COMPUTER EXPERIENCE IN EXTENDING TUBE LIFE

by

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ABSTRACT

An effective improvement in the life and reliability of receiving-type vacuum tubes has been obtained on the Whirlwind Computer Project at M.I.T. by applying a combination of three principles: (1) using only those tubes which have been determined to have a good life expectancy, (2) avoiding operating procedures that are detrimental to tube life, and (3) choosing circuit designs which as far as possible are insensitive to changes in tube characteristics.

Procedures for tube selection have been worked out along two lines, the first to predict whether cathode-interface deterioration will occur and the second to detect tubes with mechanical weaknesses or improper processing. The formation of an interface, which produces the effect of a parallel resistance-capacitance network in the cathode circuit of a tube, was first observed on the Project in early 1948; it is the most serious type of deterioration that has been encountered. It has been found that a 500-hour life test at an elevated cathode temperature on a sample of tubes from a given production lot is a satisfactory method for determining whether tubes from that lot will remain essentially free of interface deterioration for several thousand hours of normal operation. Before final selection of tubes is made, each tube is preburned for about 100 hours. This tends to stabilize plate current as well as to precipitate failures that would result from mechanical defects or gas within the tube.

To extend the life of the tubes selected for use, cautious operational procedures are observed. In particular, the tubes are not left for extended periods with heater voltage alone applied, since this condition promotes the formation of cathode interface. Since the tubes must be turned on and off daily, heater voltage is applied and removed gradually over automatically controlled 5-minute cycles to reduce thermal shock to the filaments.

As a final consideration, wide operating margins have been provided in the circuit designs both with regard to tube performance and to dissipation ratings. Records of the performance of selected tubes over a period of more than 10,000 hours show that they have a life expectancy considerably greater than would be predicted by most design engineers.

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INTRODUCTION

A widespread impression among design engineers, including those in the electrical field, is that of all the common electronic components the receiving-type vacuum tube is the least dependable. Consequently if equipment is to be built in which reliability is an important consideration, there is a strong tendency to avoid electronic circuits if possible.

Of course, the vacuum tube is the most complicated of the circuit components to construct, but why should not a vacuum tube be as reliable as other precision devices, for example, a watch? A partial answer is that the majority of the commercially available tubes are not precision products but are like inexpensive watches intended primarily for a large number of consumers who are interested mainly in economy rather than dependability. In addition, the final steps in the manufacture of receiving tubes involve chemical processes over which there is no direct control, so that variation among tubes is inevitable.

From the engineering point of view, extending tube life is only a part of the problem. Actually it is the life of the circuit of which the tube is a part that is important. One way of extending circuit life is to select only those tubes which will not fail within a specified length of time. In this way circuit life is extended without changes in tube production techniques. Tube life itself may be extended in some cases by observing certain precautions in operating the tubes. A combination of these two procedures, careful selection and cautions use, has been successfully employed by Project Whirlwind to obtain improved life and reliability from electronic circuits.

KINDS OF TUBE FAILURES

The question of what changes take place as tubes age has to be answered before adequate selection methods can be worked out. Experience has shown that tube failures may be roughly classified as follows:

1. Change in characteristics
2. Mechanical defects
3. Gas within the tube
4. Heater burn-out
5. Physical damage.

The first of these is a broad classification covering decreases in emission, change in cutoff, etc. Such changes are usually the result of deterioration of the cathode structure in the tube. Mechanical defects and rise of gas pressure within the tube can be attributed to faulty construction and processing. Some of these cannot be detected by ordinary testing methods until the tube has been in use for some time. Heater burn-out may be induced by repeated sudden application of full voltage to the filament, which makes the initial heating of the filament non-uniform, so that stresses are set up which weaken the structure and hasten its failure. Physical damage, of course, is largely accidental. It includes such causes as breakage and inadvertent application of excessive voltages. The careful selection and operating procedures used on our project have reduced the incidence of failures in all of these classes.

