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# HYDROGEN THYRATRON PERFORMANCE IN THE SLAC TWO-MILE ACCELERATOR*

by

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## I. INTRODUCTION

The Stanford two-mile linear electron accelerator, located at Stanford University, is being constructed under a $114,000,000 contract with the U. S. Atomic Energy Commission. The machine is designed to produce an electron beam of 10 to 20 BeV at 15 to 30 microamps of average current.

Physically, the accelerator consists of two 2-mile-long buildings, one on top of the other, separated by 25 feet of earth shielding. The lower building houses the accelerator tube itself, and the upper building houses the klystrons, modulators, and related equipment.

The accelerator tube is supplied radio-frequency energy by 245 klystrons, each klystron producing from 6 to 24 megawatts peak power at a pulse repetition rate of 60 to 360 pulses per second. Each klystron is pulsed by its own line-type modulator, containing a hydrogen thyratron switch tube.

The Klystron Gallery, or upper building, is divided into 30 sectors. The variable voltage input to each of the 8 modulators comprising one sector is supplied by a common variable voltage substation, which in essence means that all modulators in a given sector (330 feet) are operating at the same voltage.

The principal specifications for the modulator are shown in Table I. A simplified diagram of the modulator is shown in Fig. 1.

## II. MODULATOR DESIGN CONSIDERATIONS

The principal modulator design considerations affecting switch tube stability are the end-of-line clipper, the line-to-load impedance match, and the de-Q'ing system.

### A. End-of-Line Clipper

In order to protect the modulator components and switch tubes from over voltage during load faults, it is necessary to remove the inverse voltage from the pulse-forming network. In addition, the clipper circuit must present a high impedance to

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the normal inverse voltage in order to obtain adequate recovery time for the switch tube and at the same time must remove the high inverse voltage fast enough during load faults to prevent the switch tube from arcing back. These functions are accomplished in the SLAC modulator by an end-of-line clipper consisting of a thyrite assembly in series with resistors and 150 semiconductor diodes.

B. Line-to-Load Match

In general, it is necessary to apply inverse voltage to the switch tube anode during the inter-pulse period to facilitate switch tube recovery. The required amount of inverse voltage and recovery time depends on the rate of rise of the pulse-forming network voltage. In the case of the SLAC modulators, with a 2.2-millisecond charge time, a minimum of 200 microseconds of recovery with approximately 2 kV of inverse voltage is required to obtain long-term, high-voltage stability or mean time between faults.

In order to obtain the required inverse voltage, one may take either of two approaches: Use a "negative" match (pulse-forming network impedance higher than load impedance), or a "positive" match where the pulse-forming network has a lower impedance than the load. In the first case, the pulse-forming network voltage reverses immediately after the pulse due to the negative reflection on the network. In the second case, the energy stored in the pulse transformer is transferred to the pulse-forming network in a 1/4 LC time constant, where L is the shunt inductance of the pulse transformer and C the total network capacitance.

The advantages of the positive match are the reduction in anode spike dissipation, peak inverse anode voltage, and an increase in high-voltage stability. In some tube types, a 10:1 reduction in the number of switch tube faults for a given period has been observed. Figure 2 shows the equivalent post-pulse recovery circuit for the SLAC modulator. Figure 3 shows a typical anode post-pulse recovery condition. The horizontal scale is 50 microseconds per centimeter and the vertical scale is 2 kV per centimeter. The peak charging voltage, in this case, is 43 kilovolts.

C. De-Q'ing System

The function of the de-Q'ing circuit is to regulate the pulse-forming network voltage for a line or load variation. The L/R time constant of the de-Q'ing circuit is such that, at high repetition rates, there is a little energy left in the de-Q'ing circuit at the start of the next charging period, which results in energy being delivered to the pulse-forming network during the switch tube recovery period and which reduces the available recovery time for the hydrogen thyratron. The amount of energy transferred to the pulse-forming network from the transactor, or de-Q'ing circuit, during this inter-pulse period, depends upon the pulse-repetition rate and the percentage of de-Q'ing. In general, the recovery time in the SLAC modulator is reduced approximately 70 microseconds for a 360-pps pulse rate and 3% de-Q'ing.

## III. SWITCH TUBE PERFORMANCE

The decision was made in the early part of 1963, after considering many types of switching devices, to use hydrogen or deuterium thyratrons for the switch tubes. Table II shows the primary specifications for the SLAC hydrogen thyratrons. In early 1963, there were no single hydrogen thyratrons which would meet all the SLAC specifications, so the modulators were constructed to permit the use of any known hydrogen thyratrons at that time, including two of the smaller tubes in a split-line setup. Table III shows the primary specifications for the drive circuit. Figure 4 is a schematic diagram of the SLAC drive circuit.

The delay time stability through the SLAC modulators is an important parameter because we want to be able to utilize as much of the flat-top portion of the modulator pulse as possible for acceleration of the electrons (the sloping skirts of the beam pulse are unusable). One could compensate for anode delay time variations, but it becomes expensive and complicated.

The instantaneous start requirement is necessary because all eight modulators in a given sector are operating at the same power level. Should an external fault occur, the modulator is automatically turned off and then turned back on at the sector operating level, which might well be at 43 kV charging.

The long mean-time between faults is required because there are 250 modulators in the line; even at four faults per 100 hours, the mean-time to fault for all the accelerator switch tubes would be six minutes.

The most stringent requirements imposed upon the SLAC hydrogen thyratrons centered around the anode delay-time variation, coupled with the required instantaneous start, or snap-on ability, at full voltage, as well as the mean-time between faults requirement.

In general, the tighter the grid baffling the larger the anode delay-time variation for a given tube. However, tight-grid baffling is required, particularly in triode thyratrons, for maximum hold-off voltage. For this reason, triode switches were eliminated in favor of tetrode, or gradient grid tubes. Figure 5 is a typical plot of anode delay-time variation for a triode hydrogen thyratron (in this case, the 7390) vs. repetition rate for a given anode voltage. This plot is typical for most triodes that have been tested. Figure 6 shows the typical anode delay-time variation for a KU275A tube in the standard trigger mode. It should be noted that these variations are much greater than allowed in our specifications.

In order to meet the anode delay-time specifications and the snap-on requirements, it was necessary to incorporate a pre-trigger or additional electrode between the control grid and the cathode to establish ionization in the cathode region prior to commutation. The manufacturers incorporated this electrode in order to meet specifications.

Two different modes of utilizing the pre-trigger electrode have been investigated. The first technique suggested by the manufacturers is to connect the pre-trigger electrode through a 250-ohm resistor to the input side of the de-spiking network. The pre-trigger electrode, which is in relatively close proximity to the cathode, will draw current when pulsed positively and establish ionization at a relatively low voltage. The de-spiking network yields approximately 100 nanoseconds delay, so that we draw on the order of 100 to 200 milliamperes of pre-trigger current prior to control grid load-over or breakdown. This technique has reduced the anode delay-time variation from 240 nanoseconds to 140 nanoseconds or less.

