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DESIGN AND PERFORMANCE OF THE LAMPF 1-1/4 MW KLYSTRON MODULATOR

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Summary

A design for a very reliable single-triode modulator for a 1-1/4 MW modulating-anode klystron is presented. The operating voltage is 86 kV and the variable pulse length ranges from 200 μsec to 1.2 msec. The basic modulator circuit, which uses a novel Zener diode bias circuit, and several of the individual components are described in detail. Over 140,000 high-voltage hours have been accumulated on these modulators. The principal failure mechanism is grid emission from the triode. These failures can be anticipated and repaired during a normal maintenance period. The triode is then reprocessed and reused. Tube life data and a summary of the failures modes are presented.

I. Introduction

Forty-four 1-1/4 MW klystrons are used at the Los Alamos Scientific Laboratory, Clinton P. Anderson Meson Physics Facility (LAMPF), to accelerate protons from 100 to 800 MeV.

The critical requirements which influenced the modulator design are the long video pulse length of 1.2 msec and the reliability at the 86 kV operating voltage. Since the proton beam is constantly gaining velocity along the accelerator, the failure of a single modulator makes it impossible to accelerate the beam beyond that rf module.

The klystron and modulator assembly is shown in Fig. 1. The entire assembly can be moved on an airpad by two men. A complete spare klystron module is located in each of the rf cluster buildings and it takes two hours to replace a module.

II. Design Details

A. Electrical Design

A single triode is used to switch the potential of the modulating anode from the cathode potential of -86 kV to about -10 kV. The basic modulator circuit is shown in Fig. 2. The triode is biased slightly beyond cut-off and driven into saturation by the 250 V drive pulse through the 3:1 pulse transformer T2. The low end of the 100 kΩ resistor is thus grounded and the modulating anode voltage is reduced to a low value, which turns on the klystron current. The 100 kΩ resistor is made of twenty 5-kΩ wafers; thus, the "on" voltage of the modulating anode is adjustable in 5% steps. One 5-kΩ wafer may be replaced with a 2-kΩ wafer, if it is desirable to adjust the voltage in smaller steps. This feature is used to compensate for perveance variations between klystrons.

The three isolation transformers, the 100-kΩ resistor and the switch-tube enclosure are the largest components in the modulator, which is shown in Fig. 3. The transformers required special care in design. The cores are 12-mil tape-wound with 11-3/4 in. square windows. The klystron and triode filament transformers have a 2 in. x 2 in. core cross section, while the pulse transformer has a 3 in. x 3 in. core. A double Lucite shield is placed around the primaries to improve the voltage hold-off capability. The secondary windings form a 3 in. diam bundle to reduce the fields at the secondary surfaces, and copper corona shields are placed around the interior of the windows. The 3:1 pulse transformer has 125 turns on its primary and is shown in Fig. 4.

One current transformer is used to monitor the total high voltage current in the modulator. This transformer is read by the crowbar system. A second current transformer is used to monitor the cathode current in the klystron. The current transmission through the klystron can be checked by comparing the voltage developed across the 0.1 Ω collector resistor with the output of the cathode current transformer. A capacitor voltage divider is attached to the modulating anode to check the output of the modulator.

The 10 Ω resistor in the plate lead of the LPT-44 is used to monitor the triode's plate current. The duty factor of the LPT-44 and its dc plate current are monitored by a diode clipping circuit which is in parallel with a trip-off meter. The meter shuts off the high voltage supply whenever the duty factor or dc plate current exceeds a preset value.

B. The Zener-Diode Bias Circuit

The modulator was originally designed with a tetrode as the switch tube. The switch-tube power transformer had three secondaries; the filament supply, the screen grid bias and the control grid bias.

Subsequent calculations showed that the tetrode was driven to its dissipation ratings in this circuit. In addition, the screen and control grid bias rectifiers would sometimes fail when a crowbar occurred. These problems were overcome by substituting an LPT-44 triode (a lower-voltage version of the ML-8495) for the tetrode and using a high-power Zener-diode self-bias circuit, which is now discussed in some detail.

