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REDUCTION OF RECOVERY TIME IN HIGH-TEMPERATURE CESIUM VAPOR THYRATRONS

by A. W. Coolidge, Jr.

Prepared by
GENERAL ELECTRIC COMPANY
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16. Abstract

In this program, an existing cesium vapor thyratron design was modified with the goal of reducing the recovery time from 300 to 100 microseconds. The approach taken was to facilitate ion-electron recombination by reducing the path lengths traversed by the ions after the cessation of current conduction. This included reduction of grid-to-anode spacing, grid-to-cathode spacing, and a reduction in the width of the grid slots. Although the tubes fabricated with these modifications were more difficult to fire and exhibited slightly increased voltage drop, stable operation was achieved for extended time periods in an inverter circuit.

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FOREWORD

The work described herein was performed by the Tube Department of the General Electric Company under NASA Contract NAS 3-9423 with Mr. Ernest A. Koutnik of the Space Power Systems Division, Lewis Research Center, as the NASA Project Manager.

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REDUCTION OF RECOVERY TIME IN HIGH-TEMPERATURE CESIUM VAPOR THYRATRONS

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SUMMARY

In the design of electrical equipment for use aboard space ships, rectifiers and inverters characterized by short recovery times permit operation at the higher frequencies, with attendant advantages in weight and efficiency.

In this program, an existing cesium vapor thyratron design was modified with the goal of reducing the recovery time from 300 to 100 microseconds.

The approach taken was to facilitate ion-electron recombination by reducing the path lengths traversed by the ions after the cessation of current conduction. This included reduction of grid-to-anode spacing, grid-to-cathode spacing, and a reduction in the width of the grid slots. Although the tubes fabricated with these modifications were more difficult to fire and exhibited slightly increased voltage drop, stable operation was achieved for extended time periods in an inverter circuit.

INTRODUCTION

Power conditioning of the large nuclear space-power systems currently being developed will require switching devices capable of operating at high temperature and in a high radiation flux environment. To meet this need, a program of cesium-vapor thyratron development was undertaken.

The basic design, which evolved under an earlier NASA contract[1]; utilized a tungsten filamentary type cathode, a copper grid, a molybdenum anode and a cesium reservoir atop the anode. Tube dissipation and heat sinking were balanced in such a way that the cesium reservoir was the coolest spot in the tube, thus assuring that the pressure of the cesium vapor would be determined by the temperature of the reservoir.

The desirable aspects in the use of cesium are its low ionization potential, which contributes to a low tube drop, and its ability to form a potent cathode merely by residing as a thin film on a hot surface. Since a cesiated cathode of this type is not subject to depletion, as is the case with the oxide-coated cathodes normally used in thyratrons, long life should be attainable.

Because cesium is a heavy element, however, it also presents a basic disadvantage when used in low recovery time tubes. In order to maintain a monolayer or more on the cathode surface -- a necessary condition for efficient cathode emission -- the cesium pressure must be in the range of 0.1 torr. This pressure, combined with the heavy weight of the cesium ion, produces a shortcoming in terms of low switching speed, thus limiting a tube to very low operating frequencies. This limitation is undersirable because it can adversely affect the size and weight of the power conditioning equipment.

In general, a thyratron or switch has two modes of operation:

(1) the conducting mode, when the thyratron is ionized, or the switch is said to be closed;

(2) the non-conducting mode when the thyratron is devoid of ions, or the switch is said to be open.

Further, the amount of power that can be controlled by a thyratron, or switch, is a function of the amount of current that can flow through the device during the conducting mode and the amount of voltage that the device can hold off or withstand during the non-conducting mode.

Tube switching time is the sum of the ionization and deionization (recovery) times. Deionization or "recovery" time may be defined as time required for the ions to be cleared from the tube so that it will remain non-conducting when a positive anode voltage is reapplied. Ionization time presents no problem because it is usually less than one microsecond in duration.

Deionization time, on the other hand, does become a problem in reducing tube switching time because its duration may be several hundred times greater than that of ionization time.

This report, then, describes the work done to reduce this deionization or "recover" time toward the achievement of a device capable of operating in rectifier circuits at frequencies up to 2000 hertz and in inverter circuits at frequencies to 500 hertz.

The results have been significant. While recovery times in existing mercury vapor tubes, and indeed in the early cesium thyratrons, were several hundred microseconds, the major goal set for this program was a recovery time of 100 microseconds or less. This objective was met by effecting design modifications in the thyratrons that had been developed under the earlier contract and by testing each tube in a circuit which allowed measurement of the time between the cessation of anode current and the re-application of positive anode voltage.

This accomplishment, and the means by which it was achieved, is discussed in subsequent sections herein.

APPLICABLE SYMBOLS

C	Capacitance
C_1, C_2, C_3, C_4	Arbitrary constants
D	Ambipolar diffusion coefficient
D_1	Differential operator
e	2.7183
F	Function
I_b	Average anode current
i	Instantaneous current
L	Inductance
ℓ	Slot width
N_o	Ion concentration at time zero
n	Instantaneous ion concentration
q	Number of ions per cubic centimeter per second being produced
R	Resistance
R_g	Resistance between grid supply and grid of the tube
t	Time
$T(t)$	Function of t
v	Instantaneous voltage
$X(x)$	Function of x
x	Distance from a point within a grid slot to the nearest point on the wall of the grid slot
α	$K\pi/\ell$, where K = 1, 2, 3, 4 . . . . ∞
∇^2	$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$

IONIZATION MECHANISM

A thyratron differs from a vacuum tube in that it has a filling of gas or vapor which plays a key role in the conduction of relatively large currents with only a nominal voltage drop across the tube.

Electrons emitted from the cathode of a vacuum tube encounter a negative gradient or space charge caused by the presence of other electrons that have been previously emitted. The result is that most of the electrons return to the cathode while only those emitted with the highest energy succeed in penetrating the negative space charge and moving on to the anode.

Because of the presence of gas or vapor molecules in the thyratron, an emitted electron that travels a sufficient distance is likely to collide with a neutral gas molecule, and if the energy of the electron is sufficient it will cause the gas molecule to ionize. The positive ion, which is relatively long lived, will migrate toward the most negative region of the tube (where the aforementioned space charge is most dense). In doing so, partial neutralization of the negative space charge occurs, a condition which is conducive to an increased flow of electrons from the cathode. This process is cumulative in that the increased flow of electrons further increases the probability of ionization until the process, when carried to its completion, entirely eliminates the negative space-charge region. Thus, in addition to the higher-energy electrons, practically all of the electrons emitted become available for anode current flow, with the maximum current being limited only by the size of the cathode.

The small voltage drop across the thyratron is usually independent of the current over a wide range. A portion of this drop represents the energy required to form new ions to replace those that are neutralized as they drift into the electrodes and sidewalls; it also supplies the positive gradient adjacent to the cathode to produce field-enhanced emission.

DEIONIZATION MECHANISM

Any process by which positive and negative ions lose their charge or become neutralized is considered a deionization process. In gaseous discharge devices, positive and negative ions (electrons) may neutralize by recombining after collision, in which case the deionization process is termed "volume recombination". A second process involves deionization by diffusion of the ions to a surface of an electrode or sidewall, where neutralization takes place by the exchange of charge with conduction electrons in the metal.

The question of which of these two processes may govern or dominate deionization depends largely on the pressure of the gas or vapor. In high-pressure arcs, volume recombination will predominate because of the high probability of ion-ion collisions before a surface is reached. Conversely, deionization in a low-pressure device, such as the cesium thyratron, is largely governed by the diffusion process.

The recovery time of the cesium thyratron developed earlier by conventional design methods was 400 microseconds. A 1/4-inch thick grid, with slots 3/32-inch wide, was utilized. Assuming that the controlling deionization process occurs within these grid slots, the most critical ion to be considered is one that has to travel the longest distance to reach a slot sidewall. This would be one that was at the center of the grid slot at the end of current conduction.

Cobine[2] states that the rate of change of the concentration of ions, dn/dt, at any point in a gas with q ions per cubic centimeter per second being produced uniformly throughout its volume, is given by:

$$\frac{\partial n}{\partial t} = q + D \nabla^2 n$$

where D is an ambipolar diffusion coefficient for the particular gas or vapor under consideration. This coefficient tends to vary inversely with the gas pressure.

After current conduction ceases, there is no longer a source of ionization present in the tube. For purposes of solving the above equation, it is reasonable to assume a single-dimension case, eg., along a line traversed by an ion in traveling from the center of a grid slot to the sidewall of the slot. This represents the shortest path for any of the ions in reaching a surface and so would be the governing case for deionization considerations.

If such line is assumed to be the X axis, the above equation becomes:

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2}$$

for which the solution (see Appendix A) is:

$$n = \frac{4 N_o}{\pi} \left[e^{-D\pi^2 t/\ell^2} \sin \frac{\pi x}{\ell} + \frac{1}{3} e^{-D 9\pi^2 t/\ell^2} \sin \frac{3\pi x}{\ell} + \frac{1}{5} e^{-D 25\pi^2 t/\ell^2} \sin \frac{5\pi x}{\ell} + \ldots \right]$$

where N_o = the ion density at the center of the slot at $t = 0$, and ℓ = slot width.

The higher order spatial harmonics decay so much more rapidly than the fundamental ones that they may be ignored here.

Therefore, a close approximation may be obtained from:

$$n = \frac{4}{\pi} N_o e^{-D\pi^2 t/\ell^2} \sin \frac{\pi x}{\ell}$$

and if the point of maximum ion concentration at the center of the grid slot is the only one considered, we have:

$$n = \frac{4}{\pi} N_o e^{-D\pi^2 t/\ell^2}$$

The above expression indicates that the time constant for the decay of the ions to $1/e\ N_o$ is $\ell^2/D\pi^2$, or about 80 microseconds (using a value of $D = 60\ cm^2/sec$ for cesium at 0.1 torr, and ℓ = 0.090 inch = 0.23 cm). While this figure sounds conveniently small, it must be borne in mind that several time constants must elapse before the ion population has diminished to the point where positive anode voltage may be sustained without current conduction.

METHOD OF APPROACH

The starting point for the effort to be devoted to the reduction of recovery time was the cesium thyratron evolved earlier under Contract NAS3-6005. This tube, shown in Figures 1 and 2, had been proven capable of operating up to 15 amperes average, with anode voltages up to 300 volts. Its high-frequency performance had also been checked using an electronic generator with a variable frequency output of up to 1500 hertz.

High-frequency performance was appraised by connecting the tube and load to a variable-frequency power supply and determining at what frequency grid control deteriorated. The anode voltage was set at 110 volts RMS since, with available equipment, it was impossible to have high voltage and high current simultaneously.

It was determined that up to a certain frequency, grid control was not altered from the 60-cycle case. Above this frequency, there was a rapid rise in the negative grid-supply voltage needed to maintain grid control. This reflected the need, at high frequency, for collecting ions more rapidly at the grid or permitting the grid bias to contribute to the deionization of the tube. The increase in grid-supply voltage over that needed for the 60-cycle case was termed excess bias-supply voltage, and the latter was plotted as a function of frequency (Figure 3) for various average currents. A full half-cycle was available for deionization and recovery. If 1200 hertz is taken as the maximum frequency, the time of a full cycle is 830 microseconds. The recovery time (equivalent to the half-cycle time) was therefore approximately 400 microseconds.

Relative to the deionization mechanism, once the gas or vapor is fixed the mass of the ion is fixed, and the two remaining variables that control deionization are the length of path traversed by ions before neutralization occurs and the gas or vapor pressure.

