Sandia Corporation

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**TUBE DESIGN AND CIRCUIT
CONSIDERATIONS FOR
FAST-HEATING ELECTRONIC
SYSTEMS**

by

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ABSTRACT

Fast-heating electronic systems are becoming increasingly important in military applications. Operational requirements in the range of 10 to 12 seconds must be accomplished with a combination of tube and circuit design. Definitions of tube and system operational time are numerous and interrelated so that selection of an appropriate test depends on the circuit application, ease of measurement, and test equipment capabilities. Circuit designs which minimize differences among tubes will also minimize drift during warm-up so that a stable operating point is reached more quickly. Properties of the vacuum tube classed as detrimental, such as interelectrode leakages, are more critical in fast operational tubes. Gains in operational time are achieved by: (1) reduction of the heated mass, (2) high cathode activation, and (3) reduction of conduction losses. General design considerations of the heater, cathode, and tube assembly are discussed. Six tube types encompassing subminiatures, miniature, hydrogen thyratron, and power triodes have been developed and produced which function at 10 seconds in a fast operational system. Tube characteristics are given.

TUBE DESIGN AND CIRCUIT CONSIDERATIONS FOR FAST-HEATING ELECTRONIC SYSTEMS

INTRODUCTION

Fast-heating electronic systems are becoming increasingly important in military applications. Operational requirements in the range of 10 to 12 seconds have become necessary and must be accomplished with a combination of components and circuit design. Many methods of reducing system operational time can be postulated, depending upon use requirements and allowable complexity. A few of the more apparent approaches are listed:

1. Using preheat power, the system is maintained in a "stand-by" condition. Preheat power might be full or reduced, depending on time available from a function signal to actual function time.
2. Overvolting a "cold" system through a programmed cycle to achieve fast operational time. This method will reduce the operational time of some receiving tubes to the order of 10 seconds. But the number of fast-heating starts must be limited or heater burnout will occur. This method will not reduce operational time of types such as the 2C39 beyond perhaps 15 seconds.
3. Nominal heater voltage applied to a cold system is the ideal approach. Preheat power and the complication of an overvolting cycle are eliminated.

As usual, the third approach, which is most desirable, is also most difficult to achieve. The first approach, probably among the least desirable, is most easily accomplished but is not truly a fast-heating system. Discussions in this paper are limited to the third approach.

CIRCUIT TUBE CONSIDERATIONS

Many definitions of operational time, as applied to the tube itself, are possible; and selection of the proper test depends on the circuit application, ease of measurement, and test equipment capabilities. In deciding upon required system performance at fast operational times, such as 10 seconds, one must keep in mind the fact that many tubes are involved, each operating at

some defined lower performance level. These considerations make fast operational systems quite impractical unless considerable care is exercised in circuit and tube design. Figure 1 shows stage loss characteristics of a fast-heating subminiature pentode in a transformer-coupled audio circuit. For an IF, audio or video amplifier, 90 per cent of final static plate current at operation time is often suitable, depending upon circuit design. For the particular circuit of Fig. 1, a tube capable of 90 per cent plate current will give 90 per cent of the available circuit gain in 7 seconds. The plate current test is comparatively simple to perform, although the current must be recorded by graph and the acceptability computed. If stability is not so important, only a lower limit -- a minimum plate current at function time -- may be specified. Transconductance has been specified but normally will give no better information than the plate current test and is considerably more involved to measure. Figures 2 and 3 give a comparison of operation time for various circuit conditions for subminiature pentodes. From these data, it may be seen that rapid stabilization of plate current is influenced by bias method and supply voltage source impedances or circuit loads. Cathode bias improves warm-up considerably by providing DC negative feedback. Signal bypassing of the cathode resistor does not affect warm-up time. Nonaligned grid pentodes, such as data were obtained from, will stabilize from 1 to 2 seconds faster if a screen-dropping resistor is employed to provide a more constant current; conversely, warm-up time is impaired by high source impedance in the plate circuit.