The second mode of operation utilizes a constant dc current to the pre-trigger electrode to establish a minimum plasma density in the cathode area during the inter-pulse period. We are able to achieve anode delay-time variation of less than 20 nanoseconds over the SLAC power range. In addition, the dc keep-alive mode of operation has increased the cathode life of the thyratron by about a factor of three. To date, we have not run a SLAC tube to cathode depletion in the keep-alive mode. Two tubes on life test using this mode of operation failed at 7000 hours and 7700 hours, respectively. The first had an open heater and the second developed a pre-trigger electrode short. In both cases, approximately 30% of the cathode material was left when the tubes were opened. This gives us some reason to believe that it is possible to achieve 10,000 hours of operation per tube. Figure 7 is a schematic diagram of the keep-alive power supply.

To date there are eight life-test tubes near the 4000-hour point at full SLAC power. However, it will be another couple of years before we have enough life data to come to any definite conclusions on life. These same tubes have been tested using the normal trigger mode without pre-trigger operation, and the average life was approximately 2000 hours to cathode depletion.

The reason for the extended life is not thoroughly understood. We feel that the cathode is better utilized because during the interpulse period the keep-alive plasma tends to be spread evenly over the cathode and contains a ready supply of ions.

We have not noticed any degeneration in hold-off ability in the keep-alive mode of operation. High-potting of tubes has shown no difference in hold-off voltage with or without keep-alive current. Of course, if keep-alive current were increased to several amperes, the tube would fire through. In pulse operation (in the large single SLAC tubes) the deionization time constant in the gun or cathode region is of the order of 10 milliseconds, so that at repetition rates above 50 or 60 cycles there is substantial residual ionization in the gun region anyway. We have found that the variation in residual ionization plays an important part in anode delay-time variation.

Figure 8 shows a plot of anode delay time vs. auxiliary electrode current for the large SLAC tubes. This plot looks approximately the same for both the Tung-Sol CH1191 and the I.T.T. KU275A. We are using from 320 to 350 milliamperes of keep-alive current. The 320-mA keep-alive current was adequate for time stabilization even after 7700 hours in a life-test tube.

Figure 9 shows a plot of anode delay time vs. pulse repetition rate for the three different modes of triggering at minimum SLAC power.

Figure 10 shows a plot of anode delay time vs. pulse repetition rate for the three trigger modes at full SLAC power.

## Ranging

A time-consuming maintenance problem encountered in running 250 hydrogen thyratrons is the periodic ranging that is required. The SLAC thyratrons have a typical reservoir range of approximately 0.8 volt or $\pm$ 0.4 volt from center range. It is necessary to check the center point at approximately 500-hour intervals to insure optimum life, because the reservoir center point shifts. This shift cannot be predicted and, in some instances, there has been no significant reservoir shift at all. However, until more life test experience has been gained, the reservoir center point will be checked at 500 hour-intervals. Figure 11 shows a plot of reservoir voltage center range vs. life for three different tubes at full SLAC power.

Three methods of ranging the hydrogen thyratrons have been investigated. The first method, which has been used most extensively to date, is the traditional hot-ranging technique whereby the reservoir voltage is lowered in 0.1-volt intervals until the grid hash, or commutation spikes, is observed, which is the low-pressure limit. The reservoir is then raised in 0.1-volt intervals until the thyratron faults, which is the high-pressure limit. Halfway between the two extremes is the reservoir center point or center range. The disadvantage of this method is that it is time-consuming. It takes approximately 15 minutes per tube or over 60 man-hours to range the tubes in the accelerator.

A second method under investigation utilizes the thyratron plasma oscillations occurring within the tube during the first microsecond of the conduction period. There are numerous frequencies generated within the tube which change in amplitude with tube pressure and which are independent of the external circuit. The band between 50 kilocycles and 150 megacycles has been investigated. Figure 12 shows a plot of the variation of rf amplitude vs. reservoir voltage at 10 megacycles, 24 megacycles, and 77 megacycles.

The most useful oscillation frequency occurs around 24 megacycles. At this frequency the rf amplitude peaks at the center range and drops off about 4 dB at the range limits for any given SLAC power level or voltage level. To date, we have repeated this test on some 25 to 30 different tubes and found the results to be essentially the same. The accuracy of the method is $\pm$ 0.1 volts, as compared with the hot-ranging technique. Both the Tung-Sol CH1191 and the I.T.T. 275A tubes behave in the same manner. Figure 13 is a plot of rf pickup at 24 megacycles vs. reservoir voltage for a typical SLAC single tube. We have observed that for the small trigger thyratrons the rf peaks at 24 Mc do not coincide with center range. Perhaps at another frequency they would coincide.

The third possible method of ranging is to incorporate a Pirani gauge in the tube, which would allow us to measure tube pressure directly. Pirani gauge tubes have been ordered from both I.T.T. and Tung-Sol and are expected by mid-year.

## IV. SUMMARY

To date, we have received over 350 single thyratrons. The gradient grid tubes are yielding mean-time between faults of better than 100 hours with a klystron load. The life of the SLAC thyratrons has been increased to 7000 hours at full SLAC power level through the use of dc keep-alive. The anode delay-time variation has been reduced to less than 20 nanoseconds over the power range through the use of dc keep-alive. Monitoring hydrogen thyratron plasma oscillations at 24 megacycles is proving to be a time-saving and accurate method of ranging switch tubes in the accelerator.

## ACKNOWLEDGEMENTS

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TABLE I

PRINCIPAL SLAC MODULATOR SPECIFICATIONS

| | |
|---|---|
| Peak Power Output (max.) | 64 MW |
| Average Power (max.) | 75 kW |
| Output Pulse Voltage Range | 158 - 255 kV |
| Output Pulse Current Range | 120 - 258 amps |
| Load Impedance Range | 1320 - 962 ohms |
| Rise and Fall Time 0 - 99% | 0.7 $\mu$sec |
| Pulse Repetition Rates | 60, 120, 180, 360 pps |
| Pulse Height Deviation from Flatness (max.) | $\pm$ 0.5% |
| Pulse-to-Pulse Time Jitter | $\pm$ 10 nsec |
| Pulse-to-Pulse Amplitude Jitter | $\pm$ 0.25% |