It can be seen from Fig. 5 that:

$$e_{gk} = e_s - e_z$$

Thus, between pulses, when the input signal is zero:

$$e_{gk} = e_z$$

The next figure will show that the Zener voltage under zero-drive conditions (as well as with signal present) is actually the same value as the rated Zener breakdown potential, E_z. For proper operation it is necessary to select E_z to be the same as the rated cutoff voltage for the particular vacuum tube under consideration. A value for E_z that significantly exceeds the rated cutoff potential will increase the requirement for grid drive power. Our modulator requires nine 45 V Zeners in series to produce the proper bias.

Figure 6 illustrates the method of arriving at a graphical method for simultaneous solution of the two equations:

$I_p + I_g = I_k + f(E_{gk})$ (Plate voltage is constant)

$I_z = g(E_z)$

These curves can be plotted on the same axis, because:

$I_z + I_k$ and $E_z = -(E_{gk} + e_s)$

The Zener characteristic curve is represented by the dotted line to the left of the vertical axis for the case where $e_s = 0$. The intersection with the tube characteristic determines the vacuum tube operating point with no signal present. The level of cathode and Zener current on the graph in this area is exaggerated so that the intersection of the two curves can be clearly seen. Whenever e_s is not zero, the Zener curve must be shifted to the right by an amount equal to the level of e_s. For example, the dotted Zener curve to the right of the vertical axis represents the situation when e_s has reached a value of $E_z + E_1$ ... the case where the grid is E_1 volts positive with respect to the cathode.

It is important to realize that the voltage across the Zener diode remains essentially constant during the cutoff and the conducting modes of vacuum tube operation. While Zener dissipation during the cutoff mode can usually be ignored, the grid and anode currents flowing through the Zener in the "on" mode create a significant Zener dissipation. In the case of our modulator, these currents reach a peak of approximately 1 A, so that the peak Zener dissipation is about 400 W. Since the duty factor should rarely be higher than 14%, and since there are actually nine series-connected Zener diodes, the average dissipation per diode is limited to about 6.2 W.

For application of this method of biasing on higher power modulators, one can overcome the dissipation problem to some extent by the use of "synthetic Zener" circuitry similar to that shown in Fig. 7.

The total current carried by this circuit is $(\beta + 1)$ times that current carried by the Zener used in the circuit. This means that the transistor dissipation is β times that of the Zener, where β is the dc current gain of the transistor. Thus, with careful transistor selection, it is possible to increase the power capability by a factor of $(\beta + 1)$ over that of the original Zener. (The assumption is naturally made that the transistor has sufficient dissipation capability, i.e., $P_t + \beta P_z$, where P_t is the transistor dissipation rating and P_z is the Zener rating.)

General advantages of the Zener self-biasing method for high-voltage modulators include:

1. Increased reliability; due to the simplicity of the circuitry.

2. Economy; due to the reduced number of parts, particularly the high-voltage interface power transformer.

3. Performance; because one does not experience the pulse droop problem that is present whenever grid currents tend to charge the output capacitor in a conventional floating bias supply.

C. Mechanical Design

The complete modulator tank is 47 in. x 86 in. and contains about 400 gal of transformer oil. Several of the modulators have operated for three years with no maintenance. An oil pump is mounted on the lid of the modulator to circulate oil through the LPT-44 anode and through a heat exchanger. This heat exchanger is used to maintain a 100°F oil temperature. There is a small door on each modulator tank lid which may be opened to change either the Zener-diode bias board or the switch tube without removing oil from the modulator.

The complete modulator assembly weighs 7,000 lb. These modulators are moved over the half mile between the accelerator cluster buildings and a test building on a large forklift. The modulators are moved within a building on airpads.

III. Performance and Reliability

The capacitance of the floating deck and transformers is 500 pF, which limits the rise time to 50 μsec. About half of this capacity is associated with the modulating anode. This rather long rise time is acceptable for our application because the fill time of the accelerator is a few microseconds. The rf is turned on during the video pulse rise to reduce arcing at the klystron and accelerator rf windows. The droop on the pulse transformer doesn't affect the output pulse because the switch tube is driven well into saturation by the drive pulse.