Since cesium vapor pressure cannot be reduced below approximately 0.1 torr and continue to support a cesiated cathode with adequate emission, it is evident that the reduction of spacings in the tube becomes the most appropriate approach toward achieving a lower recovery time. Although the provision of extra baffling in the arc stream or other changes to provide

Figure 1 - Cesium Thyratron No. 22 Developed Under Contract NAS3-6005

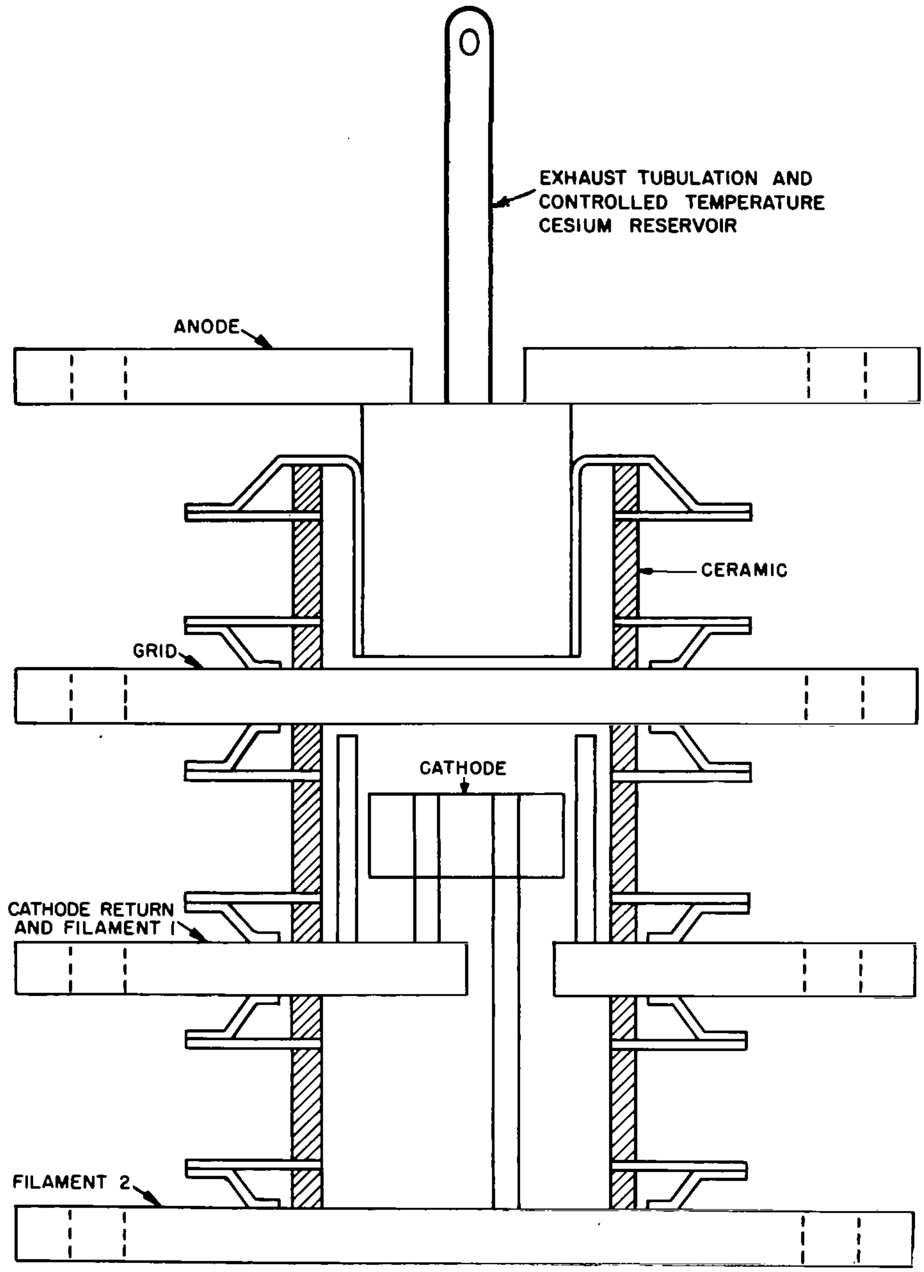

Figure 2 - Basic Structure of the Cesium Thyratron

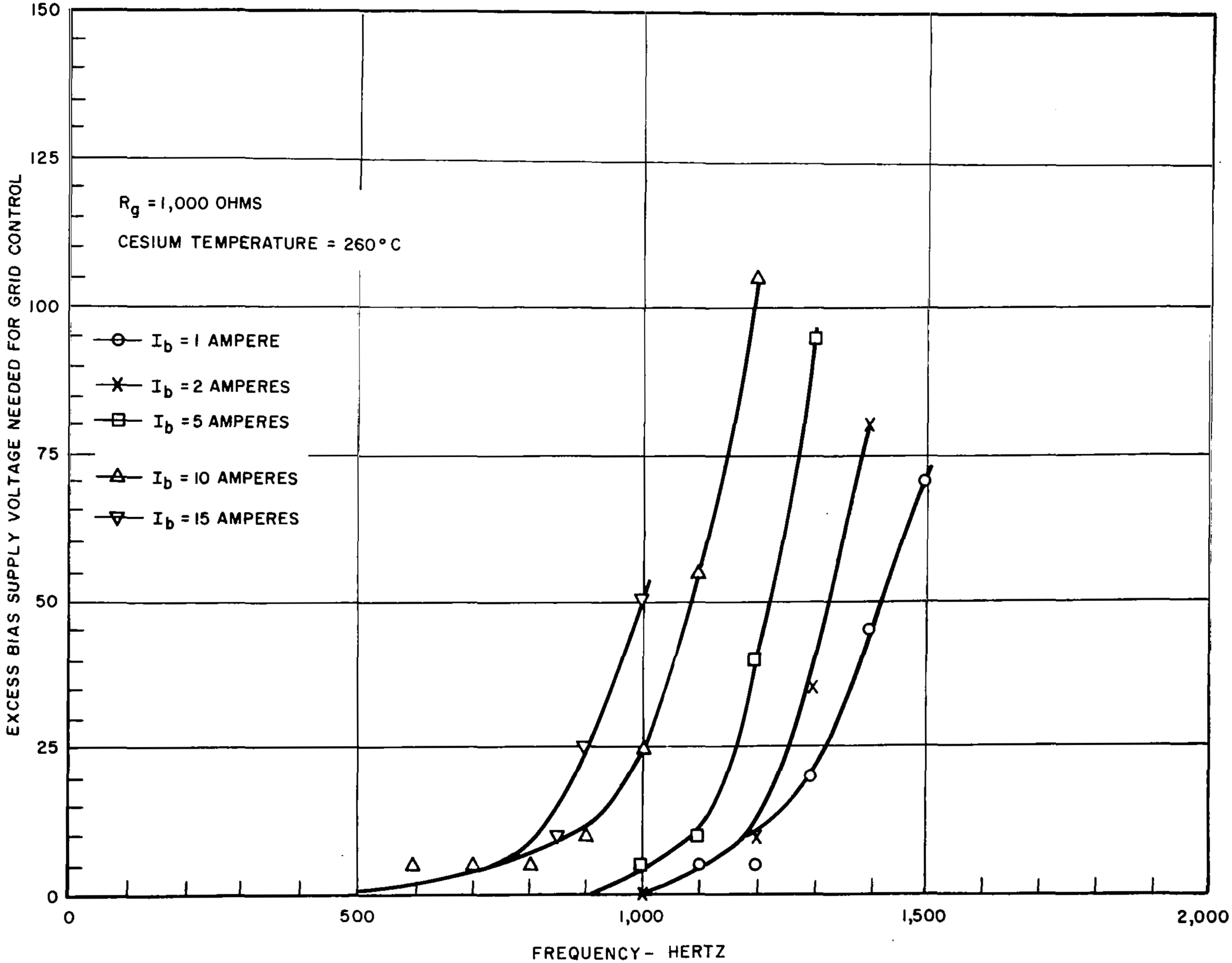

Figure 3 - High-Frequency Performance, Tube No. 22

additional surfaces for ion collection may produce minor improvements, the modification of spacings remains the most direct factor.

While the tubes were ultimately to be endurance tested in an inverter circuit, a simpler circuit was constructed for comparative measurement of recovery time. This circuit, shown in Figure 4, is manually operated. The time of application of inverse voltage to the tube under test is set by an RC time constant. The sequence of operation of the one-shot circuit is as follows:

(1) The thyratron is fired, and R is adjusted to provide the desired average current flow (15 amperes).

(2) C is made large and switched to position 2 for negative charging.

(3) Grid bias is set at the desired value.

(4) A recovery time trial is made by switching C to position 1, causing cessation of anode current and application of inverse voltage to the anode.

(5) Anode voltage recharges positively in accordance with the relationship $v = 125\,(1 - 2\,e^{-t/RC})$, the speed of recharging depending on the time constant of RC. If C has been set large enough, the anode voltage will charge as shown in Figure 5(A), and current through the tube will not restrike.

(6) C is reduced in successive trials until the tube fails to recover as evidenced by no permanent interruption of current. Anode voltage for such a case recharges as shown in Figure 5(B), with breakdown recurring as the voltage reaches a positive value with respect to the cathode. Recovery time is considered to be the minimum time measured between current cessation and the reapplication of a positive anode voltage, for the cases where the tube does recover. By setting v to 0 in the above formula we have $1 - 2\,e^{-t/RC} = 0$, or $e^{t/RC} = 2$ and t/RC must equal 0.7. The recovery time is, therefore, evaluated as $t = 0.7\ RC$.