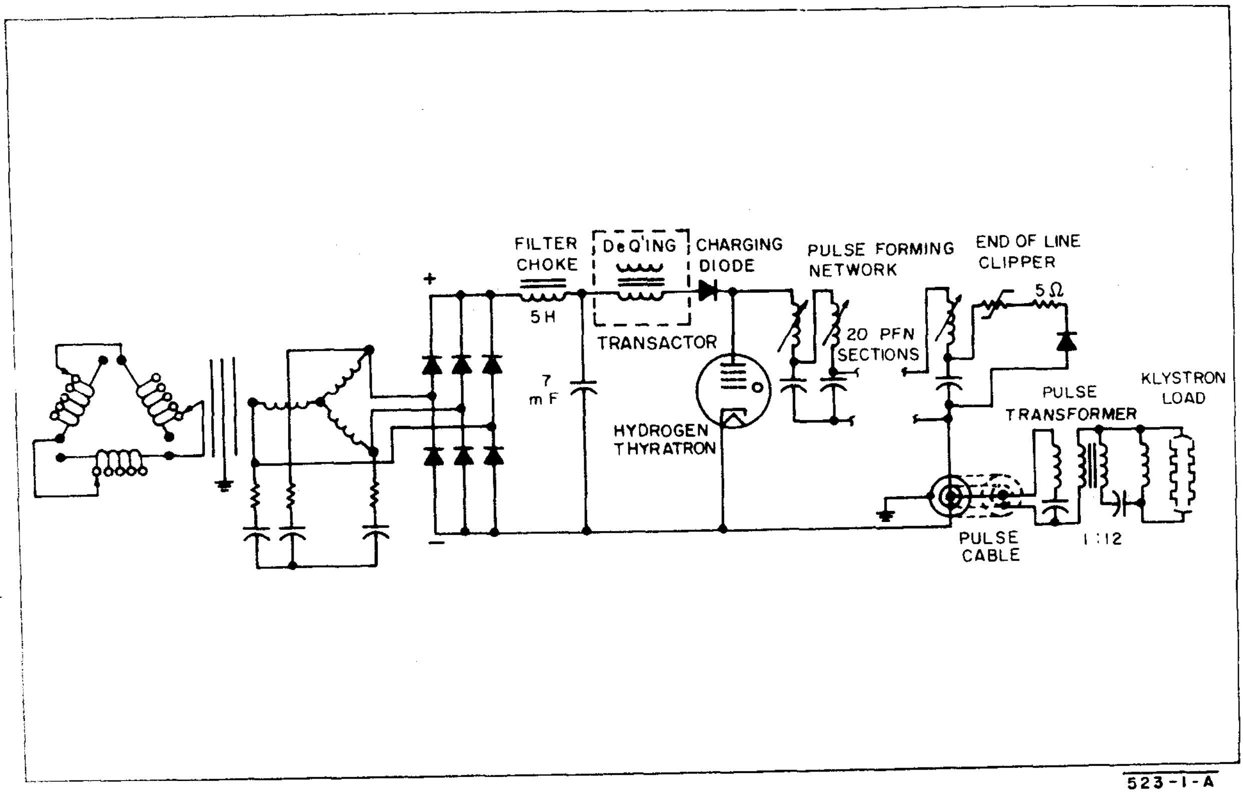


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FIGURE 1 - SLAC MODULATOR SIMPLIFIED SCHEMATIC

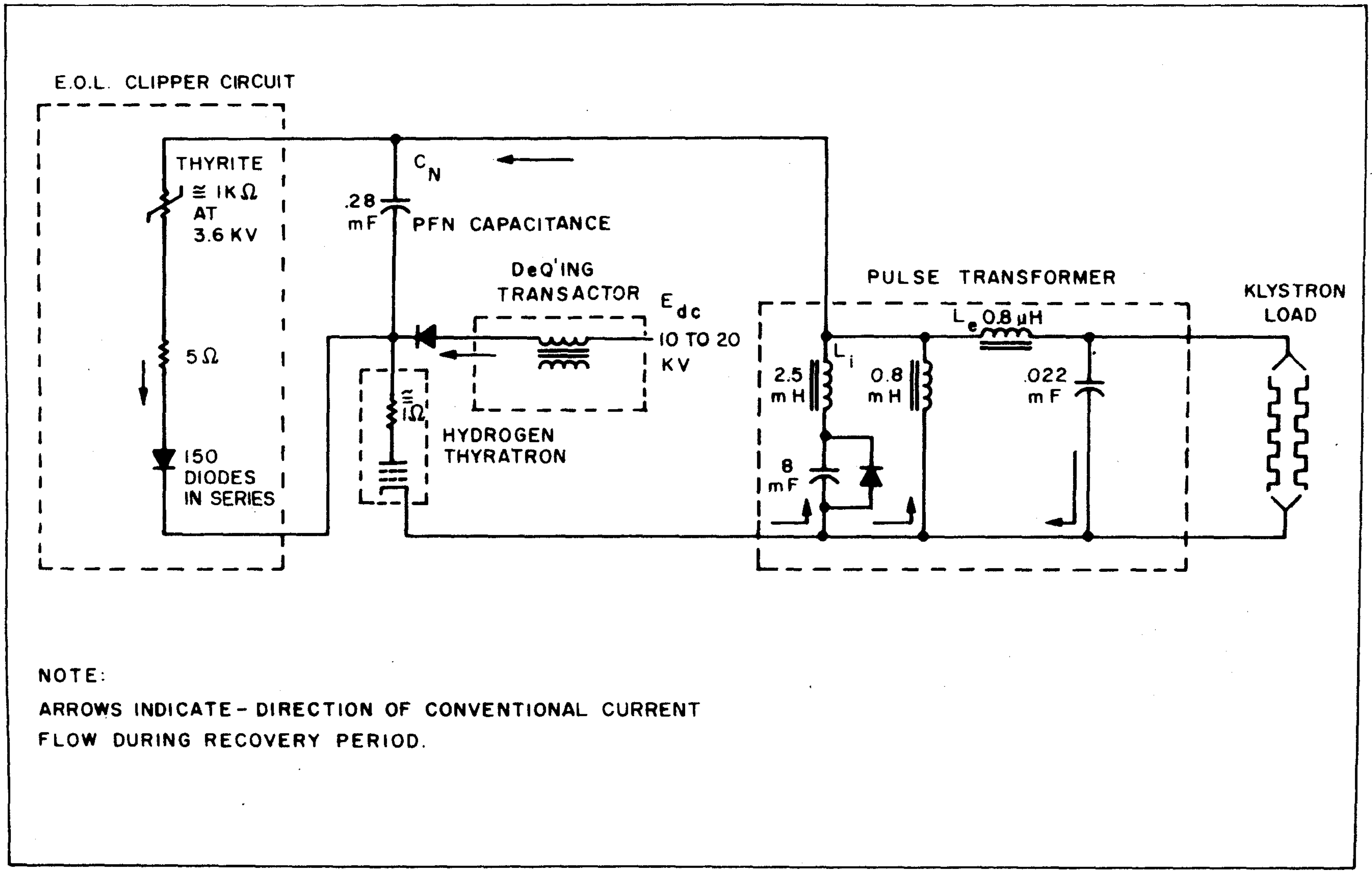

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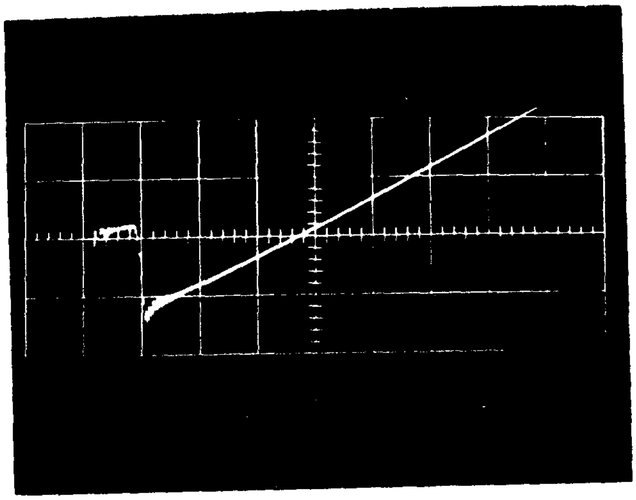
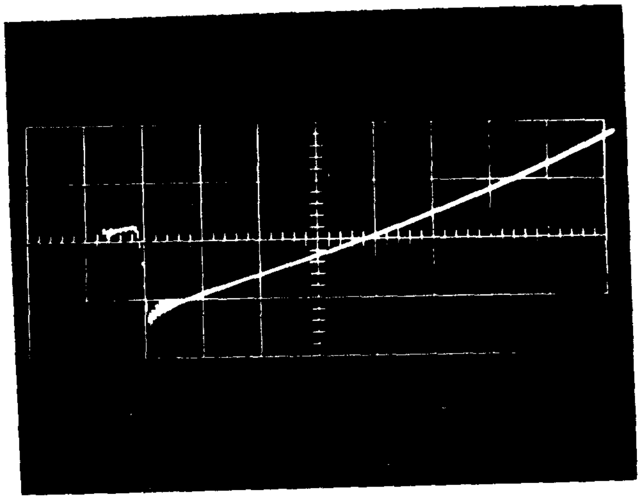
FIGURE 2 SLAC MODULATOR EQUIVALENT RECOVERY CIRCUIT