Over 140,000 high-voltage hours and 160,000 filament hours have been accumulated on these modulators. The maintenance required is summarized in Fig. 8 where the modulator faults which required operator action are plotted for the past eleven calendar quarters. The high-voltage hours are shown as horizontal lines and the light symbols are faults which were corrected during normal maintenance periods. The present operating cycle for LAMPF is twelve days on, followed by nine days down time. The rf systems are normally checked two days before each run period and serious faults which could shut the machine down (shown shaded in Fig. 8) are often corrected during down time. Thus, the three serious faults in 1973 were all corrected during the normal down time periods.

Excessive leakage current due to grid emission is the cause for 23 of the 24 switch tube faults, where a fault is defined as more than 3 mA leakage at 86 kV. At this level, enough x rays are produced to be a hazard at the modulator surface, although the plate dissipation rating of the LPT-44 is not approached. These tubes are reprocessed by electron-bombarding the grid with a 200 W, 200 V ac power supply. The average age of the triodes in service is 2,515 filament hours, while the average age of the triodes which need grid processing is 1,884 h. These ages indicate that the grid emission problem is only evident on a small subset of the total population. Although some reprocessed triodes are back in service, not enough time has been accumulated on them to form definite conclusions about their life.

A total of two switch-tube failures have occurred in the 140,000 h of modulator operation to date. One occurred when a filament broke after the modulator was moved and the other was a grid to filament short after an attempt at reprocessing the grid.

Of the 16 modulator faults shown in Fig. 8, 6 were faults in the oil system, 5 were shorted or open connections, 3 were Zener diode failures, and 2 were open circuits in the 100 kΩ resistor.

The survival curve for the LPT-44's is plotted in Fig. 9. From this curve, an estimate of 7,200 filament hours can be made for the tube life. Only six LPT-44's have been operated for more than 5,000 h. Thus, the life estimate may be modified as more operating hours are accumulated. The life estimate has increased by 200 h in the past year (66,500 filament hours) of operation.

IV. Summary and Conclusion

The modulator described in this paper achieves the electrical and reliability goals which are required for long-pulse accelerator applications. The size, weight, and rise time of the modulator were all increased for the sake of reliability. The most frequent failure modes can be corrected during the normal accelerator down-time periods. Thus, no accelerator shutdowns due to modulator malfunctions have occurred in the present calendar year, which includes over 33,000 high-voltage hours of modulator operation.

Fig. 1 Klystron and modulator assembly.

Fig. 2 Basic modulator circuit.

Fig. 3 Modulator components.

Fig. 4 Pulse transformer, 3:1.