CHANGES IN CHARACTERISTICS

Changes in characteristics which take place over a long period of use cause the majority of tube failures, so I should like to devote most of my remarks to this problem. Figure 1 shows the circuit of a simple pulse amplifier used to amplify and invert a positive rectangular pulse. An analysis of the action of this circuit may be made simply by considering that the control-grid bias is suddenly changed from one constant value to another. Neglecting what occurs during the transition period, it is obvious that the plate current which flows in the tube should likewise jump from the value corresponding to one grid voltage to that corresponding to the new grid voltage. The waveform of the plate current may be examined on a suitable cathode-ray tube synchroscope by observing the voltage developed across the plate load resistance. Figure 2 shows a typical waveform obtained with a new tube. The duration of this pulse is 2.5 microseconds and the transitions take place in about 0.05 microsecond. The vertical deflection of about four divisions corresponds to a plate current of less than 2 percent of the peak space-charge-limited emission for this tube.

An example of one type of deterioration which takes place in some tubes is shown in Figure 3. This is the waveform of plate current produced by an aged tube using the same grid signal as for the preceding figure. Initially the current jumps to approximately the same value as for a new tube, but then it decays exponentially to less than one-third of its initial value. When such a tube is checked on a standard tube tester, readings corresponding to the reduced value of plate current are obtained. The evidence, then, is that the tube has lost some of its emitting capabilities, although actually the pulse test shows that this is not the case. These results indicate that a type of deterioration other than the classical decay in emission takes place, but the two phenomena cannot be distinguished by the static measurements obtained with a commercial tube tester.

The waveform of Figure 3 would result if a parallel resistance-capacitance combination were present in the cathode circuit of the tube. This circuit is illustrated in Figure 4. Initially the cathode-to-ground voltage is zero, but during the pulse the capacitance becomes charged to cause an effective negative bias between grid and cathode. Plate current therefore falls off as a result of this bias voltage. Approximate values for the effective resistance and capacitance can be determined from measurements of the decrease in plate current and of the time constant for its decay. Resistance values up to a few hundred ohms and capacitances of the order of 0.01 microfarad are typical. Time-constants for the decay fall in the range from 0.5 to 0.8 microsecond. Considered in terms of frequency response, this circuit in an amplifier stage would act as an unbypassed cathode resistance except at frequencies greater than 200 or 300 kilocycles.

CATHODE INTERFACE

A theory which accounts for the effects I have just described is that as the tube ages an interface layer is formed between the cathode sleeve and its oxide coating, this layer being a chemical combination of active metals and impurities in the cathode structure. This is illustrated in Figure 5. The presence of such a layer actually introduces a physical resistance-capacitance network into the cathode circuit of the tube. This theory was suggested to us by Prof. W. B. Nottingham of the Physics Department of M.I.T. Previously Dr. Albert Eisenstein, working at the M.I.T. Radiation Laboratory during the war, had studied the formation of interface in magnetrons which was causing voltage breakdown in their cathodes.

Our first observations of cathode-interface deterioration were made over two years ago, when circuits became inoperative after the tubes had been in use for about 1500 hours. The tubes concerned were high-transconductance pentodes. The results of initial tests were published in a project report in June 1948. Since that time similar effects have been observed in other types of tubes, both pentodes and triodes. Some of the more significant characteristics of this type of deterioration are the following:

1. The rate at which deterioration occurs is substantially faster if the tube is operated at a low duty factor rather than as a Class "A" amplifier. In some cases, 500 to 1000 hours is sufficient for a low-duty-factor circuit to become inoperative. At first it was thought that the interface formation occurred only at low duty factors. Controlled life tests in which some tubes were completely cut off while others passed current continuously showed that the decay effects appear in both cases, although it takes a considerably longer period of operation in the latter.

2. Deterioration is faster at elevated cathode temperatures. Tests in which tubes were operated at heater voltages of 8.0 volts instead of their normal 6.3 volts showed that the rate of interface formation increased by about one order of magnitude. Data taken on one tube type has indicated that a 500-hour test under such conditions is suitable for predicting that a given lot of tubes will remain essentially free of interface effects for several thousand hours when operated under rated conditions.