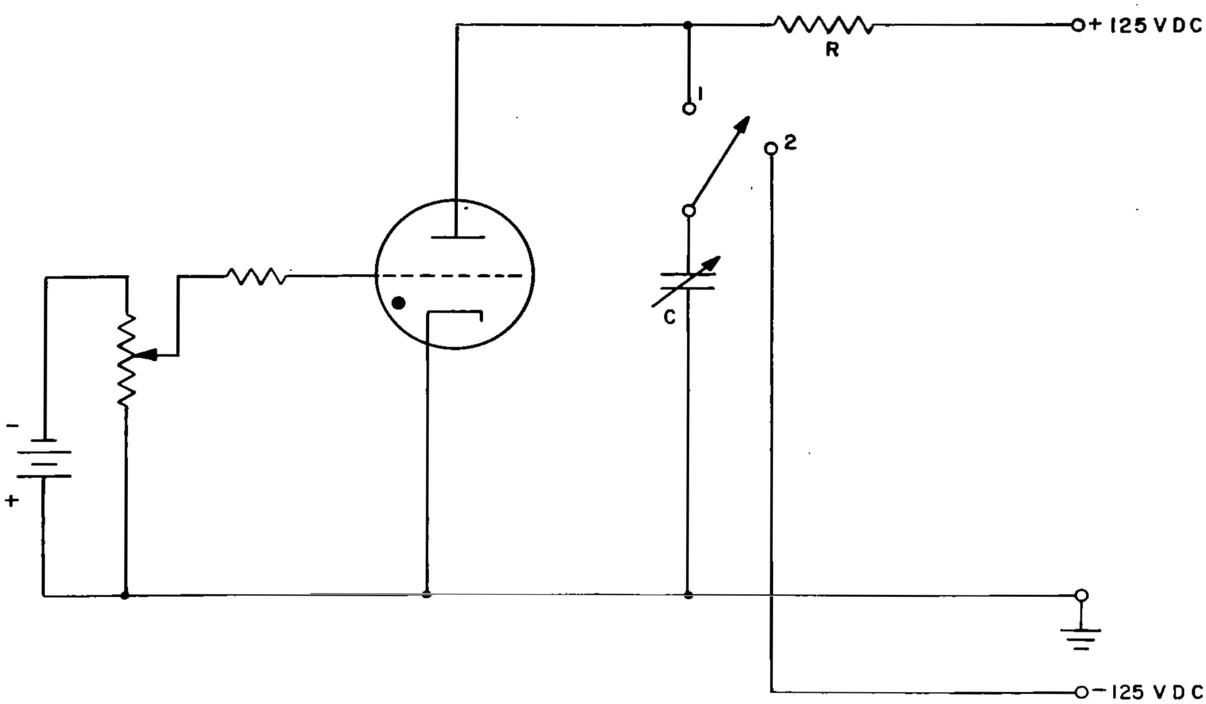

Figure 4 - One-Shot Recovery Time Circuit

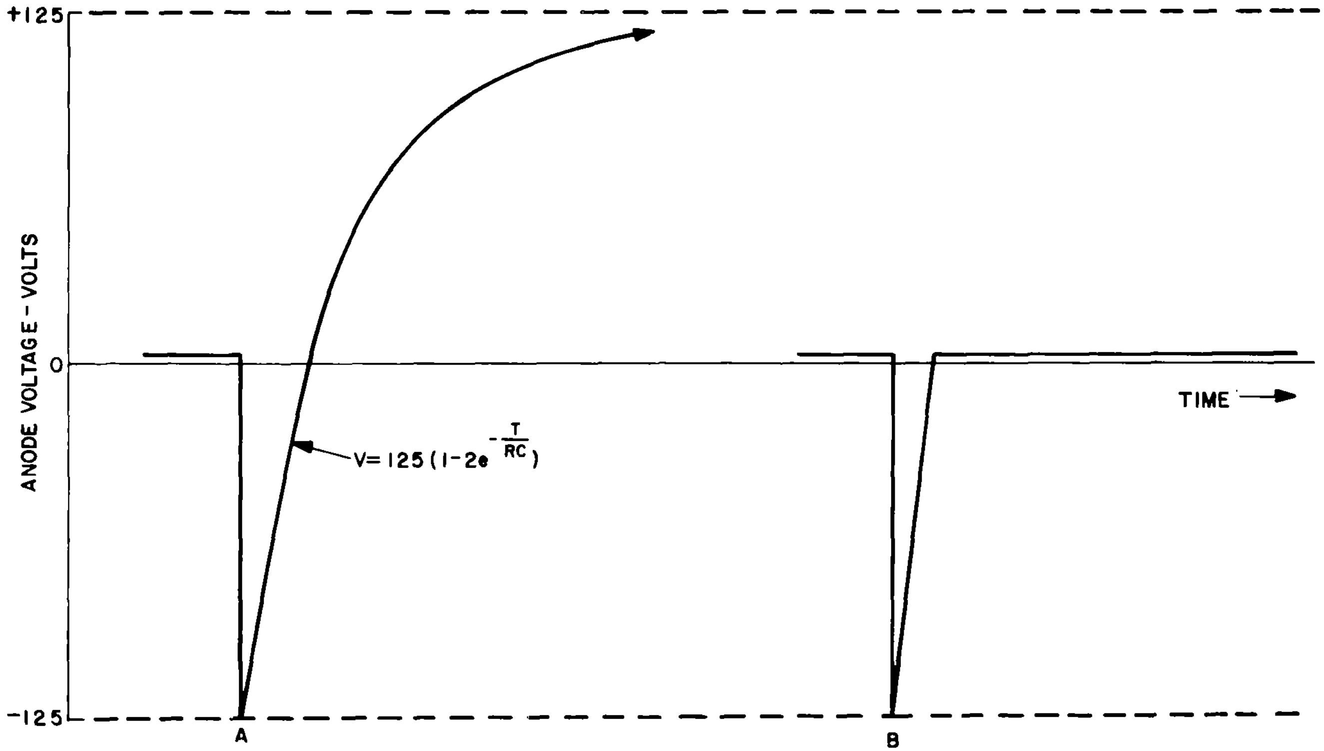

Figure 5 - Anode Voltage Versus Time in Recovery Circuit
(A. Tube recovers; B. Tube does not recover)

TEST RESULTS

Various dimensional changes designed to reduce recovery time, were made in test thyratrons, and their electrical performance was evaluated. These tests are described in the paragraphs which follow. Tube Nos. 21 and 22 were built under the previous contract (NAS3-6005). The various tube designs tested herein, for the purpose of reducing recovery time, were identified consecutively as Tube Nos. 24 through 29. Table I summarizes the salient dimensions of the various devices.

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Table I - Salient Dimensions and Recovery Times for Test Thyratrons

Tube No.	Shield Over Cathode	Shield Slots Aligned	Grid-Anode Spacing	Grid-Cathode Spacing	Grid Slot Width	Grid Thickness	Observed Recovery Time* (μSEC)
21	no	-	1/8	~1/4	1/16	1/8	310
22	no	-	1/8	~1/4	3/32	1/4	280
24	no	-	1/16	~1/4	3/32	1/4	250
25	yes	no	1/8	~1/16	3/32	1/4	260
26	no	-	1/16	~1/4	1/16	1/4	160
27	yes	yes	1/16	~1/16	1/16	1/4	140
28	yes	yes	1/16	~1/16	1/32	1/4	100
29	yes	yes	1/16	~1/16	**	1/4	70

All dimensions in inches
*Cesium temperature in the range of 200 to 220°C
**Grid openings are 1/32 inch diameter holes

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TUBE No. 24

In Tube No. 24, the grid-to-anode spacing was reduced from 1/8 to 1/16 inch. The recovery time was improved to 250 microseconds.

TUBE No. 25

The grid-to-anode spacing of this tube was 1/8 inch, but addition of a shield above the cathode had the effect of reducing the effective grid-to-cathode spacing. This shield was a slotted disc located 1/16 inch from the grid, and its slots (1/16 inch wide) were oriented at right angles to those in the grid. Addition of the shield produced a slight benefit in recovery time (Figure 6).

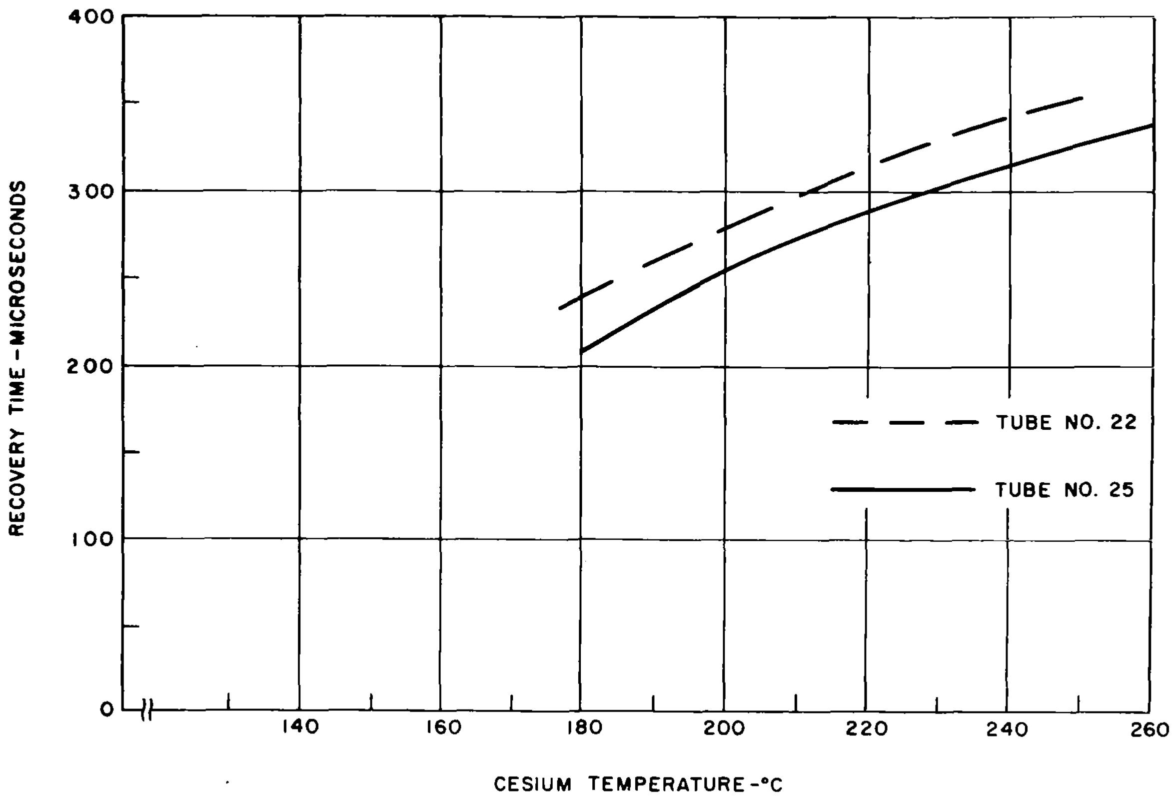

Figure 6 - Recovery Time Versus Cesium Temperature, Tubes Nos. 22 and 25

TUBE No. 26

The slotted shield above the cathode was not included, but the width of the grid slots was reduced from 3/32 to 1/16 inch, Figure 7, and the grid-to-anode spacing of 1/16 inch was reinstated. The marked improvement in recovery time, Figure 8, focused attention on the size of the grid openings as the key parameter. Although the anode-to-cathode voltage drop was satisfactory, more power was needed for triggering.

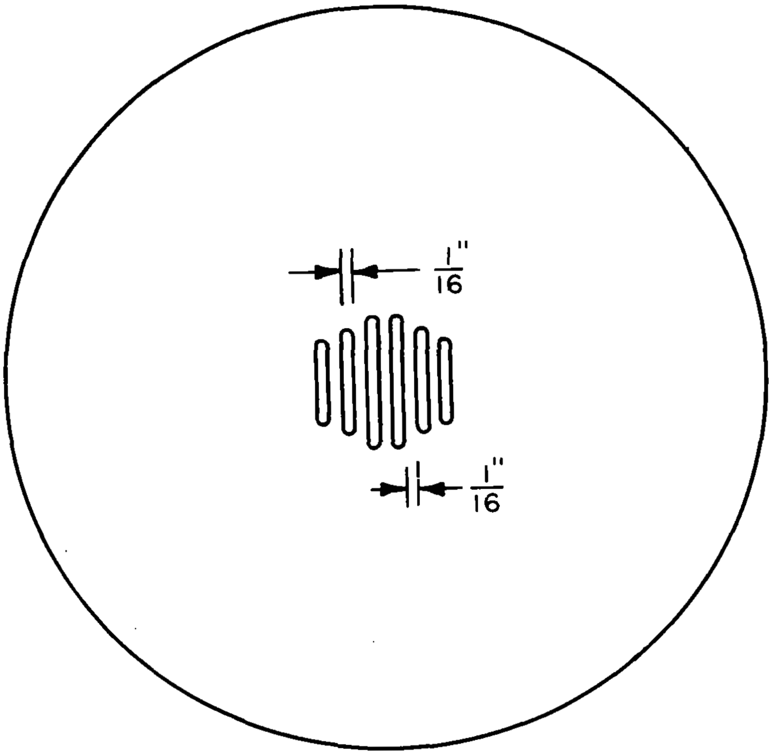

Figure 7 - Grid Pattern for Tube No. 26
(Actual Size)