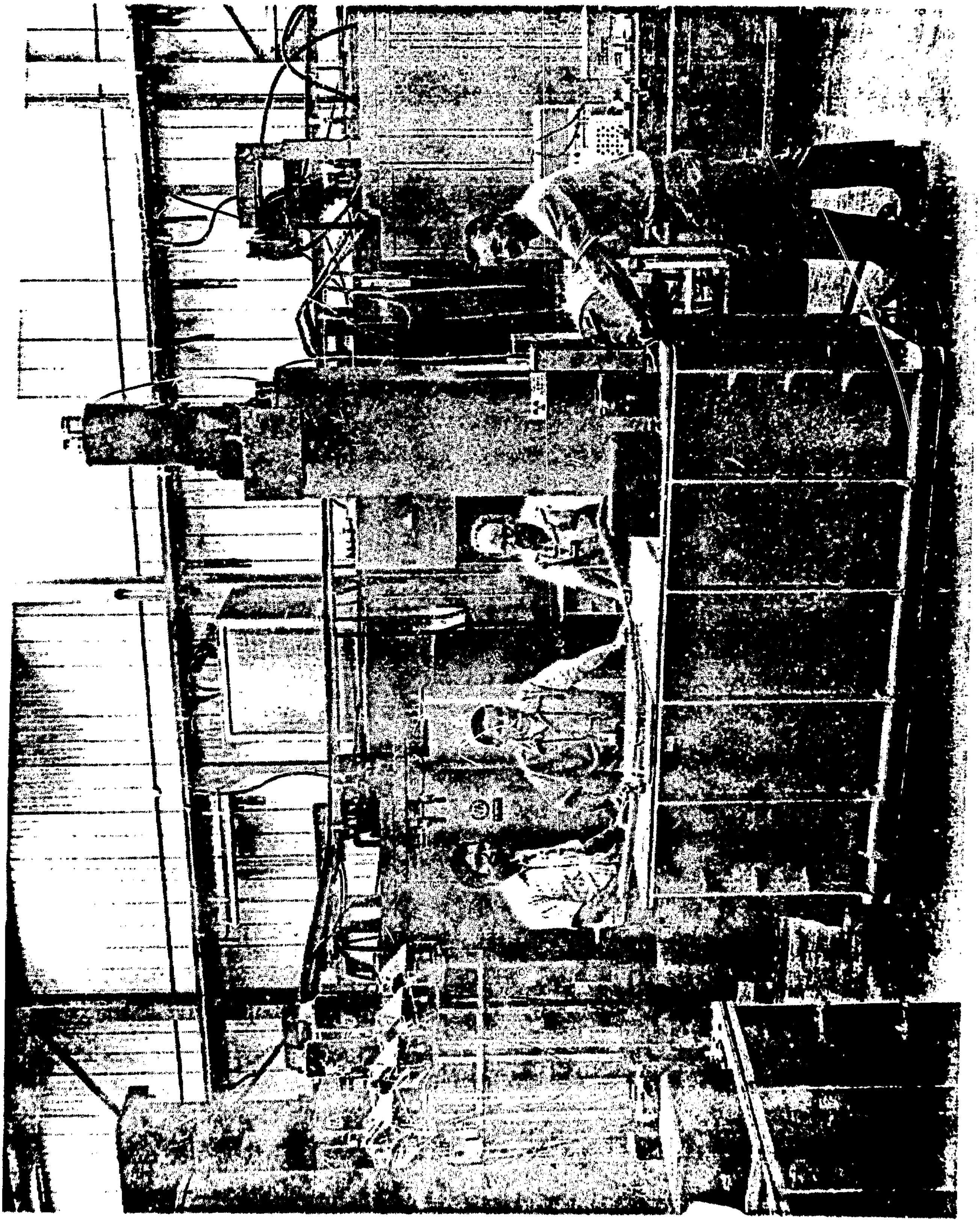
Fig. 5 Grid voltage.