3. A relatively high percentage of silicon impurity in the cathode sleeve, such as is found in the so-called "active" cathodes, causes rapid deterioration. This has been confirmed by spectrographic analyses of the cathode structures of both new and deteriorated tubes and by life tests on special lots of tubes in which active, normal, and passive alloys were used for the cathode sleeves. These alloys are distinguished mainly by their silicon contents, the active alloy having the highest silicon content and the passive having the lowest. It is not true that use of cathode alloys with low silicon contents will guarantee freedom from this sort of decay since some lots of tubes with such alloys have shown deterioration while others have not. This implies that impurities necessary for interface formation may come from other sources within the tube envelope, so that both the selection of materials used in the tube construction and the methods of processing the tube may be important manufacturing considerations.

4. Some characteristics typical of semi-conductors have been observed. In particular, the resistance component shows a negative temperature coefficient; that is, the effective resistance present is less for higher cathode temperatures. Since high cathode tmperature speeds the formation of interface, it is obvious that operation in this manner is not a practical method of minimizing interface effects. However, the use of subnormal heater voltages during tests for the presence of interface does increase the sensitivity of the measurement.

Cathode interface formation has been the most frequent type of deterioration encountered on the project. By choosing tubes which are known to be constructed with low-silicon-content cathode sleeves, and by operating samples of each production lot for 500 hours at elevated heater voltages and testing them for interfaces, it is possible to select tubes which can be expected to be reasonably free of this type of deterioration for several thousand hours of life. The assumption that, in general, the same characteristics appear in all tubes of a given production lot seems to be a valid one, since it has been substantiated by historical records which we have compiled during the past two years on a few thousand tubes.

PREBURNING

Other selection procedures are used for showing up some short-time changes in tube characteristics and for picking out some tubes which have mechanical defects or are gassy, but which satisfactorily passed their initial tests. Those tubes which pass the initial tests are preburned for a period of about 100 hours. A steady current is passed through the tubes so that the plates and screens operate between one-half and full rated dissipation. Then before being selected for use all tubes are thoroughly checked by tests similar to those listed in JAN specifications. The most important function accomplished by preburning is the stabilization of plate current. Changes in plate current of 10 to 20 percent during this period are not uncommon in some tube types. Usually the drift is in the downward direction and is most rapid during the first 10 or 20 hours. Shifts in contact potentials and variations in cathode activation contribute to these changes.

Examples of mechanical defects which may not be observable until the tube has been in operation for a short time are warping or sagging grid structures, poor welds, and cracked glass envelopes. Also included in this classification are monentary shorts between electrodes which result when the envelope is tapped lightly. In several cases it was found that these tap shorts were caused by foreign matter such as lint within the tube. For many applications tap shorts are not objectionable, but in circuits which are sensitive to pulses, a tap short may cause a transient which will be transmitted through the system as erroneous information. Since a conventional neon-lamp tester does not give a positive indication of such shorts, a special thyratron trigger circuit was built for detecting the defective tubes.

OPERATION PRECAUTIONS

Obviously, the effective life of tubes in a given circuit can be increased by using only those tubes which have been selected for long life, but it can be further increased by observing certain precautions in their operation. It has been noted that low-duty-cycle conditions are the most unfavorable because they promote formation of cathode interfaces. Therefore extended periods in which heater voltage alone is applied are avoided whenever possible. In the Whirlwind system this is accomplished by turning heater voltages on and off daily. To reduce thermal shock to the heaters, voltage is applied and removed gradually over automatically controlled 5-minute cycles. It is felt that this procedure has greatly reduced the danger of heater burn-outs usually present when full voltage is applied suddenly. In a system of over 3000 tubes which is turned on and off each day, only one such tube failure has occurred in about nine months.

OPERATING EXPERIENCE

Unfortunately no life data are available on tubes which were not carefully selected, so that a quantitative evaluation of the effectiveness of the procedures I have described cannot be made. However, an examination of the performance of some selected tubes over a period of 10,000 hours shows that they have a life expectancy considerably greater than would be predicted by most design engineers.