Plate current warm-up of a fast-heating triode, Fig. 4, is very similar to the pentode characteristics with one notable exception; a triode will stabilize more quickly with a relatively high impedance plate load whereas the pentode requires a low impedance plate circuit. In general, circuit designs which minimize differences among tubes will also minimize drift during warm-up so that a stable operating point is reached more quickly.

Figure 5 gives a comparison of several circuits classed as fast operational and slow operational, based on the measurement of tube static characteristics.

Pulse circuits such as blocking oscillators and multivibrators operate the tube in a saturated condition and demand control of peak emission capabilities rather than small signal characteristics. Operational time of pulse circuits does not bear any necessary or predictable relationship to the tube's DC plate current warm-up. Tubes for such application should be developed to give high peak emission capability, which is stable with life, and improved cathode warm-up time. An appropriate definition of tube operational time for pulse circuit applications would require a minimum peak current or minimum percentage of peak current capability at the function time. Free-running circuits, blocking oscillators, or multivibrators, are most critical to changes of peak emission during warm-up and should be operated with positive bias whenever

frequency stability is necessary during warm-up. Triggered stages can accept considerably less peak emission stability during warm-up and still give sufficient amplitudes for succeeding stages. In fact, for triggered stages, it has been found that a test for peak emission and a plate current warm-up test will satisfactorily control circuit warm-up time. Peak emission warm-up, as is required for complete definition, is rather involved to perform, presenting equipment and technique difficulties. For this reason it is advantageous to define characteristics more easily measured.

Balanced circuits should be avoided altogether unless the circuit can be made practically insensitive to wide tube parameter changes, which may involve either peak emission or DC emission. It is very difficult to maintain close balance during warm-up, and for critical circuits, the balance would have to be maintained during life. Circuits of this type sometimes operate with one cathode off ground so that heater-cathode leakage balance during warm-up may also effect circuit operations.

Operational time of power circuits, including oscillators, amplifiers, and pulse modulators, are best defined by their power output or pulse output at function time. Simple plate current warm-up tests on the tube would not indicate operational times of these circuits, therefore tube tests are functional, using the actual circuit or cavity. A percentage of final power output at function time or a minimum acceptable power output, either peak or average, is specified. Stability may be improved if it is possible to take advantage of cathode back-heating as quickly as possible during the turn-on cycle, consistent with cathode life. For example, reduced anode voltage might be applied to an oscillator or gas tube modulator 4 or 5 seconds after application of heater power. Just prior to the required function time, full anode voltage is applied.

Tube specification control of operation time is determined by application requirements, circuit design, and ease of measurement. For Class A circuits, such as video, audio and IF, a tube specification test-controlling plate current warm-up is indicated. For saturating circuits, such as blocking oscillators and multivibrators, control of peak emission warm-up is essential. Since it is rather difficult to measure relatively fast pulses by oscilloscope observation during warm-up, substitute measurements such as plate current warm-up and stringent control of life-emission capabilities are desirable. Specification warm-up control of power tubes is probably best carried out by functional tests in the actual system to be used. Choice of "percentage" stability requirements or "minimum" requirements will depend strictly on the desired circuit function.

TUBE DESIGN

Properties of the electron tube classed as detrimental, some of which are controlled by tube specifications, become even more important in the fast operational tube. Some of these detriments are: heater-cathode leakage, warm-up-life characteristics, insulation of electrodes, heater-life characteristics, and microphonics. Due to higher cathode temperatures normally required for fast warm-up, and mass reductions of all materials in the heater-cathode region, heater-cathode leakage is usually higher and perhaps less stable. Circuits should accommodate higher levels of leakage and should never depend on leakage stability for proper system operation. Insulation of electrodes may fall to minimum values during life instead of remaining well above the minimum as in most MIL tubes. Detrimental properties are, for the most part, the price of fast operational time and it will be found that development and refinement of a fast-heating tube type and its specification are largely concerned with control of detrimental properties.