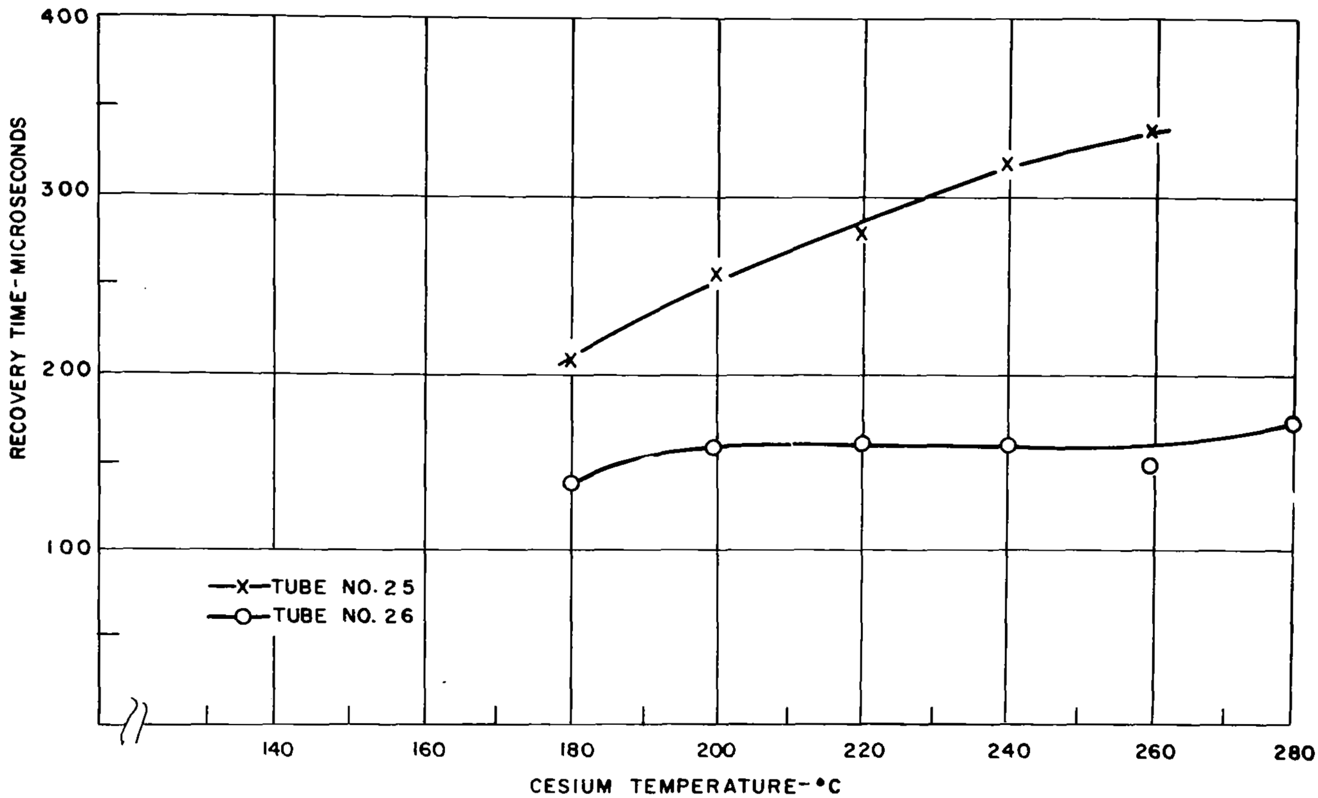

Figure 8 - Recovery Time Versus Cesium Temperature, Tube Nos. 25 and 26

TUBE No. 27

Tube No. 27 was identical to No. 26, except that the slotted disc was used atop the cathode, which reduced the effective grid-to-anode spacing from 1/4 to 1/16 inch. The disc was oriented such that its slots were parallel to, and directly below, those in the control grid. Another marginal improvement in recovery time was noted where the cesium temperature was 220°C or below (Figure 9).

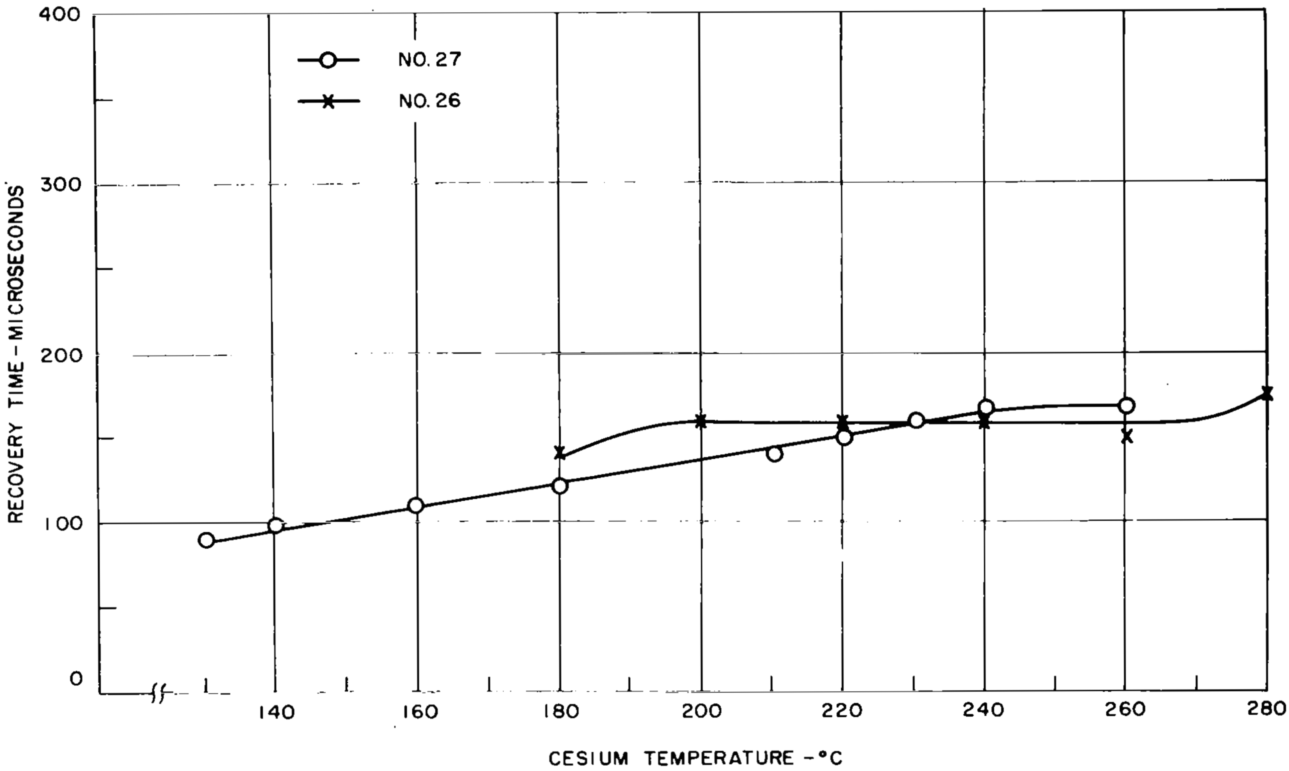

Figure 9 - Recovery Time Versus Cesium Temperature, Tube Nos. 26 and 27

TUBE No. 28

In this tube, grid-slot width was further reduced from 1/16 to 0.037 inch. Otherwise the tube was like No. 27. Again, a marked improvement in recovery time was observed (Figure 10) and, for the first time, 100 microseconds was achieved at a cesium temperature of 220°C or lower.

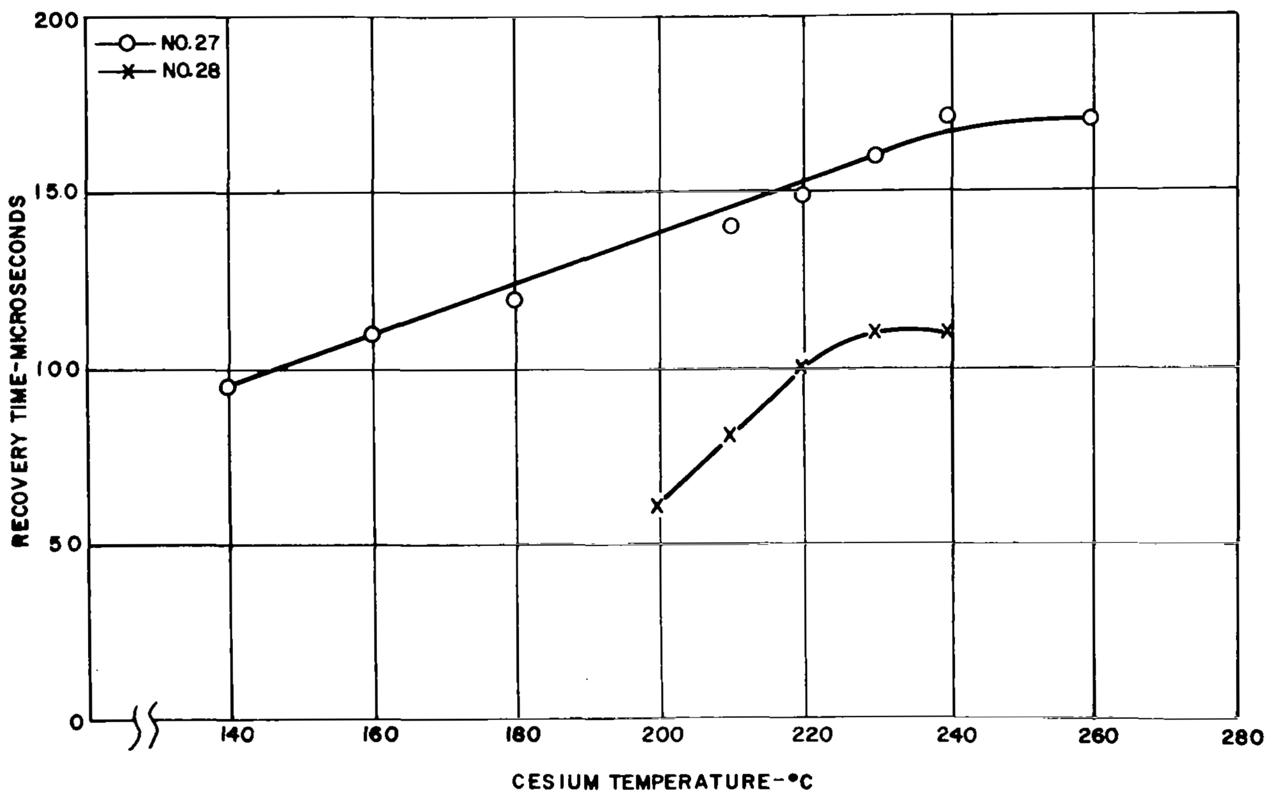

Figure 10 - Recovery Time Versus Cesium Temperature, Tube Nos. 27 and 28

TUBE No. 29

The grid of Tube No. 29 was the "tightest" of any of the grids tried. It contained 129 holes, each 1/32 inch in diameter, arranged in a pattern corresponding to that shown in Figure 11.