Figure 6 shows the life characteristics of three types of tubes operating in typical computer circuits which are being used to study system reliability. The 6AS6 and 7AD7 tubes were purchased from commercial productions, while the 7AK7 tubes are special pilot-plant production. The curves are plots of percentage of tubes remaining against hours of service. It can be seen that for both the 7AK7 and the 7AD7 types, more than 65 percent of the tubes remain in operation after 10,000 hours. It should be pointed out that a tube failure does not imply a concurrent operational failure of the system. In fact the majority of the tubes retired were removed because of changes in characteristics which were detected by periodic testing of the type which will be described by Mr. Sumner in his paper on marginal checking.

The fact that the 6AS6 has shown a higher rate of failure is at least partly because its circuits have a smaller operating margin than is the case for the other tubes. This brings out the important point that tube life in a given circuit is influenced to a considerable degree by the circuit design which is used. In choosing a circuit design, if it were possible to approach the limit in which changes in tube characteristics had no effect on circuit performance, then mechanical defects, burn-out, breakage, etc. would be the only causes of failure, and the effective tube life would be much longer than I have described.

Successful operation of an electronic computer places a high premium on circuit reliability. Our experience has shown that an accelerated life test for cathode interface on samples from each production lot of tubes and a thorough examination of each tube after 100 hours of preburning are effective in rejecting tubes which are potentially short lived. By using such selected tubes in circuits designed to have wide operating margins and by avoiding operational practices which are known to accelerate tube deterioration, a substantial improvement in the life and reliability of electronic equipment may be obtained.