Fast operational improvements in electron tubes are accomplished by: (1) reduction of the heated mass, (2) high cathode activation, and (3) reduction of thermal inertia and conduction losses. In the plate current warm-up characteristics of Fig. 6, time T_1 is controlled primarily by the heated mass; viz., heater wire, heater insulation, cathode sleeve, and the oxide coating. Time T_2 is a function of cathode activation. A tube having high peak emission will have a fast rise in region T_2 . Conduction losses through cathode-mica contact, losses through leads, and cathode tab supports or connections control time T_3 . General design considerations for fast operational tubes are presented in the following discussion.

Receiving Types

Heater design is different among manufacturers, depending on tube mechanical considerations and perhaps on preference by individual manufacturers based on more experience with one type than another. Coiled heaters, folded, coiled-folded, stagger folded, to mention a few, were investigated. The most important consideration in the heater design is probably its insulation. Mass must be held to an absolute minimum consistent with environmental and voltage breakdown requirements. A poorly controlled heater-coating process will give a wide range of warm-up times and will account for much of the variability in commercial tubes. Precise control of heater coating is likely to be the finishing touch toward production of fast operational tubes.

The cathode sleeve and its coating constitute a large portion of the heated mass. Reduction of cathode wall thickness has been incorporated in all fast-heating tubes with no significant degradation of mechanical stability,

although the balance is rather delicate and requires strict control. In some instances it was necessary to design new shapes whose dimensions were more easily controlled and which could be more efficiently supported by the mica spacers. A practical limit in wall reduction is reached when fabrication, handling, and strength become marginal. Weight of the cathode coating is tightly controlled and the coated band maintained precisely between mica spacers and over the heater. Coating composition and cathode base metal help in determining cathode activation, hence time T_2 of Fig. 6. Active nickel alloys, such as A-31, containing various amounts of reducing agents are generally used with triple carbonate coatings. The mass of the coating is minimized, consistent with life requirements. Ten-second operational tubes developed for Sandia Corporation have a life of 200 hours.

Intimate thermal contact between heater and cathode must be maintained to provide rapid heat transfer and to reduce relative movement during shock and vibration. Such close contact will also increase heater-cathode leakage. In some mechanical designs it is not necessary to have close fit between heater and cathode. Length of the heater is restricted within the cathode and falls within support micas. Any heater protruding beyond the cathode is heating an unnecessary mass of heater wire. Restricting the heater well within the cathode reduces cathode and temperature so that conduction losses through the mica are minimized. Cathode-mica fit and contact area determine largely time T_3 in Fig. 6. Conduction losses and radiation losses are low during periods T_1 and T_2 , contributing little to warm-up in these regions. Times controlled by total mass (T_1) and cathode activity (T_2) are considerably more effective in reducing and controlling operational time than cathode-mica fit. Contact with the cathode and the snugness with which the cathode is held must be a compromise among vibration noise requirement, cathode warping due to thermal cycling, and operational time.

Materials and processing used in grid and plate construction must be chosen judiciously to reduce the possibility of cathode contamination which destroys peak emission and warm-up time. Apart from materials considerations, cleanliness, processing, and aging complete the fast operational design. Cathode density, interface condition and surface conditions are affected to a large extent by processing and aging. Processing and aging are generally different among manufacturers and are adjusted to achieve the necessary cathode activity and stability.

Hydrogen Thyatron

All design considerations of the heater-cathode and its assembly apply as in receiving types. Ceramic spacers are used in place of mica and the cathode is normally supported by metal tabs at the ends. Conduction losses in the end supports may be minimized by using as small a tab as possible. The basic difference between the hydrogen thyatron and vacuum tube is found in the low thermal impedance path through the gas fill, from cathode to bulb. Hydrogen has

a thermal conductivity of seven to nine times that of air. At zero life, gas pressure is relatively high and maximum thermal losses result. Near the end of life, gas pressure is appreciably lower and conduction losses commensurately reduced. Gas pressure is held as low as possible, consistent with life and warm-up requirements. Heater current may decrease by 10 per cent in 100 hours, indicating the smaller losses and higher cathode temperature.