Recovery time (Figure 12) for this tube was the lowest of any of the tubes, as might be expected. There were, however, other indications from the testing that suggested that this grid was impractically tight. For example, the trigger power required for No. 29 was two or three times as great as that needed for No. 28 (Figure 13). The other, and major, drawback was a 7 to 8 volt drop through the grid. The drop through the grid was determined by measuring the voltage between the grid and anode when the tube was conducting. This evidence of high loss at the grid was confirmed by excessive grid heating when the tube was loaded. Indeed, with 15 amperes

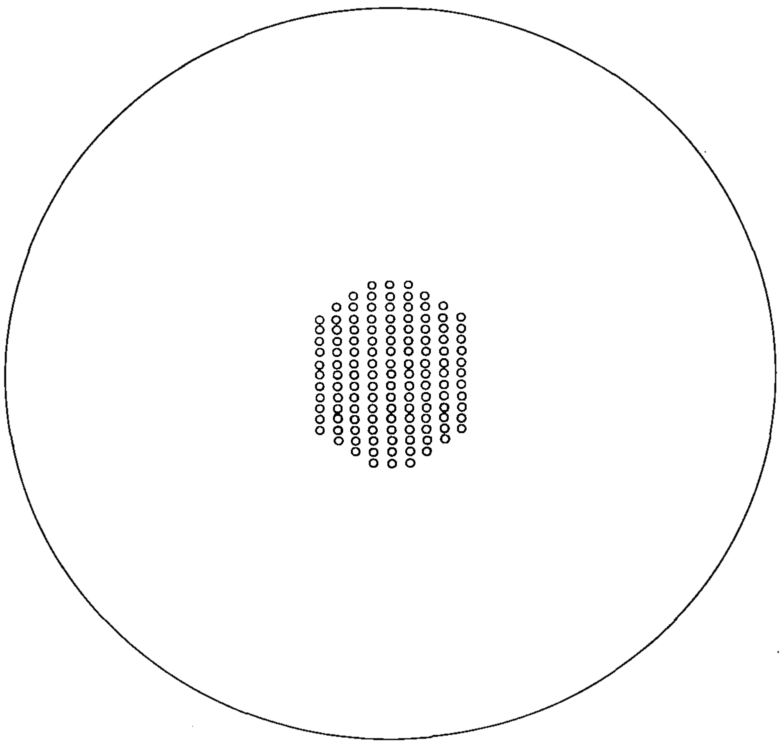

Figure 11 - Grid Pattern for Tube No. 29
(Actual Size)

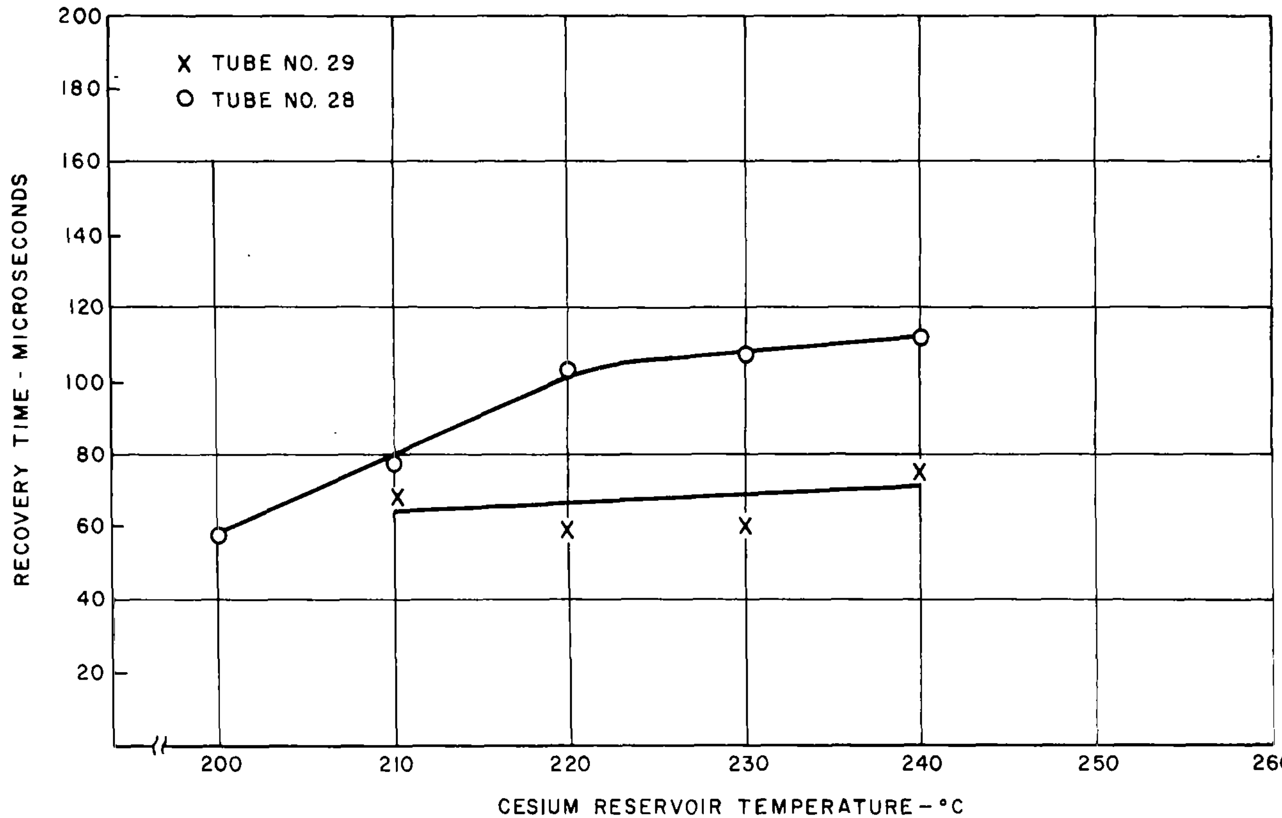

Figure 12 - Recovery Time Versus Cesium Temperature, Tube Nos. 28 and 29

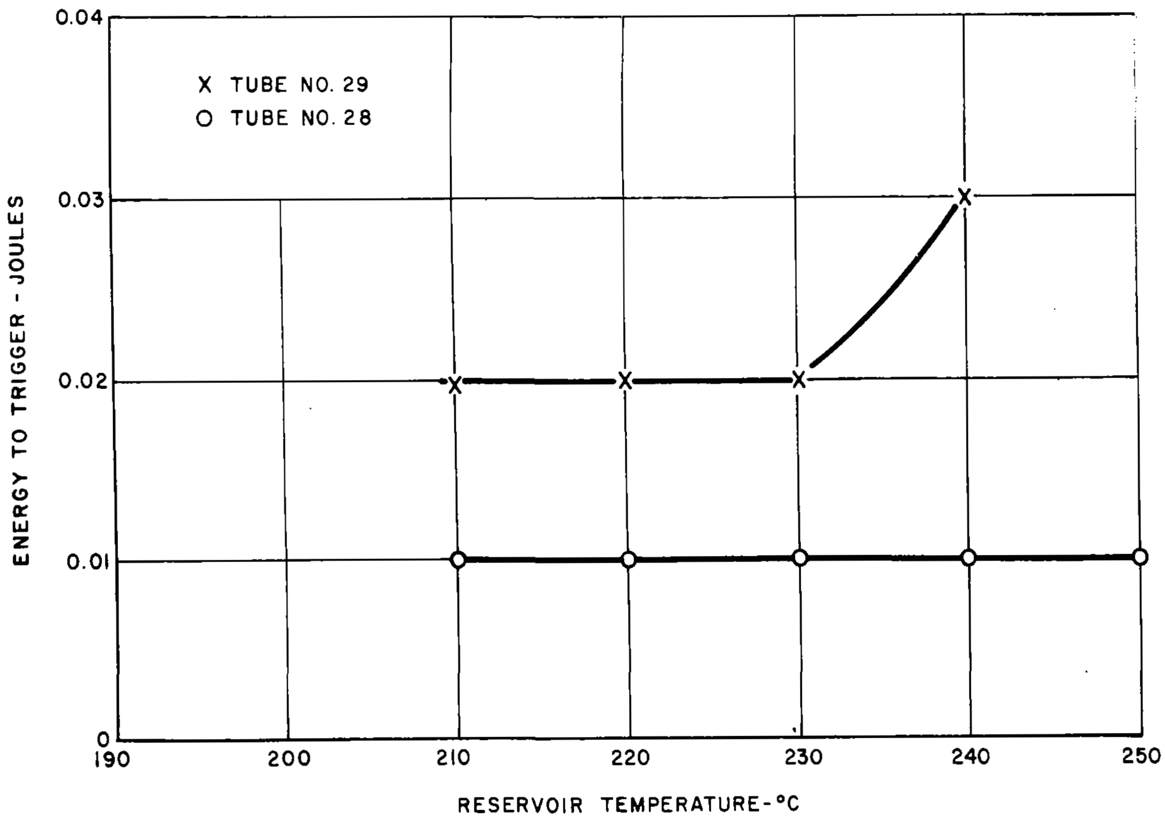

Figure 13 - Energy to Trigger Versus Cesium Temperature, Tube Nos. 28 and 29

average flowing through the grid to the anode, the grid heated more than in the case where it was connected to the anode and used as a collector for 15 amperes average. Obviously, a limit is approached in minimizing the size of openings in the grid, or in any other shields or electrodes positioned between the grid and cathode. Tube No. 29 definitely exceeded this limit by virtue of its 1/32 inch diameter grid holes. In this case, high trigger energy was required, and severe overheating attended the conduction of anode current.

TUBE Nos. 30 and 31

These tubes were duplicates of Tube No. 28 and were made for the purpose of having available several tubes with low recovery time characteristics for endurance testing.

Photographs of subassemblies of the "final" tube design appear in Figures 14, 15 and 16.

Additional measurements were made in an attempt to assess the effects of tightening the tube spacings and openings. In presenting the data which follow, it is recognized that in some cases more than one parameter at a time was changed in the construction of new tubes; nevertheless, the pattern of data points from the various tube designs permits fairly smooth curve plots.

Figure 17 summarizes the effect of slot width on recovery time as determined from the one-shot circuit shown in Figure 4. It clearly shows the strong relationship between recovery time and grid slot width.

To determine pulse-type trigger requirements, a simple LC firing circuit was evaluated. Using this circuit, the stored energy requirement versus slot width was developed, as shown in Figure 18. Reservoir temperature seemed to have no affect on the energy required to trigger (Figure 19). These tests were considered to be indicative only, since a manually operated one-shot circuit was used. To allow for variations from tube to tube, and a possible increase in requirements when a tube is operating in the steady state, any new trigger circuit planned for use with the tube should have a minimum storage capacity of 0.1 joule.