RECOVERY TIME - 20 AMPS OF DE-Q'ING

SCOPE CALIBRATION - 2 KV/cm;
50 μ sec/cm



RECOVERY TIME - NO DE-Q'ING

SCOPE CALIBRATION - 2 KV/cm;
50μ sec/cm

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FIGURE 3 - TYPICAL POST-PULSE CONDITIONS FOR SLAC MODULATORS

## TABLE II

## SLAC SWITCH TUBE SPECIFICATIONS

| | |
|---|---|
| Peak Charge in Voltage | 46 kV (maximum |
| Peak Inverse Voltage | 5 kV (maximum) |
| Peak Anode Current | 4000 amps (maximum) |
| Average Anode Current | 5 amps (maximum |
| RMS Anode Current | 140 amps (maximum) |
| Pulse Duration | 4 $\mu$sec (maximum) |
| Anode Delay Time | 400 nsec (maximum) |
| Anode Delay Time Drift | 40 nsec (maximum) |
| Anode Delay Time Variation | 150 nsec (maximum) |
| Anode Delay Time Jitter | 10 nsec (maximum) |
| Anode Voltage Drop During Pulse | 400 volts (maximum) |
| Anode Dissipation Factor | $70 \times 10^9$ |
| Pulse Repetition Rate | 60 to 360 pps |
| Number of Kickouts | 4 maximum in 96 hours |
| Instantaneous Start | 43 kV (minimum) |

## TABLE III

## PRINCIPAL SLAC HYDROGEN THYRATRON DRIVER SPECIFICATIONS

| | |
|---|---|
| Output Voltage into 25-Ohm Load | 2 kV (minimum) |
| Open Circuit Voltage | 4 kV (minimum) |
| Short Circuit Current | 160 amps (minimum) |
| Drive Source Impedance | 25 ohms (nominal) |
| Rate of Rise of Drive Voltage | 13,000 volts per microsecond (nominal) |
| Pulse Width at 70% Amplitude | 3.2 microseconds (nominal) |