UHF Medium-Power Tubes

Tubes in this category, the 2C39 and pencil tubes, employ both planar and cylindrical structures. A structure such as the pencil tube would incorporate the principles discussed for receiving types, with the exception that cathode support considerations are modified. Presently available pencil tubes exhibit warm-up times shorter than conventional planar tubes. Planar types, as manufactured, are rather inefficient in regard to heater power. Operational time improvement of the 2C39 was accomplished by reductions of total mass, heater redesign, and reduced back losses from the heater. The "hotplate" design which was perfected has proven resistant to vibration and shock and is capable of providing 1 kilowatt of peak power at 10 seconds from a cold start, operated at a pulsed UHF oscillator. Frequency drift in oscillators must be controlled during warm-up and will be determined to some extent by cavity design. Drift is smaller if backheating is utilized. Warpage during thermal cycling of the thin metals used was the primary problem. Techniques for fabrication which produced a strain-free mechanical structure were devised, allowing the use of thin metals which retained their shape.

TUBE SPECIFICATIONS

Fast operational versions of the 5896, 6111, 5702, 5814, 2C39, and 1258 electronic tubes were developed under Sandia Corporation contracts. All of these types are either in prototype production or full production. Figure 7 gives a comparison of the 5702-WA and the fast-heating SA-307 for an indication of the improvement achieved in one type. Through the courtesy of the manufacturers, brief specifications showing important characteristics, performance, and details of tube design are given.

SA-301

Prototype 2C39, developed by Machlett Laboratories

General Characteristics

Heater voltage	6.3 volts
Heater current	0.85 ampere
Cathode warm-up, minimum	10 seconds
Amplification factor	80
Transconductance (70 ma, 600 v)	16,000 μ mhos
C_{gp}	2 μ mf
C_{gk}	5 μ mf
C_{pk} , maximum	0.04 μ mf
Pulse width, maximum	2 μ s
Duty	0.001
Peak anode voltage	3500 v DC
Peak grid bias	-150 volts
Frequency, maximum	3000 mc
Peak power at 3000 mc	1200 watts
Operation time (90% power output)	12 seconds
Average life (plate-pulsed oscillator)	200 hours

Design Features

Cathode -- 2-mil thick Cathaloy A-31 cap supported by a 0.4-mil cylindrical Kovar foil. Triple carbonate coating. Area about 75 per cent of the 2C39A. Temperature 830°C.

Heater -- A flat spiral coil in close proximity to the back side of the emitter. Shielded from back radiation by a series of three thin radiation shields mounted on a small diameter Kovar post.

SA-312 (6955)

Prototype 5814-WA, developed by CBS-Hytron

General Characteristics

Interchangeable with 5814-WA, with following additional characteristics:

Operation time (80% plate current)	10 seconds
Peak cathode current	2 amperes
Maximum pulse width	10 μ s
Average grid current	5 mAdc
Peak positive grid voltage	200 volts
Heater-cathode leakage (100 volts)	10 μ a
Pulse life (2 a peak, $t_p = 1.5 \mu$ s)	200 hours
Static life (5814-WA life test)	200 hours

Design Features

Cathode -- Cylindrical Inconel 220, coated with triple carbonate. Wall thickness 0.0025 inch. Temperature 825°C.

Heater -- Folded eight-leg configuration. Controlled, thin coating especially critical at bends. Centered exactly beneath coated band of the cathode.

Other -- Alclad plates, 6 per cent gold-plated moly grids, carbonized bulb, multivibrator aging.

SA-311

Prototype 5896, developed by Sylvania Electric

General Characteristics

Equivalent to the 5896 with the following exceptions and additions:

Heater current	400 mA
Operation time (85% emission)	10 seconds
Heater-cathode leakage	40 μ a
Average life	200 hours

Design Features

Cathode -- Cylindrical, Sylvania N4 nickel. Wall thickness 0.00225 inch. Triple carbonate coating 0.0035 inch thick. Temperature 800°C.
Heater -- Straight coils, series connected. Insulation thickness 0.0035 inch. Coils individually cataphoretically coated.

SA-310

Prototype 6111, developed by Raytheon Manufacturing Company

General Characteristics

Equivalent to the 6111 with the following additions:

Operation time (90% plate current)	10 seconds
Peak cathode current	1 ampere
Peak positive grid voltage	100 volts
Average life (0.8 a section peak tp = 1 μ s)	200 hours
Average life (6111 static life)	200 hours

Design Features

Cathode -- Oval-shaped Inconel 220. Wall thickness 0.002 inch. Triple carbonate coating. Temperature 750°C.