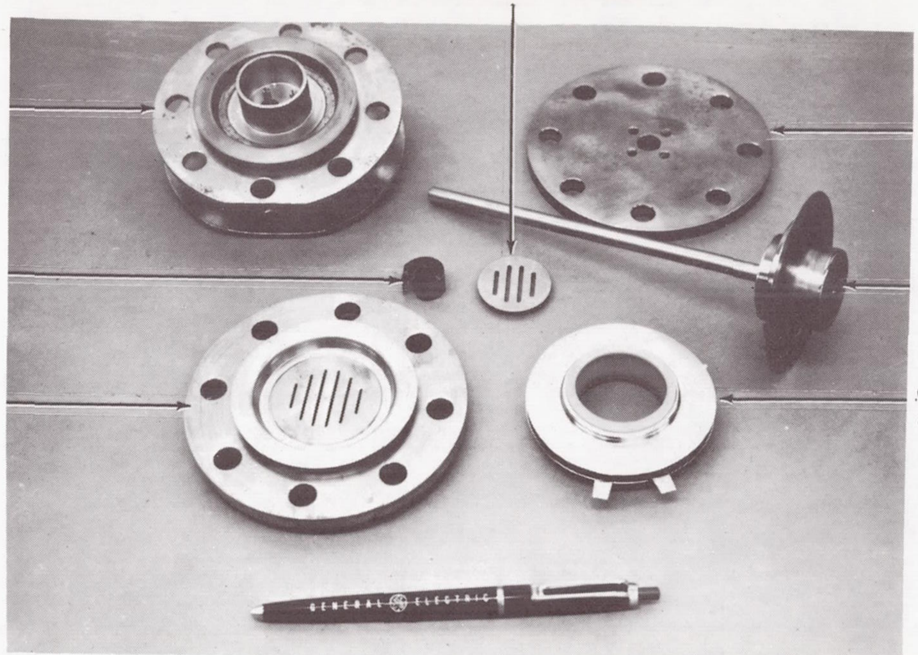

Figure 14 - Thyratron Subassemblies with Filament Exposed

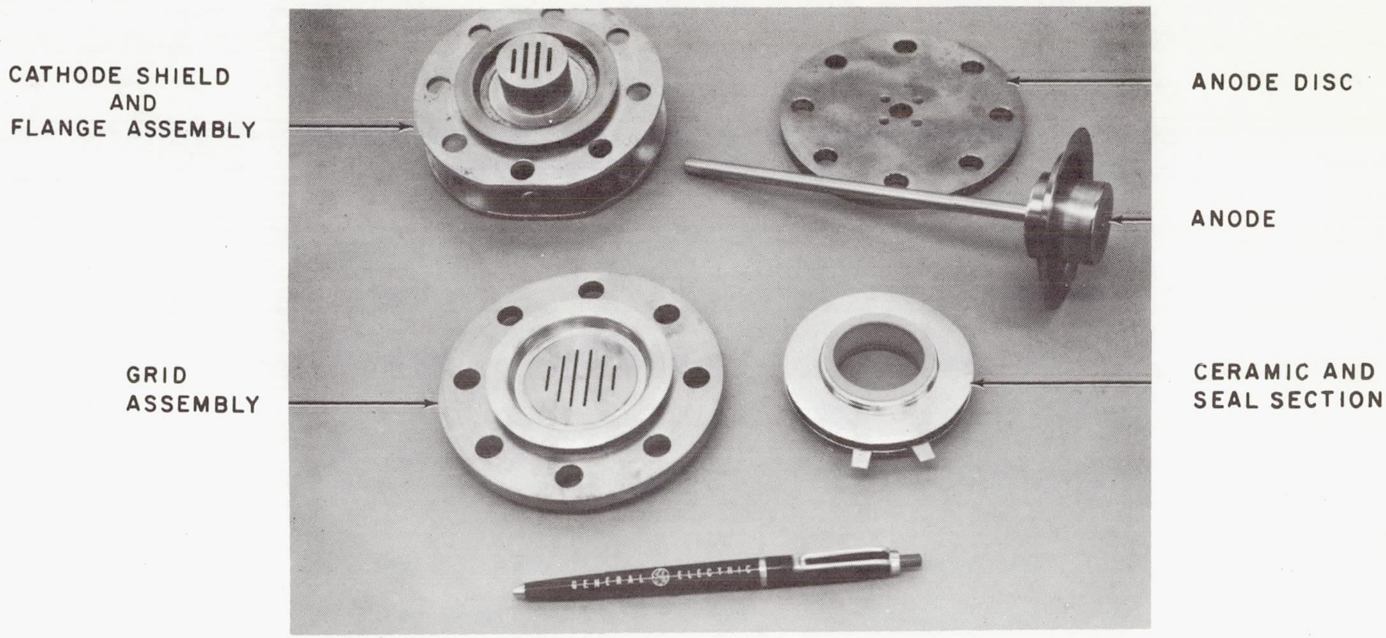

Figure 15 - Thyratron Subassemblies with Filament and Cathode Shield in Place

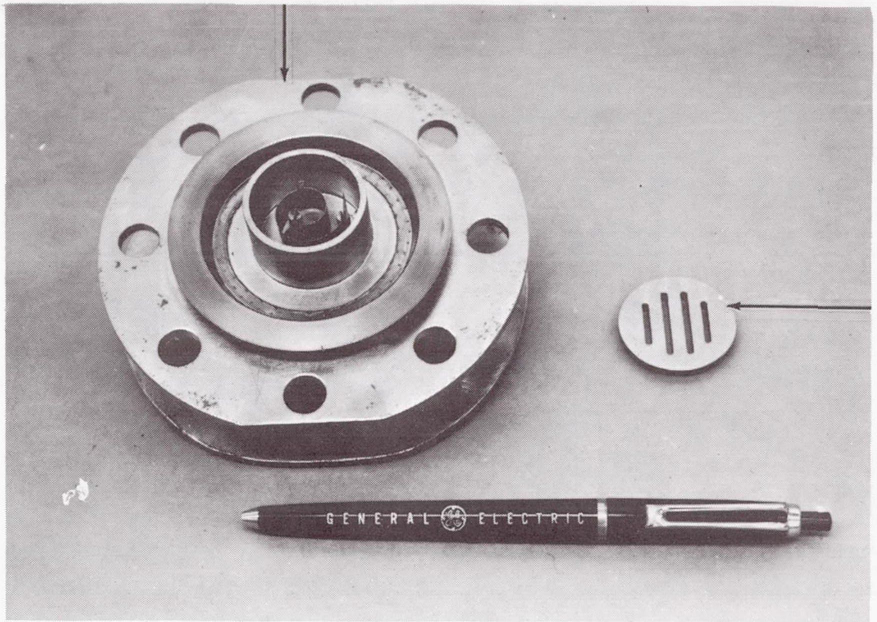

Figure 16 - Thyratron Cathode Section

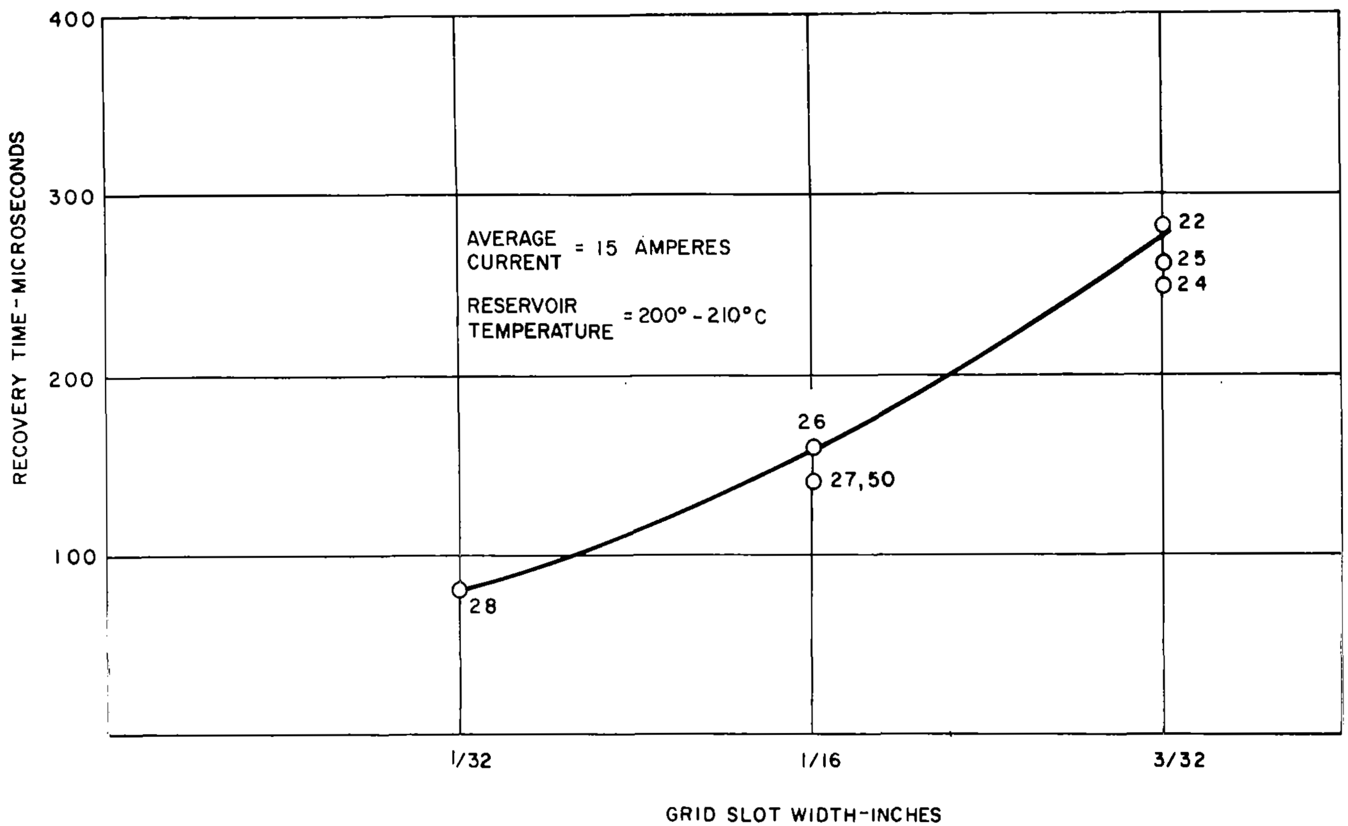

Figure 17 - Recovery Time Versus Grid Slot Width

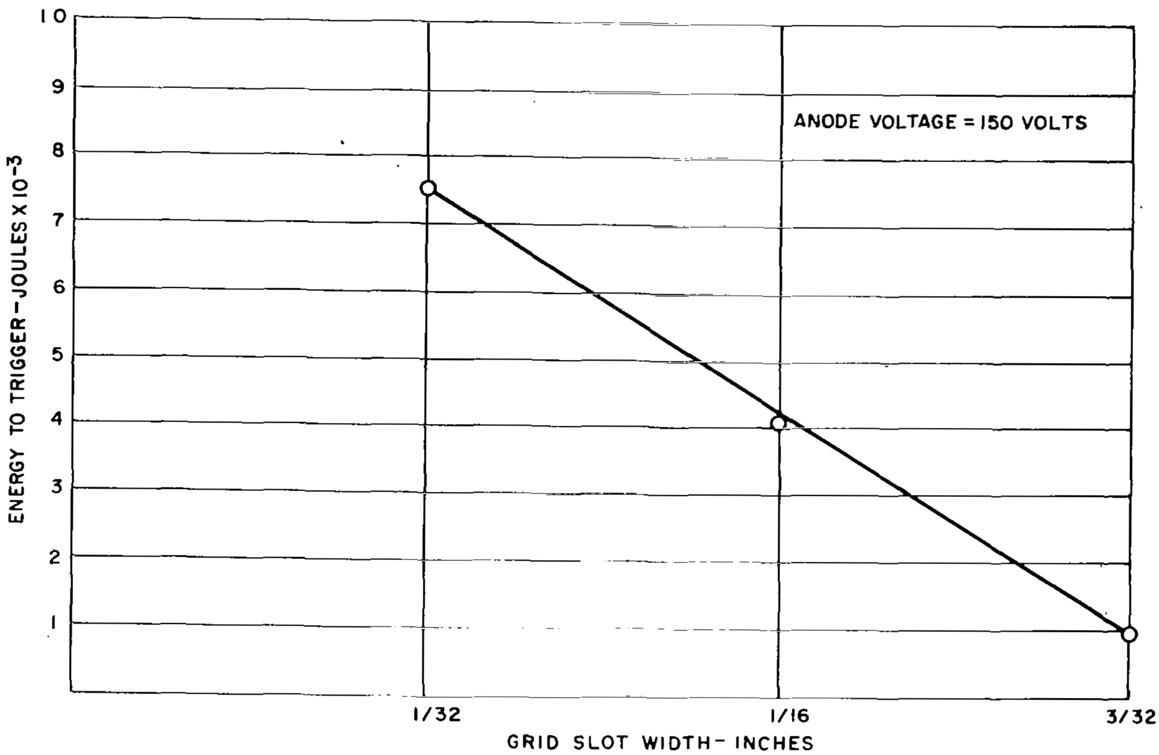

Figure 18 - Energy to Trigger Versus Grid Slot Width

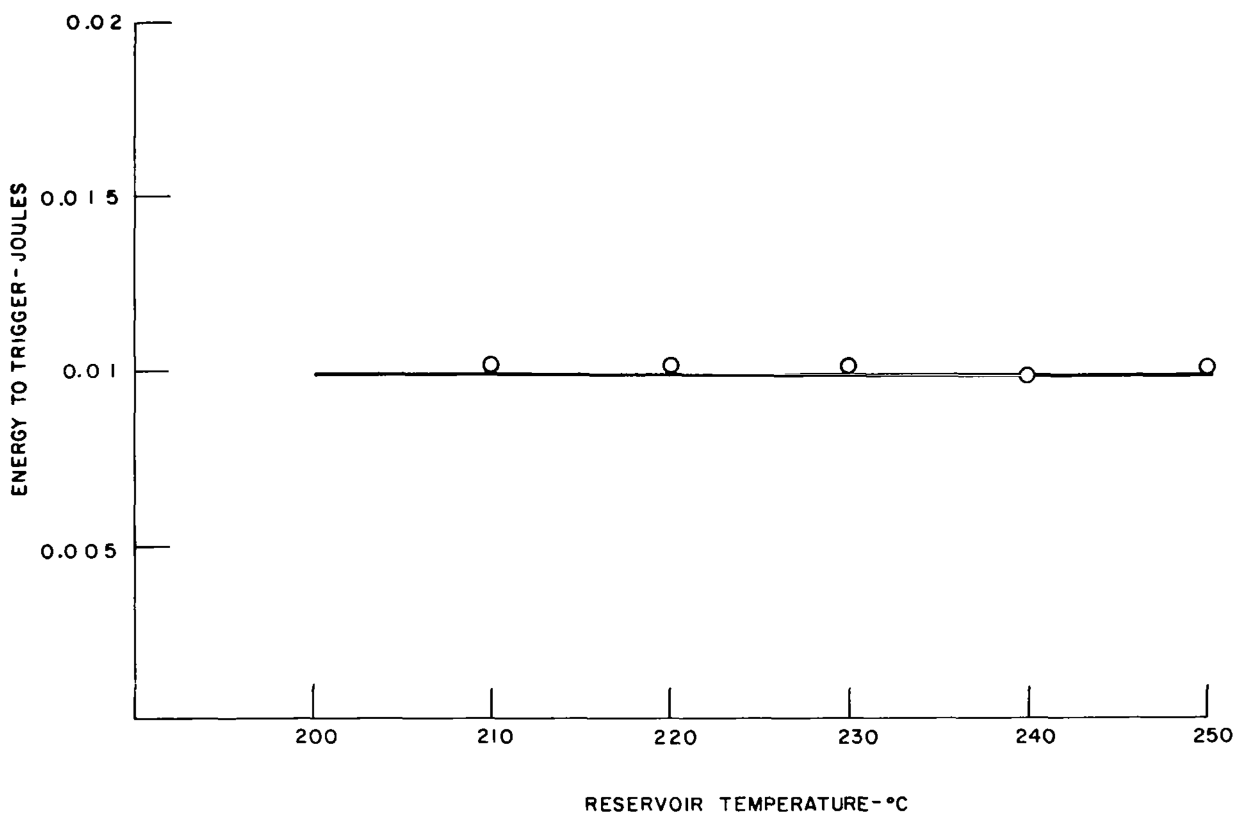

Figure 19 - Energy to Trigger Versus Reservoir Temperature, Tube No. 28

Tube drop versus slot width, which is given in Figure 20, indicates a 20-percent increase in tube voltage drop for the constricted tube at 100 amperes peak. The value of 100 amperes peak was chosen because tube voltage drop measurements had been made on many of the previous tubes at this value of current.

An abnormality not experienced with the earlier tubes was observed in operating the tight tubes; this will be referred to below as "flare-up". Intermittent tube drops of 20 volts were observed occasionally when:

(1) the tube was conducting high peak currents with a low average current,

(2) a DC load was applied after a quiescent no-load period, or

(3) a substantial increase in DC loading was suddenly applied to the tube.

Flare-ups were temporary and appeared to last for a few seconds only, as if this were the time needed to bring about a new thermal equilibrium at the filament. The condition of high tube drop was attended by an increase in the intensity of the glow showing through the cathode-end ceramic and a reduction in filament current. The phenomenon did not occur if the increase in DC loading through the tube was at a gradual rate, and it never was observed in the steady state.

As to the cause of the condition, we may speculate as follows. With six narrow slots at the grid and four slots in the shield atop the cathode, and with close spacing between grid and shield, there exist four relatively independent paths between the cathode and anode in which plasma can exist. There is no way to ensure an equal distribution of current through the parallel slots nor an even distribution of emission from the full area of the cathode. Rather, the current may commence through one channel and overload that channel before one or more additional channels ionize and share the load. The one-channel mode concentrates emission from a small portion of the cathode and can cause a cathode hot spot to develop.

