles per second into electric current variations.

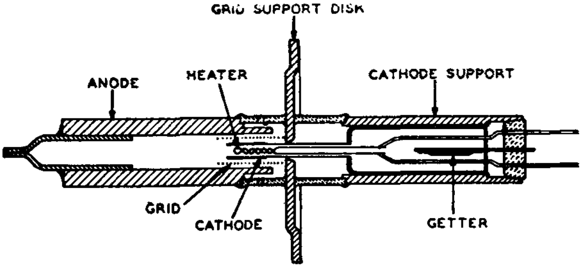

FIG. 5. Cross section of an RCA "pencil" triode. (*Courtesy Radio Corporation of America.*)

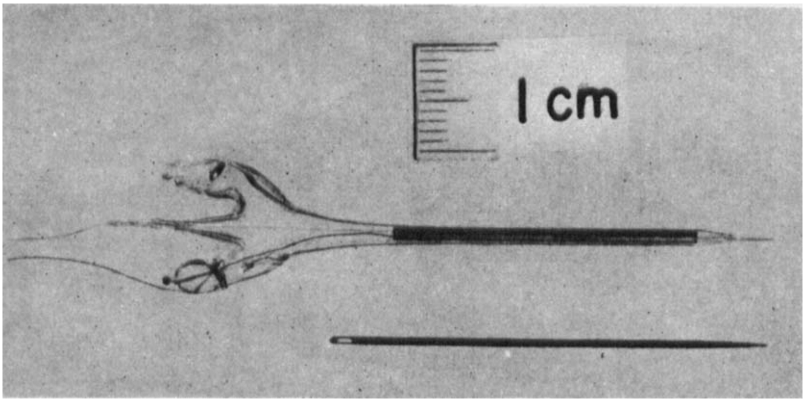

FIG. 6. Miniaturized Geiger tube. (*National Bureau of Standards.*)

Finally we have the solid state devices which are electronic without being vacuum tubes and which certainly are highly miniaturized. The diode rectifier has been known for a long time; mixers, up to tetrodes, are a logical extension. The Bell Labs transistor[13] is a triode amplifier which has done much to assure the important role of solid state devices in the tube field, especially where miniaturization is of importance.

Although all the references to foreign publications cited above deal with techniques, it should be mentioned specifically that Europe is now in production on subminiature tubes.[14]

Since selected types may already be obtained with life and reliability equivalent to that of larger sizes, the major obstacles to broad acceptance of subminiatures have been removed.

Indeed, one prominent manufacturer now advertises a line of subminiatures said to outperform in every way the corresponding miniatures.

If the author may venture a prediction, however, the next major step in size reduction and reliability improvement will be based on new design concepts, permitting a radical departure from the complex assembly procedures typified in Fig. 2.

ACKNOWLEDGMENTS

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