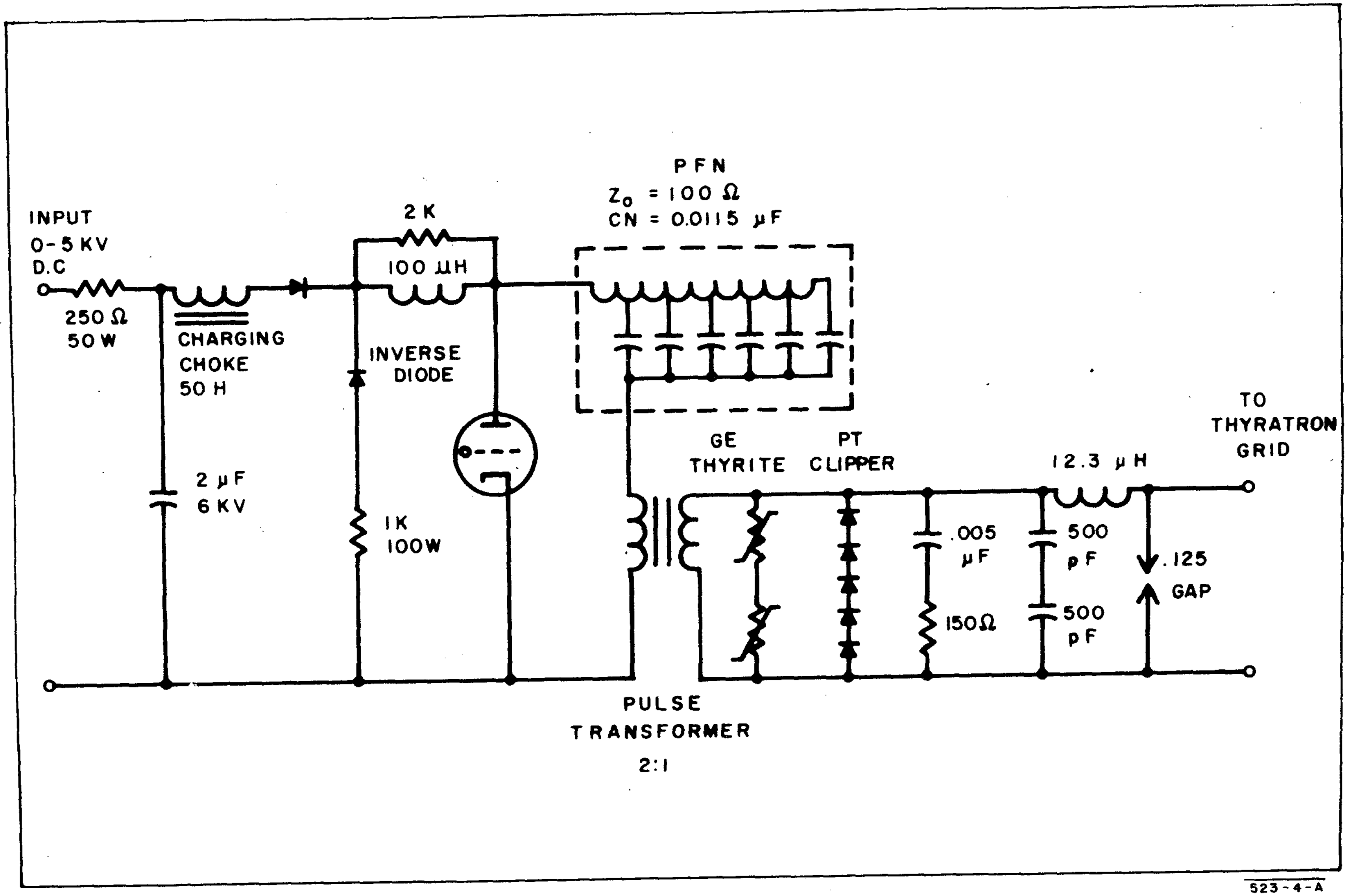



FIGURE 4 SCHEMATIC DIAGRAM OF SLAC THYRATRON DRIVER

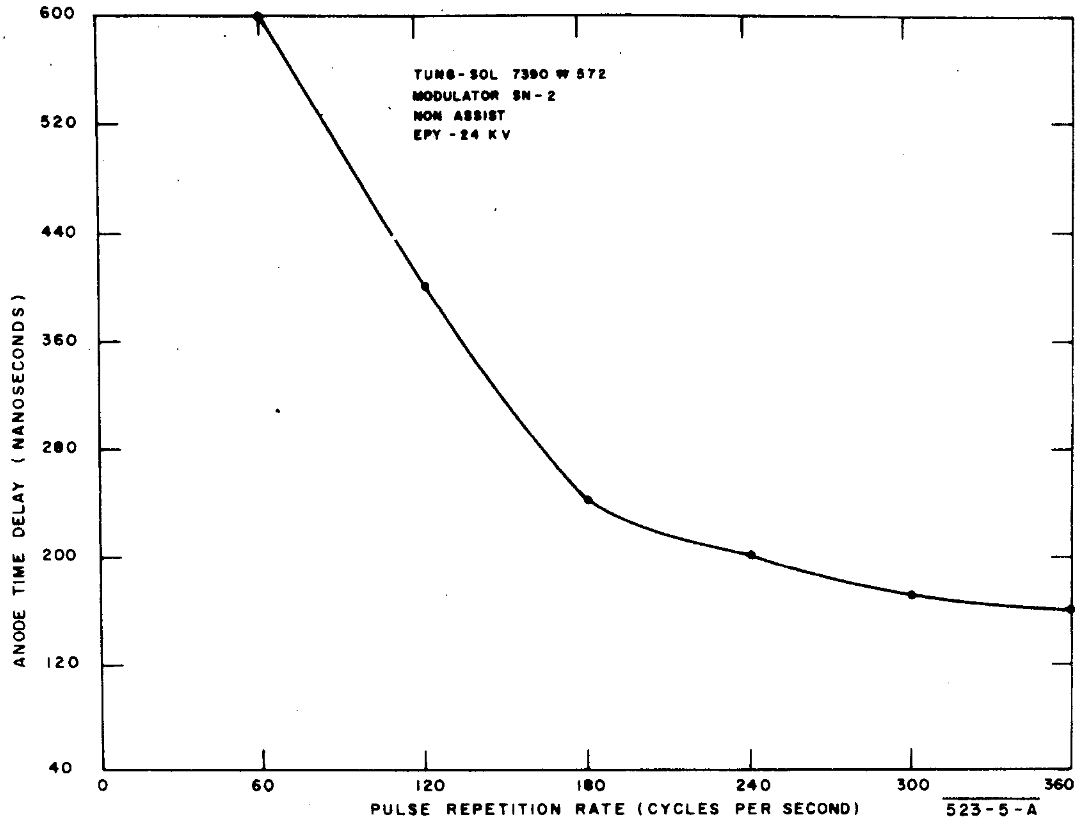



FIGURE 5 ANODE DELAY TIME VARIATION FOR TRIODE HYDROGEN THYRATRON

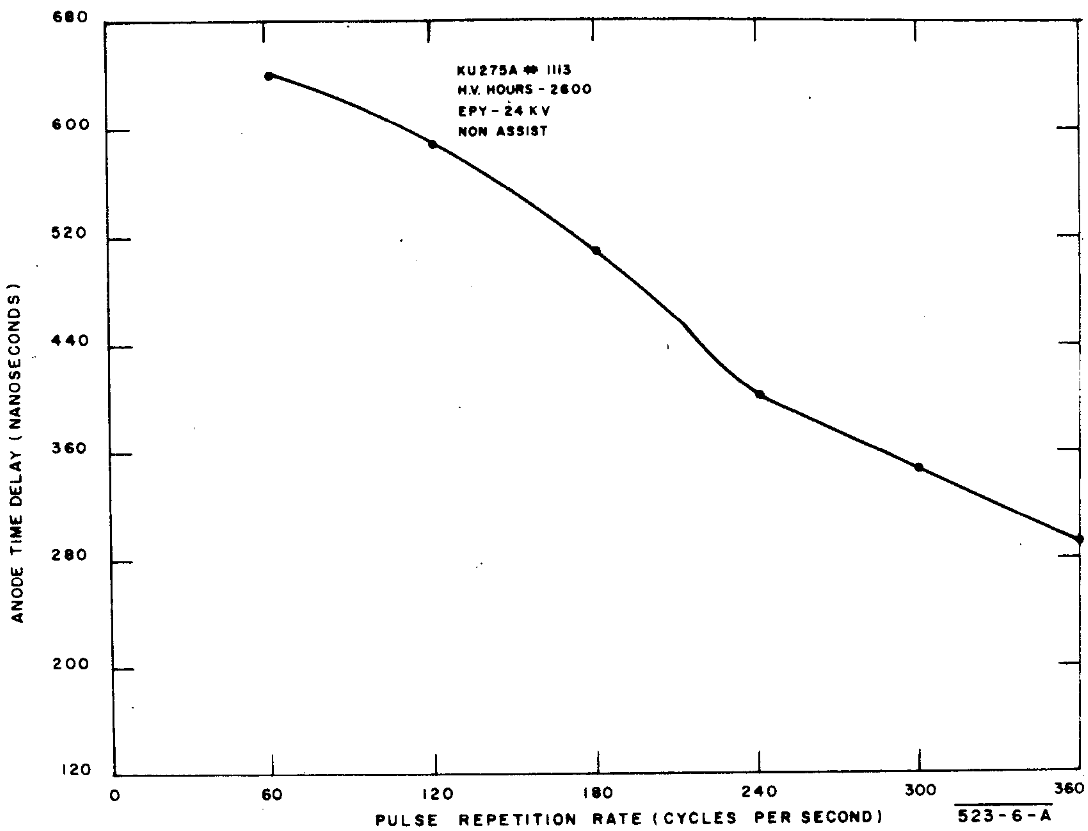
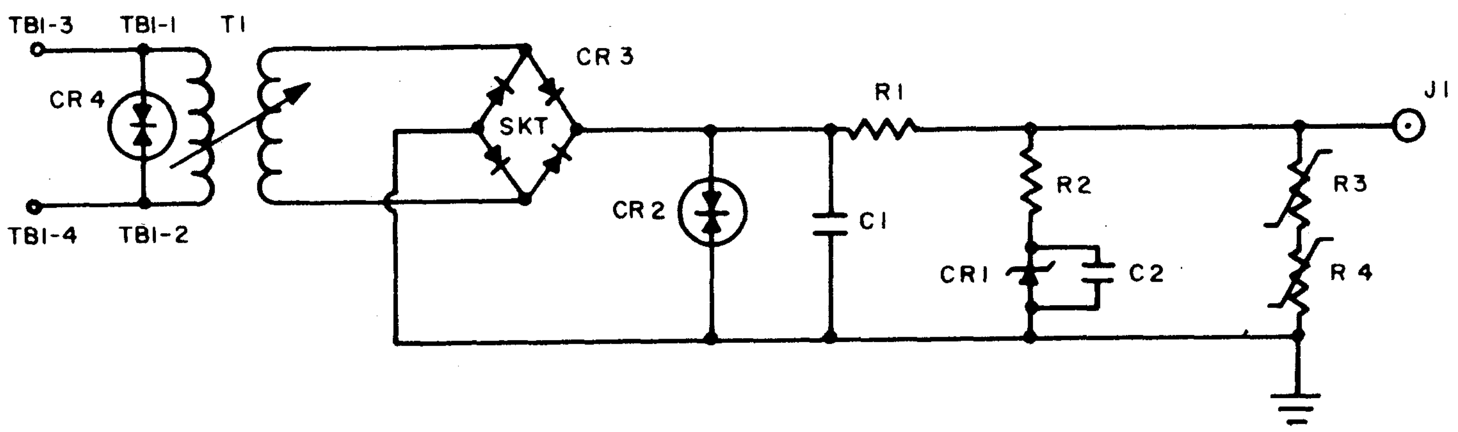