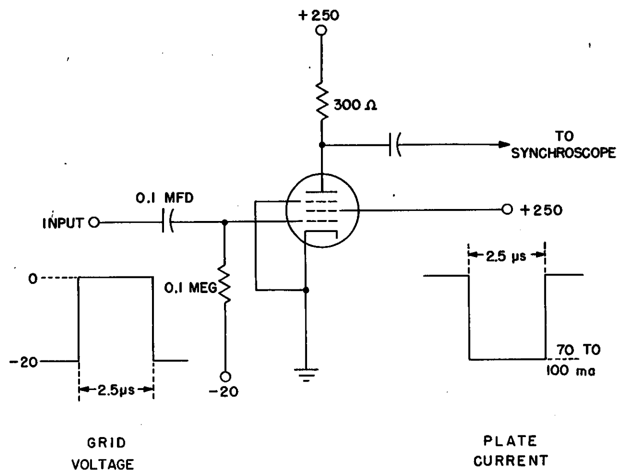

Fig. 1. Pulse Amplifier

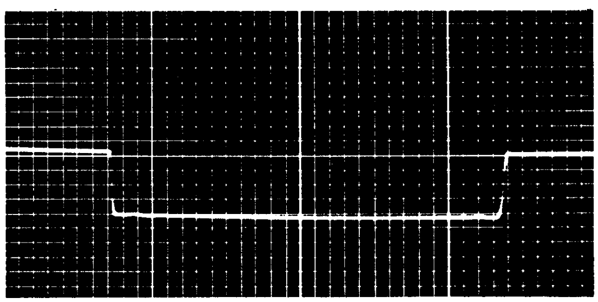

Fig. 2. Plate current waveform good tube

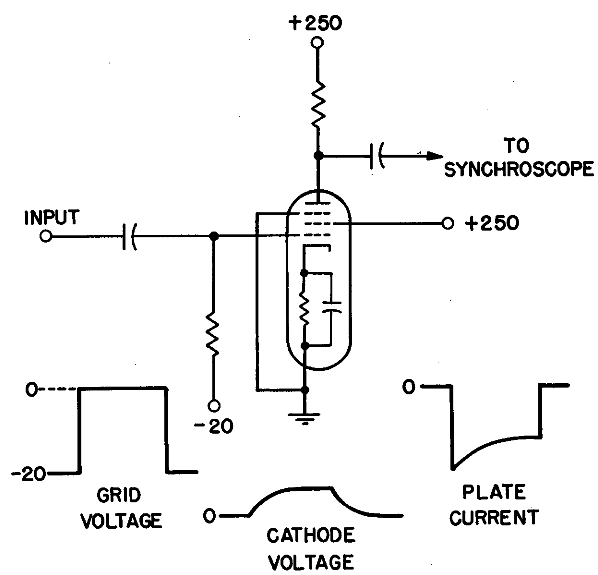

Fig. 4. Effective equivalent of deteriorated tube

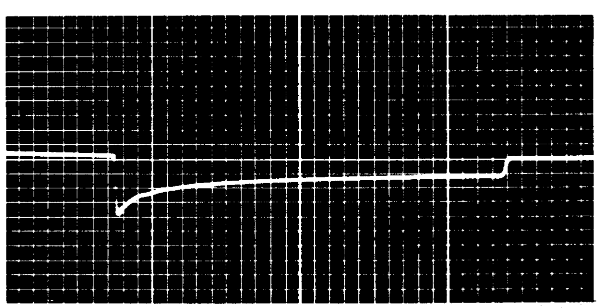

Fig. 3. Plate current waveform deteriorated tube

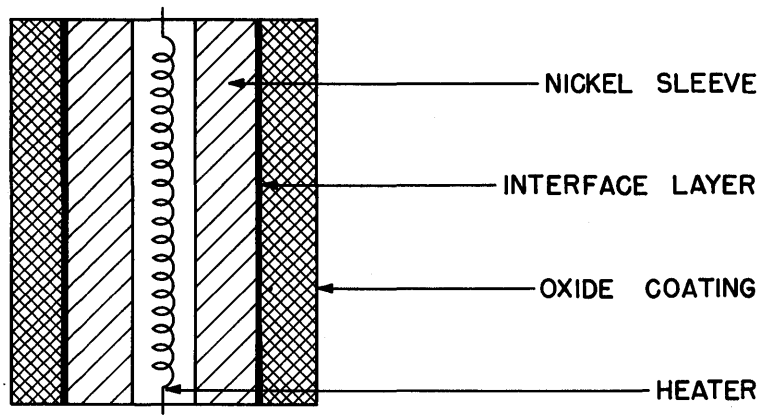

Fig. 5. Section through cathode with interface

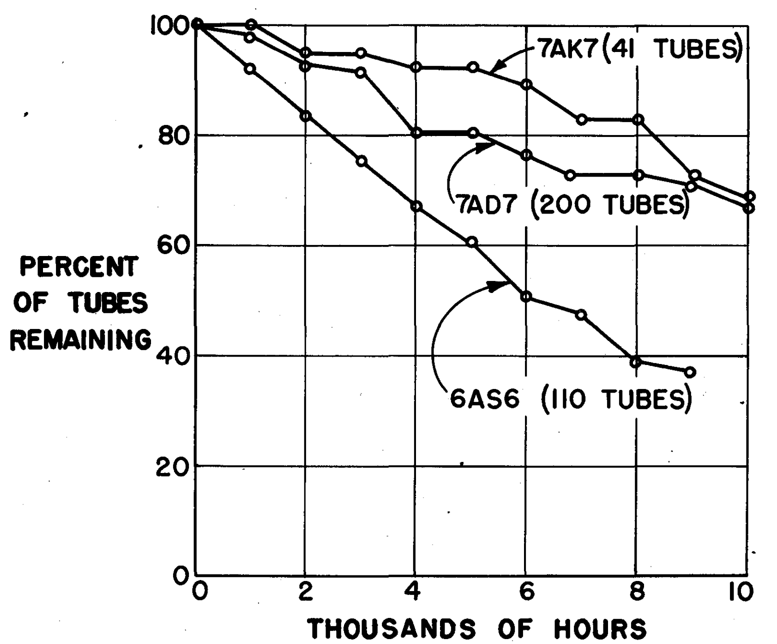

Fig. 6. Tube life experience in computer circuits