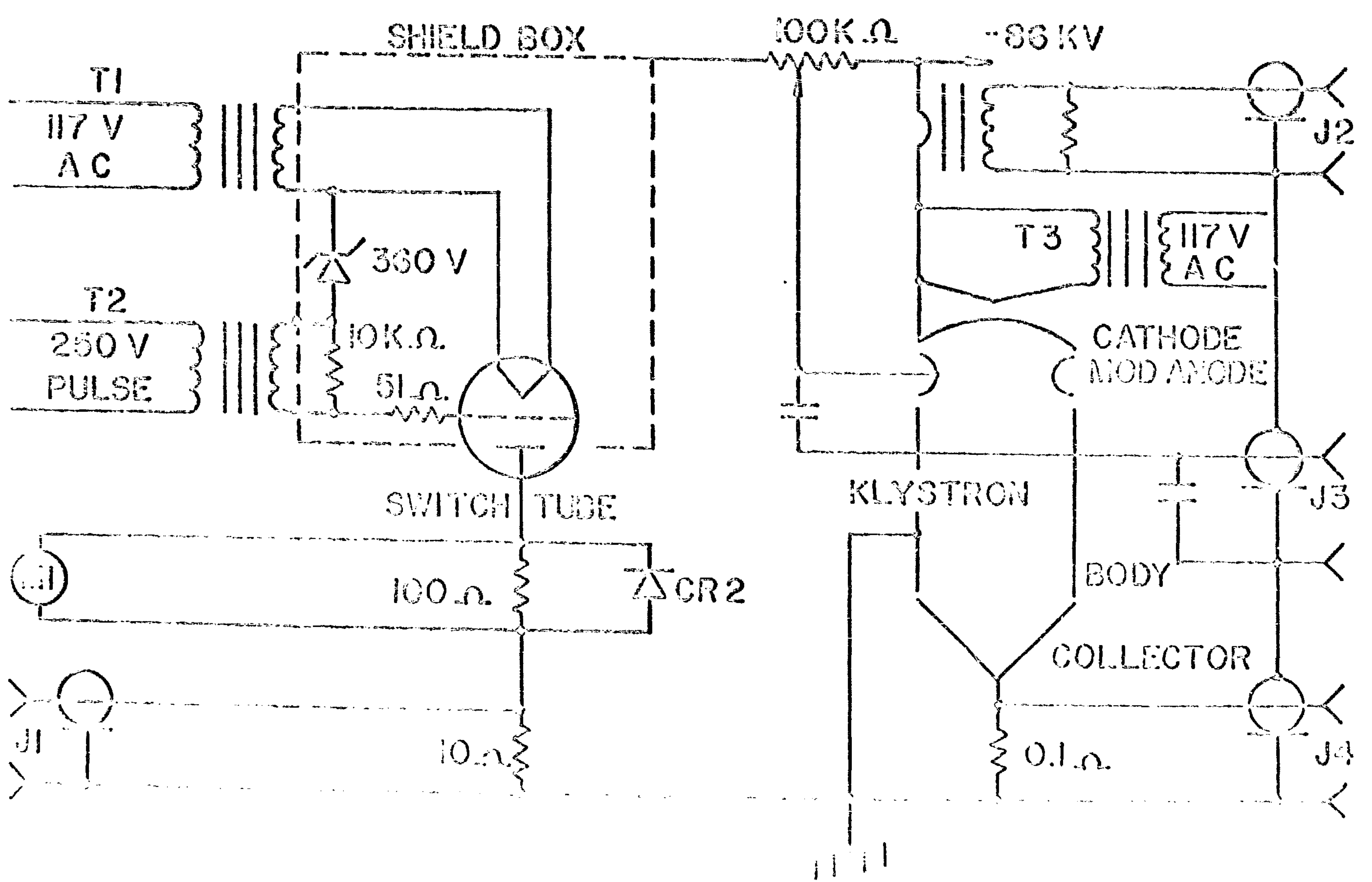
Fig. 6 Zener and switch tube characteristics.