FIGURE 6 TYPICAL ANODE DELAY TIME VARIATION FOR A KU275A GRID TUBE IN STANDARD TRIGGER MODE




PARTS LIST

CR1- ZENER-MOTOROLA-IN3340B, 50M100S25
CR2- THYRECTOR-G.E.-6RS21SA17D17D
CR3- RECTIFIER UNIT-SOLITRON-SPF-10B
CR4- THYRECTOR-G.E. 6RS21SA5D5
R1 - 100Ω-50W-WARD LEONARD-50F100WL
R2 - 100Ω-100W-WARD LEONARD-1000F100WL
R3, R4 } THYRITE - G.E. 68W30100
C1 - 135-155 μF -330VAC-AEROVOX-TYPE MSRP847
C2 - .01 μF - 1 KV-CENTRAL LAB-TYPE 1032-(11L106)
T1 - EDCO PLATE TRANSFORMER-5028
TB1 - TERMINAL STRIP GEN PRO 141-4
J1 - CERAMIC STAND OFF CRL-NS5W1216
SKT- FLOATING OCTAL SOCKET-AMPHENOL-TYPE 77-MIP8FK

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FIGURE 7 SCHEMATIC OF KEEP-ALIVE POWER SUPPLY

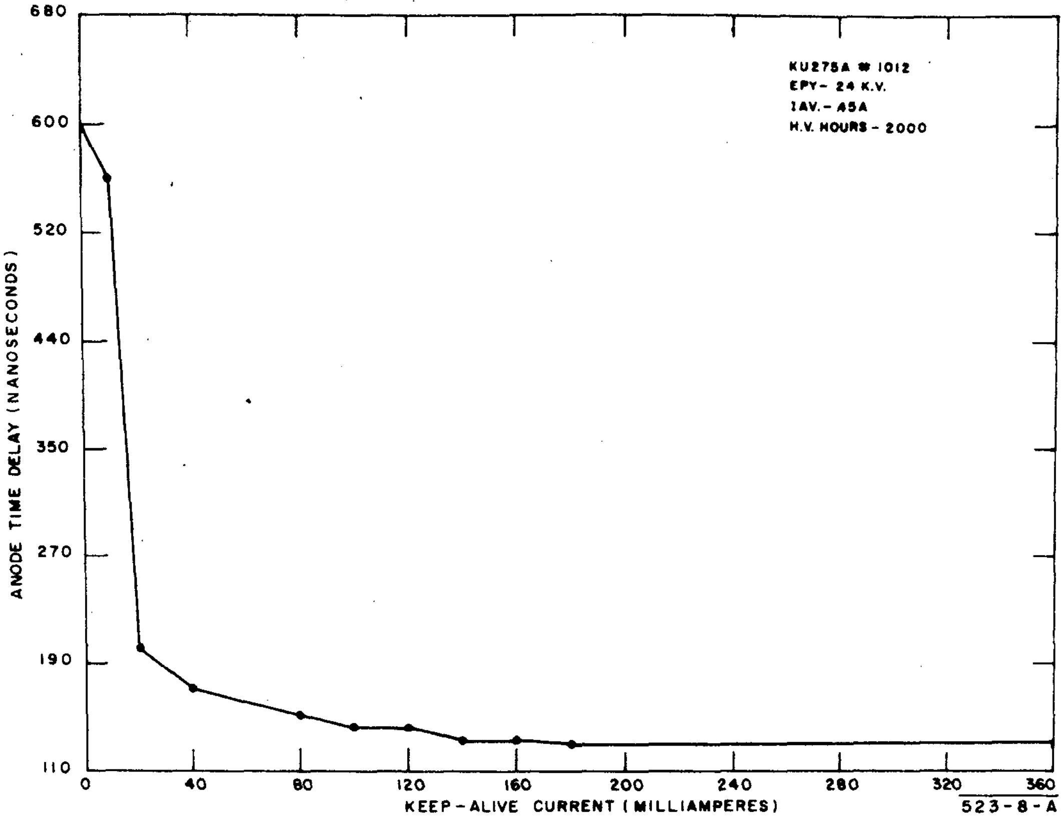


**FIGURE 8 - ANODE DELAY TIME VS. AUXILIARY ELECTRODE CURRENT**

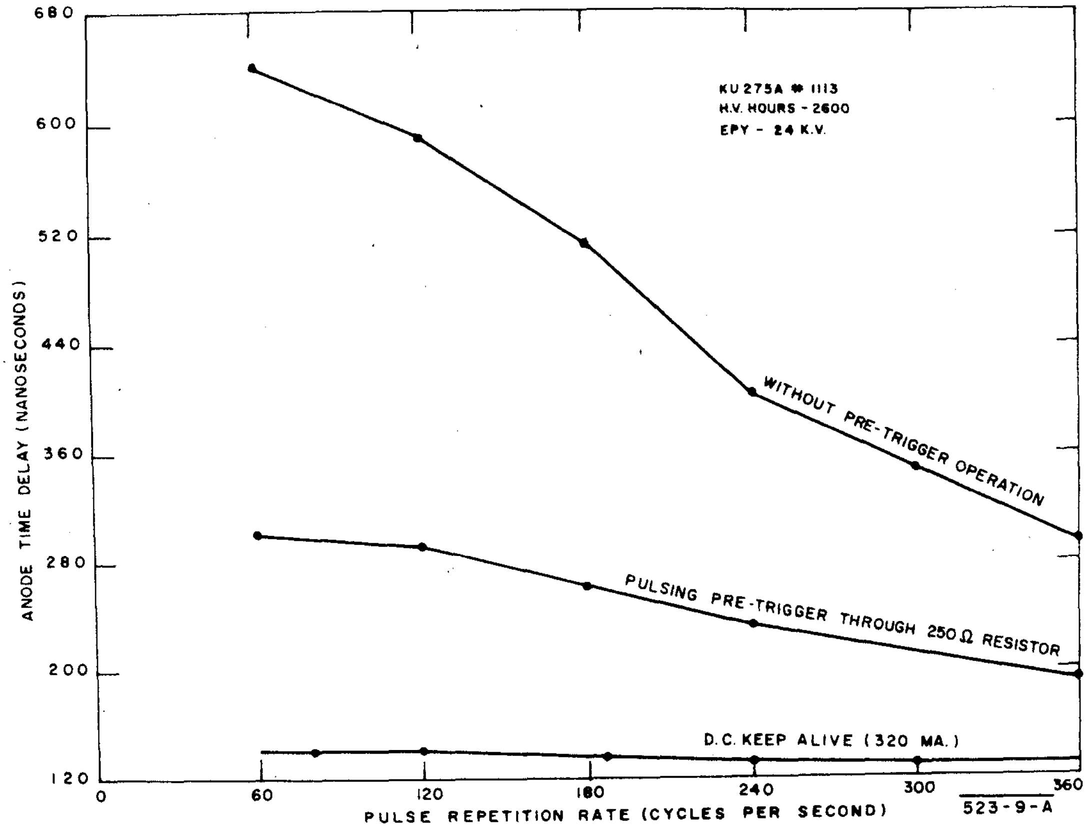