The same phenomenon can occur in tubes that are not as constricted as those used in these tests, but to a much smaller extent since ion diffusion and communication from one channel to another is greater.

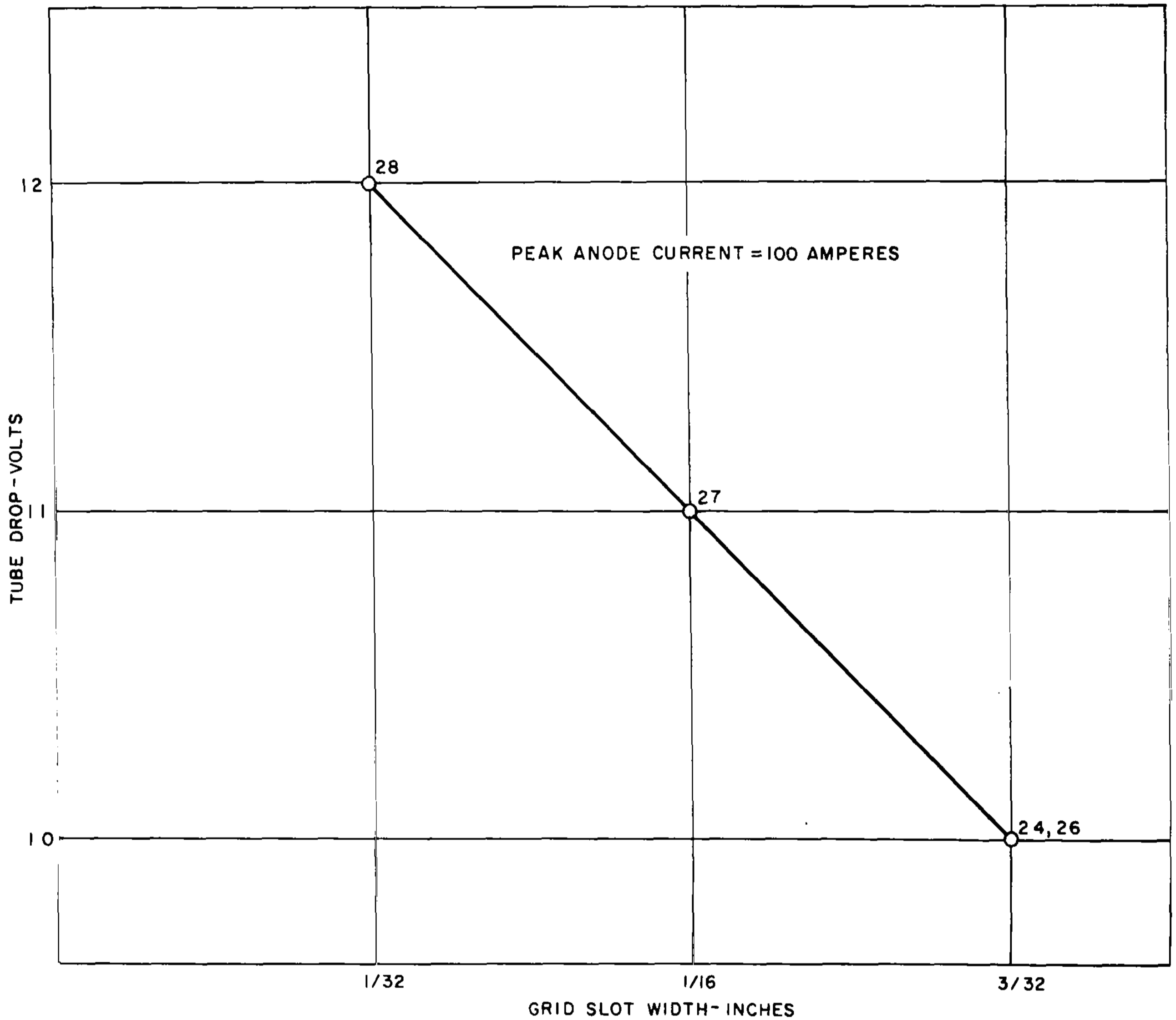

Figure 20 - Tube Drop Versus Grid Slot Width

The tube design has not been optimized with respect to the above phenomenon. An improvement program would include:

(1) substitution of an indirectly heater cathode for the filament,

(2) opening up the grid cathode region by:

a) elimination of the top shield over the cathode, or

b) increasing the width of the slots in the top shield.

DISCUSSION

The program described herein was successful with respect to achieving the goal of 100 microseconds recovery time. Several changes in tube characteristics were noted, reflecting the tightening of spacings. Of these, only one, the aforementioned flare-up, caused concern regarding the distribution of current through the tube and emission from the cathode. Since the flare-up was intermittent and of a temporary nature, it was felt that its consequences would have to be learned through endurance testing.

Because cesium was chosen as the working vapor, and because cesium pressure must be fairly high (approximately 0.1 torr) to permit the cesiated cathode to function, attempts at reducing recovery time were limited to the reduction of spacings -- electrode and slot width.

Another approach, however, would be to investigate some of the lighter alkali vapors, for if sufficient emission were available the recovery time would be much improved due to an increased ambipolar diffusion constant. We would expect recovery time to go as the inverse of the ion velocity. Since ion velocity varies as the inverse of the square root of its mass, the recovery time should vary as the square root of the mass of the ion. The significance of this approach is that low recovery time could be achieved in a more open tube with the lighter vapors, resulting possibly in a tube having lower losses, lower trigger requirements, and better internal current distribution.