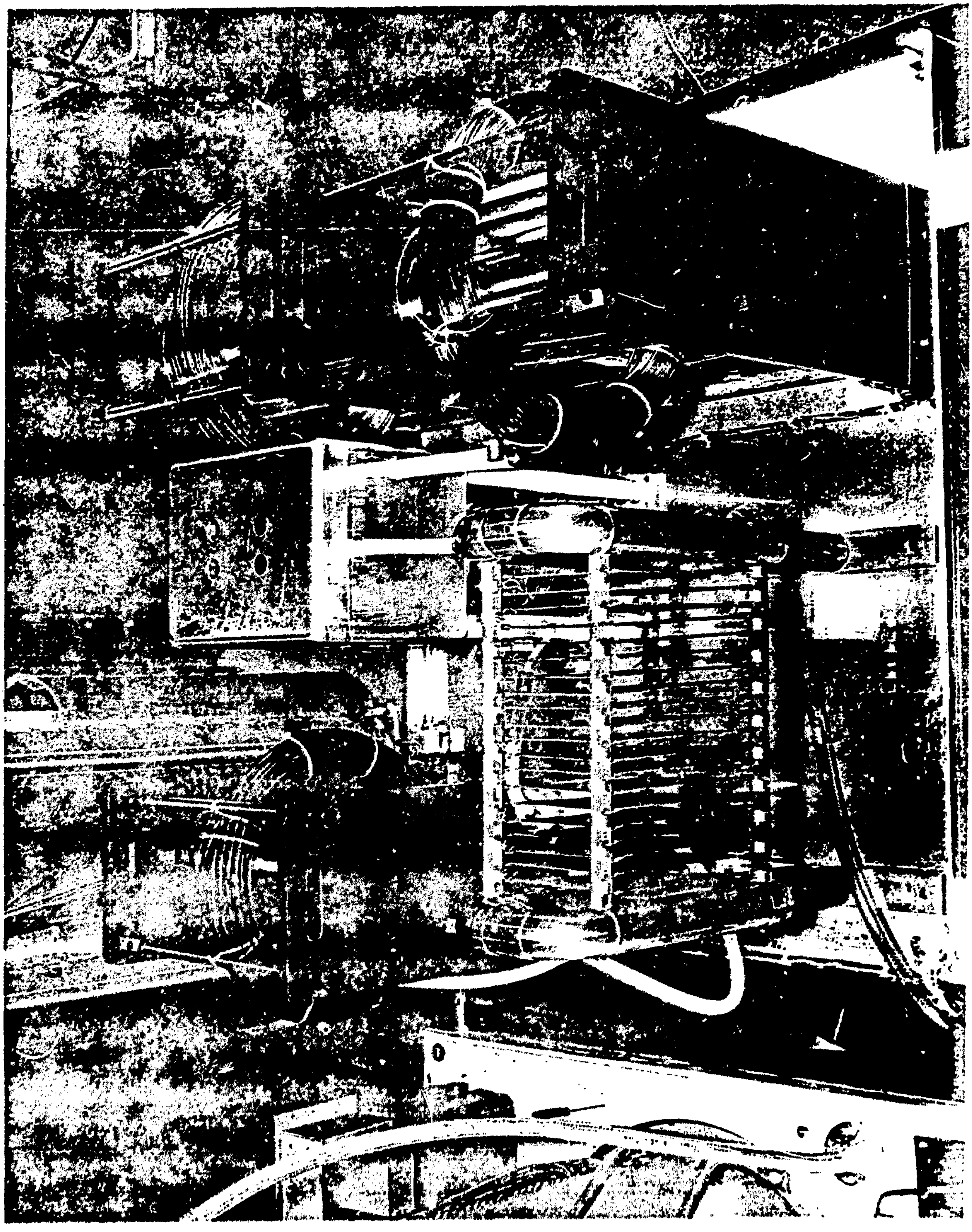
Fig. 7 Zener controlled transistor.

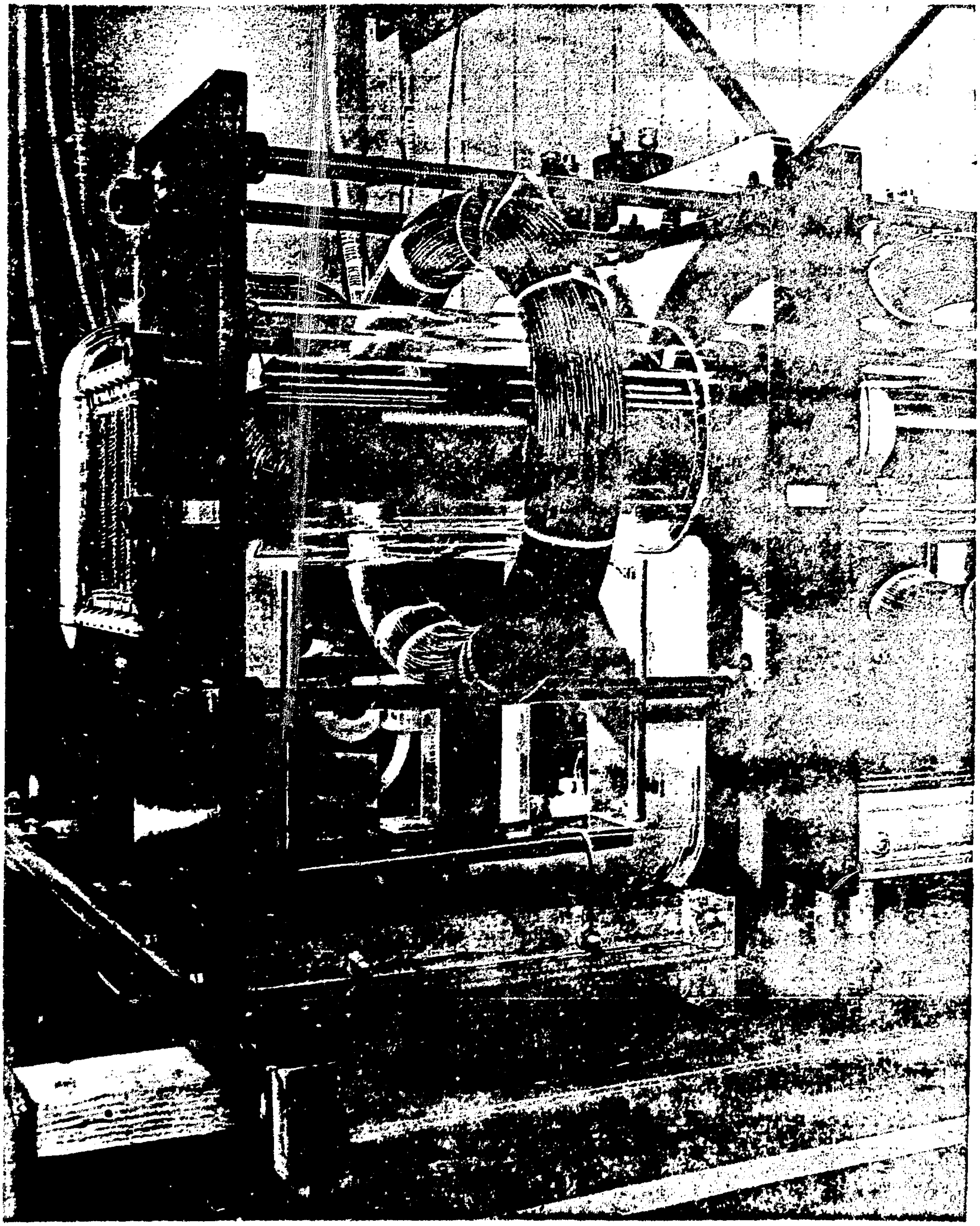
Fig. 8 Fault maintenance summary.