Heater -- Folded coils, connected in series. Very pure coating applied in extremely thin layer.

SA-303

Prototype 1258 hydrogen thyatron, developed by Chatham Electronics Division of Tungsol.

General Characteristics

Equivalent to the 1258 with the following exceptions:

Heater current	1.85 amperes
Cathode heating time, minimum	5 seconds
Operation time (85% peak emission)	10 seconds
DC anode voltage	1200 v DC
Average life ($\text{epy} \times \text{PRR} \times \text{ib} = 0.05 \times 10^9$)	200 hours

Design Features

Cathode -- Cylindrical weld-drawn P-50 nickel coated with a pulse emission coating covering 0.170 in.² of cathode area. Quiescent temperature 750°C. Wall thickness 0.0022 inch. Welded tab support for cathode top and bottom.

Heater -- Double helix, 0.007 inch Tungston wire. Coating cataphoretically applied to 0.004 inch thick. OD of coated helix is 0.001 inch larger than cathode ID to provide intimate thermal contact.

SA-307

Prototype 5702-WA, developed by Raytheon Manufacturing Company

General Characteristics

Equivalent to the 5702 with following exceptions and additions:

Operation time (90% plate current)	10 seconds
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Insulation of electrodes (end of life) 10 megohms

Average life 200 hours

Design Features

Cathode -- Oval-shaped Inconel 220. Wall thickness 0.002 inch. Triple carbonate coating. Temperature 750°C.

Heater -- Folded coil. Very pure coating applied in an extremely thin layer.

All tubes are required to meet the following environmental conditions:

Mechanical Shock:

18 impacts, 100 g's, 30 milliseconds

Vibration:

Six-hour total: 0.036 P-P displacement, 10 to 75 cps

10-g acceleration, 75 to 500 cps. Three hours cycled, three hours at noise resonance.

Temperature:

-65°C to 100°C ambient

Life:

200-hour test. Average life, 160 hours.

SUMMARY

The design of a fast-heating electronic system must be a combination of circuitry to give electronic tubes the most favorable conditions for rapid stabilization and of electron tube thermal design. Tube specification control and the definitions of tube operation time are determined by the circuit function; a digital system or circuit would utilize minimum limits on tube warm-up characteristics, while an analog system must require a certain stability for proper function. Tube designs, to achieve fast operation time, are accomplished by development of highly activated cathodes, reduction of thermal inertia in the heater-cathode structure, and very stringent controls of all processes and tolerances. Six tube types were developed under cognizance of Sandia Corporation which feature operation time of 10 seconds, from a cold start, for use in a fast-heating electronic system.

FIG. 1 OPERATIONAL WARMUP OF A
TRANSFORMER COUPLED AUDIO
AMPLIFIER COMPARED WITH
TUBE STATIC WARMUP.
5702 PENTODE

FIG. 2 TYPICAL WARMUP CHARACTERISTICS
FOR THE FAST HEATING SA-307
SHOWING THE EFFECTS OF BIAS
METHOD AND HEATER
VOLTAGE SOURCE IMPEDANCE.

FIG. 3 WARMUP CHARACTERISTICS FOR
THE FAST HEATING SA-307
SHOWING THE EFFECT OF SCREEN
& PLATE VOLTAGE SOURCE
IMPEDANCE.

FIG. 4 TYPICAL PLATE CURRENT WARMUP OF A FAST HEATING 6111 TWINTRIODE (SA-310) SHOWING THE EFFECT OF PLATE SUPPLY IMPEDANCE.

FIG. 5

FAST CIRCUITS

SLOW CIRCUITS

FIG. 6 PLATE CURRENT WARMUP CHARACTERISTIC.

FIG. 7 COMPARISON OF THE 5702
WARMUP CHARACTERISTIC
WITH A FAST HEATING SA-307
FOR TWO CIRCUIT CONDITIONS.

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