Table II lists some of the properties of the members of the alkali family, and the last column in the table estimates comparative recovery times for the various elements. Although for a different purpose, a rubidium tube was

Table II - Characteristics of the Alkali Metals

Element	Minimum Temperature (°C) Required for Pressure of 0.1 Torr	Atomic Weight	Work Function	Ionization Potential	Recovery Time with Respect to Cesium
Cesium	200	132	1.8	3.9	1
Rubidium	225	85	2.2	4.2	0.8
Potassium	265	39	2.2	4.3	0.5
Sodium	350	23	2.3	5.1	0.4
Lithium	620	7	2.4	5.4	0.2

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constructed and operated earlier under Contract NAS3-6005. It performed very much like a cesium tube. How much further one could successfully proceed down the list of alkalis can only be determined by trial.

Although a firm specification had not been developed for the cesium tube before its evaluation, an objective specification was delineated for the low recovery time tubes. This is given in Appendix B.

The switching time and the power handling capability are described by the recovery time, and the anode voltage and current ratings. In the evolution of the cesium vapor thyratron, the spacings were tightened of necessity in order to meet the 100 microsecond recovery time limit needed to achieve high-frequency operation. Where operation is limited to low frequencies ($<$200 hertz), it would be advisable to supply the more open model (with 200 to 300 microsecond recovery time) because of the reduced triggering requirements and generally less critical operating characteristics.

CONCLUSIONS

1. By reducing the electrode spacings and the grid-slot width, the recovery time for the cesium vapor thyratron was reduced from between 300 and 400 microseconds to 100 microseconds.

2. Developmental thyratrons with low deionization times were found to have somewhat increased grid triggering requirements.

3. The anode-cathode potential during conduction increased from 10 volts to 12 volts (at 100 amperes peak) when the deionization time was reduced from 400 microseconds to 100 microseconds.

4. Cesium thyratrons can now be built to operate at a 100-microsecond deionization time, with 250 volts inverse and a current rating of 15 amperes average, 50 amperes peak.

Appendix A
SOLUTION OF THE DIFFUSION EQUATION

The diffusion equation is applied to the grid slot of a cesium thyratron whose width is ℓ and whose ion concentration at slot center ($x = \ell/2$) is N_o at $t = 0$.

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2}$$

Assume that the solution is a product[3] of two functions, one of which is a function of t alone and the other of x alone.

Then: $$n = T(t)\,X(x)$$

and: $$\frac{\partial n}{\partial t} = X \frac{\partial T}{\partial t}$$

$$\frac{\partial n}{\partial x} = T \frac{\partial X}{\partial x}$$

$$\frac{\partial^2 n}{\partial x^2} = T \frac{\partial^2 X}{\partial x^2}$$

$$X \frac{\partial T}{\partial t} = D\,T \frac{\partial^2 X}{\partial x^2}$$

$$\frac{1}{DT} \frac{\partial T}{\partial t} = \frac{1}{X} \frac{\partial^2 X}{\partial x^2} = -\alpha^2$$

where: α is a constant

Thus: $$\frac{1}{DT}\frac{dT}{dt} = -\alpha^2$$

$$\frac{dT}{T} = -D\alpha^2 \, dt$$

$$\log_e T = -D\alpha^2 t + C_1$$

$$T = C_2 e^{-D\alpha^2 t}$$

$$\frac{1}{X}\frac{d^2X}{dx^2} = -\alpha^2$$

$$\frac{d^2X}{dx^2} + \alpha^2 X = 0$$

$$(D_1^2 + \alpha^2) X = 0$$

D_1 in the above is the differential operator and should not be confused with D, the diffusion coefficient.

$$X = C_3 e^{jx} + C_4 e^{-jx} = \cos \alpha x \quad \text{or} \quad \sin \alpha x$$

Therefore:

$$n = F (e^{-D\alpha^2 t} \sin \alpha x)$$

$$\text{or} \quad F (e^{-D\alpha^2 t} \cos \alpha x)$$

Let: $$\alpha = \frac{k\pi}{\ell}$$

The boundary conditions are:

at $x = 0$, $t = 0$ $\qquad n = 0$

at $x = \frac{\ell}{2}$, $t = 0$ $\qquad n = N_o$

$$\therefore\ n = N_o \left(e^{-D\, k^2\pi^2/\ell^2\, t}\right)\left(\sin\frac{k\pi t}{\ell}\right)$$

$$n = N_o \sum_{k=1}^{\infty} \alpha_k\, e^{-D\, k^2\pi^2/\ell^2\, t} \sin\frac{k\pi x}{\ell}$$

$$= \frac{4N_o}{\pi}\left[e^{-D\,\pi^2/\ell^2\, t} \sin\frac{\pi x}{\ell} + \frac{1}{3}\, e^{-D\,\pi^2/\ell^2\, 9t} \sin\frac{3\pi x}{\ell}\right.$$

$$\left. + \frac{1}{5}\, e^{-D\,\pi^2/\ell^2\, 25t} \sin\frac{5\pi x}{\ell} + \ldots\right]$$

Appendix B
FINAL TUBE PARAMETERS

The cesium thyratron described in this report could be operated in inverter and rectifier circuits consistent with its objective recovery time of 100 microseconds. Final ratings, of course, depend on the life and operating condition under which the tube is used.

Except for the evaluation resulting from such life and operating experience, the tube parameters are properly described in the "Objective Technical Information" sheet attached herein.

OBJECTIVE TECHNICAL INFORMATION FOR LOW RECOVERY TIME CESIUM THYRATRONS

This tube is a cesium thyratron for application where the environmental temperature is in the range of 200 to 300 degrees centigrade. While electrode and reservoir temperatures must be maintained by appropriate heat sinking, long life can be expected since its cathode is not subject to evaporation of emission enhancing materials. An outline view of the tube is shown in Figure 21.

GENERAL

Electrical

Cathode - Directly Heated	
Filament Voltage	0.8 Volts AC or DC
Filament Current	60 Amperes
Deionization Time, Approximate	100 Microseconds
Ionization Time, Approximate	10 Microseconds
Anode Voltage Drop, Approximate	10 Volts
Grid Drive Requirements, Typical*	
10 Microseconds Duration 250 volts x 50 amperes	

Mechanical

Mounting Position - Any	
Net Weight, Approximate	5 Pounds
Overall Dimensions	
Height, Maximum.	6-7/8 Inches
Width, Maximum	4-1/32 Inches

Thermal

Type of Cooling, Conduction to Heat Sink**	
Environment, Vacuum Maximum Pressure . .	10^{-4} Torr

MAXIMUM RATINGS, Absolute Values

	Maximum
Peak Anode Voltage	
Inverse	250 Volts
Forward	250 Volts

		Maximum
Cathode Current		
Peak	. . . .	50 Amperes
Average	. . . .	15 Amperes
Negative Grid Voltage		
Before Conduction	. . . .	50 Volts
Commutation Limits Δ		
dv/dt in volts per microsecond	. . . . .	20
di/dt in amperes per microsecond	. . . .	10

The following boundary conditions prevail for temperature considerations:

1. Anode	. . . .	250 C Minimum
	. . . .	300 C Maximum
2. Grid	. . . .	250 C Minimum
	. . . .	300 C Maximum
3. Reservoir	. . . .	200 C Minimum
	. . . .	250 C Maximum

* Driver pulse measured at tube socket with thyratron grid disconnected: Amplitude = 200 volts minimum, 300 volts maximum, above 0; Grid pulse duration = 10 microseconds minimum, measured at 70% of the peak amplitude; impedance of drive circuit = 5 ohms, maximum.

** Connections to heat sink may be made with 1/4" - 20 steel bolts and nuts. When making connections torque must not be transmitted through the tube body.

Δ The commutation period is the period in which the current is transferring from one tube to another. The di/dt is a measure of the rate of decay of anode current through the tube prior to cessation of current. The dv/dt is a measure of the rate of rise of inverse voltage at the anode after current cessation.

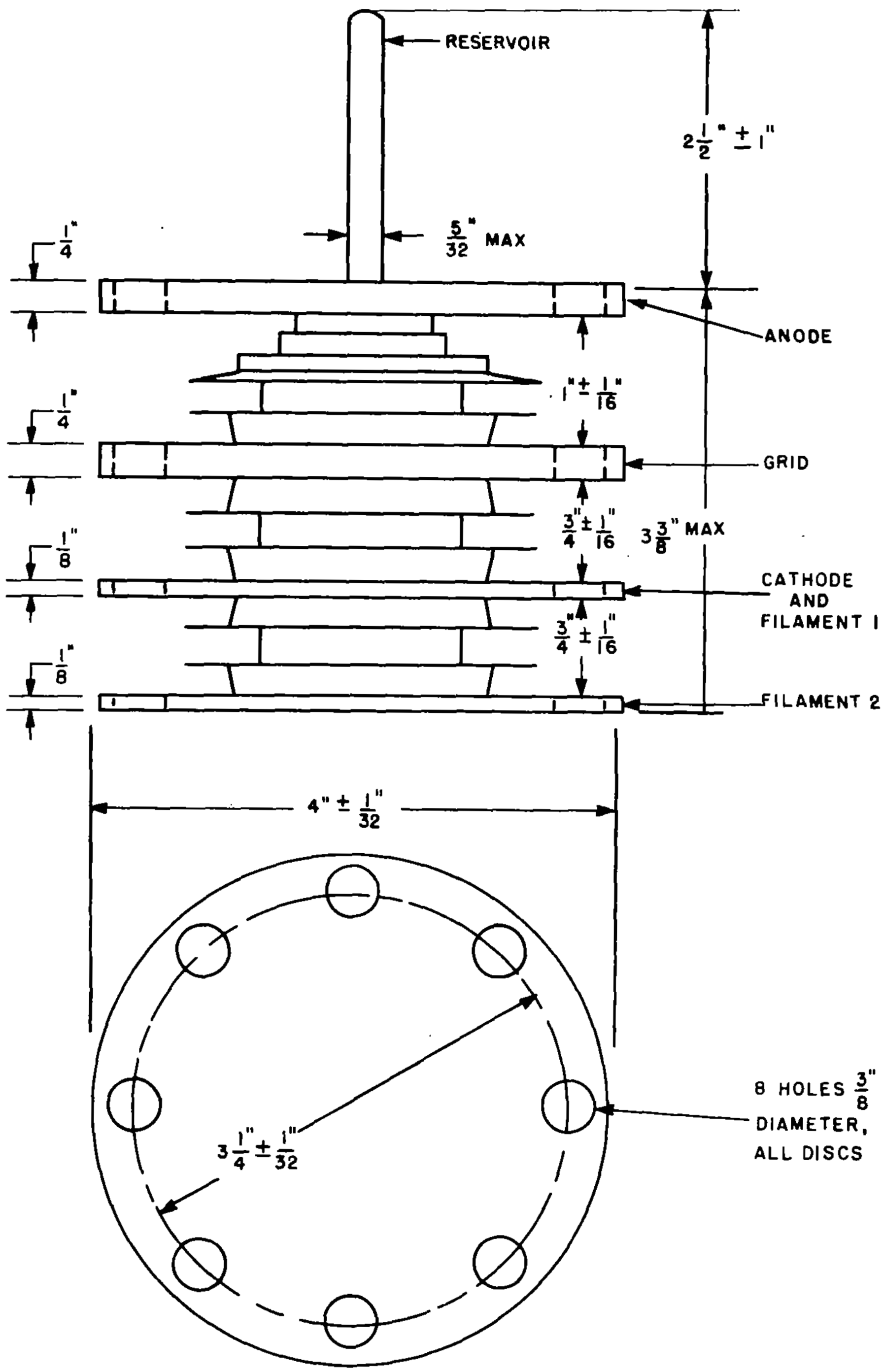

Figure 21 - Outline View of Cesium Thyratron

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