**FIGURE 9 - ANODE DELAY TIME VS. THREE TRIGGER MODES AT MINIMUM SLAC POWER**

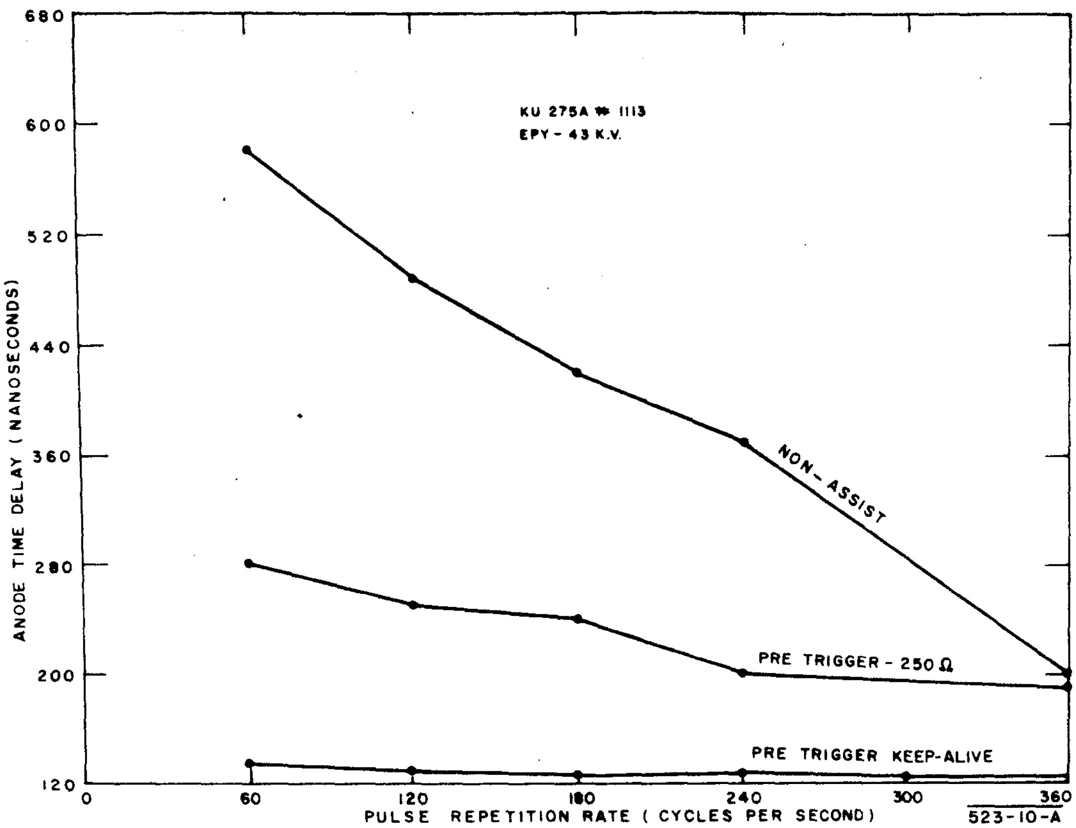


FIGURE 10 - ANODE DELAY TIME VS. THREE TRIGGER MODES AT FULL SLAC POWER

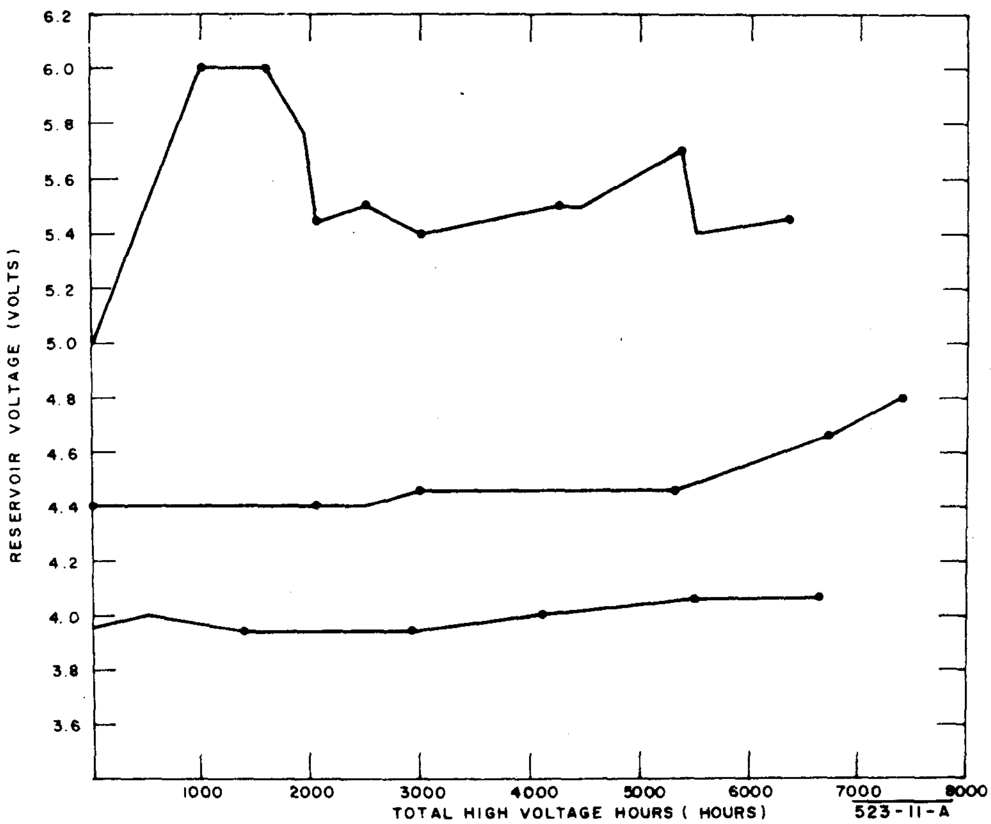


FIGURE 11 - RESERVOIR CENTER RANGE VS. TOTAL HIGH VOLTAGE HOURS

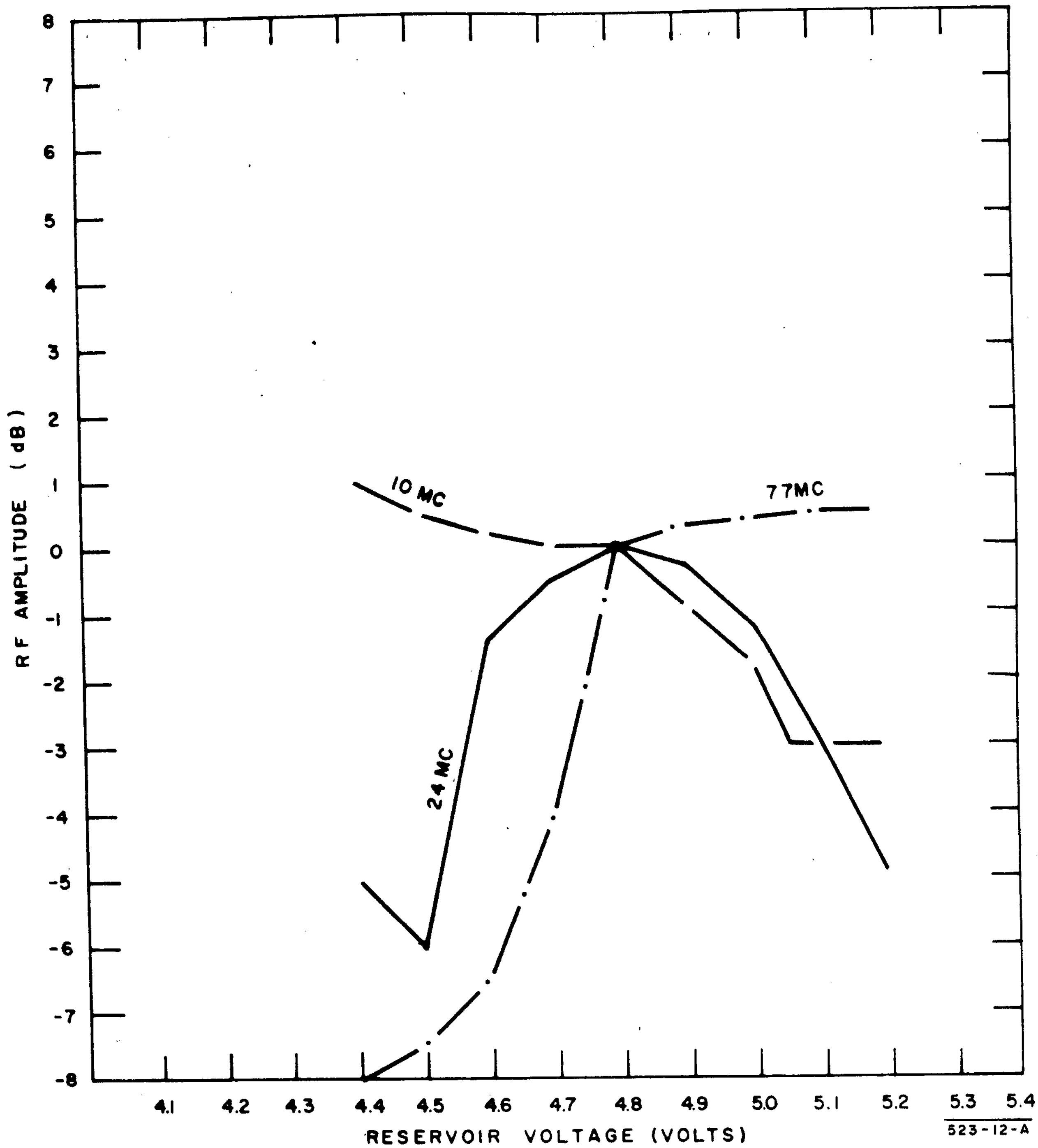


FIGURE 12 - R.F. AMPLITUDE VS. RESERVOIR RANGE AT 10, 24 AND 77 MC

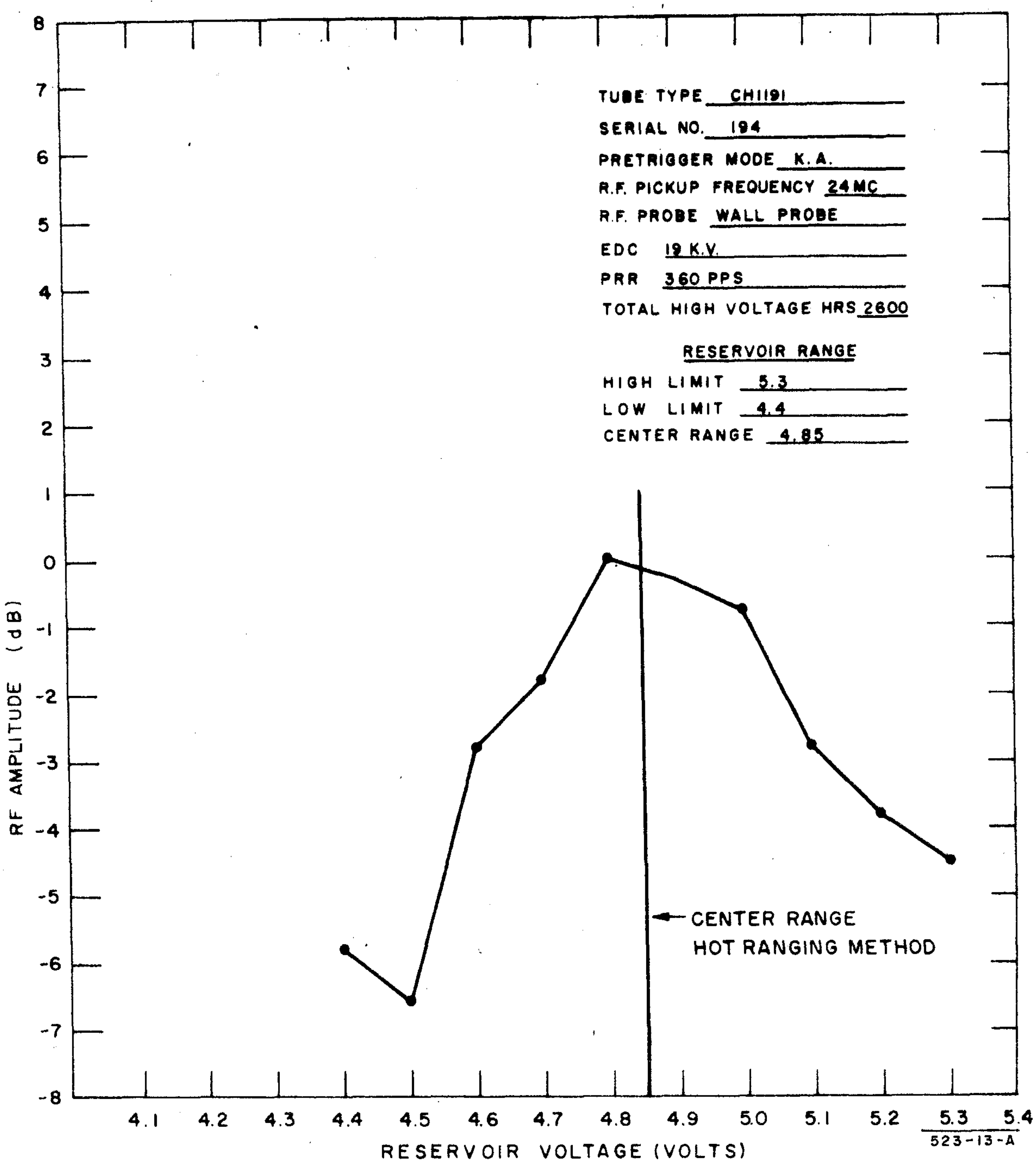


FIGURE 13-R.F. PICKUP AT 24MC VS. RESERVOIR RANGE