Fig. 9 Switch tube life.




SHIELD BOX
100K Ω
-86 KV
T1
117 V
A C
T2
250 V
PULSE
360 V
10K Ω
51 Ω
SWITCH TUBE
J1
100 Ω
CR2
10 Ω
J2
T3
117 V
A C
CATHODE
MOD ANODE
J3
KLYSTRON
BODY
COLLECTOR
0.1 Ω
J4





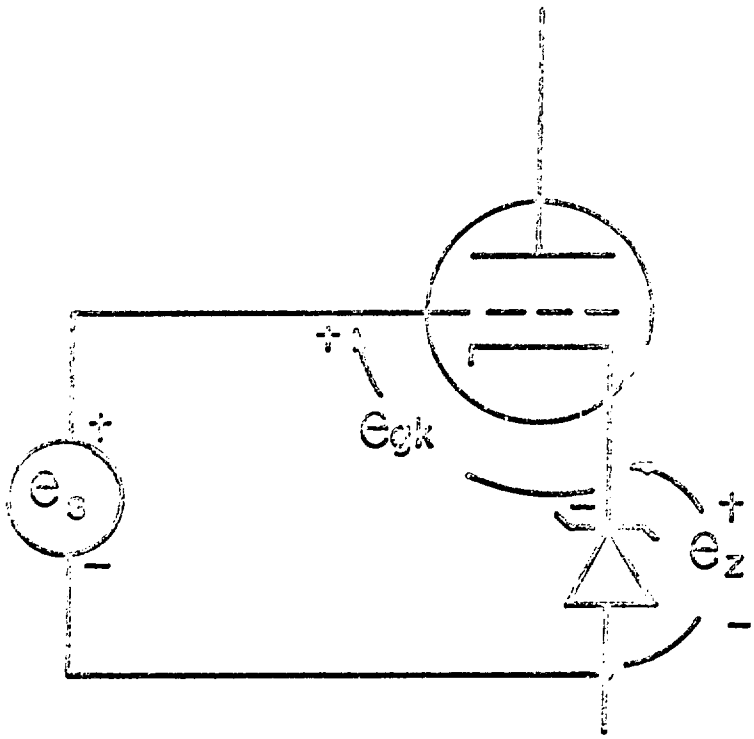
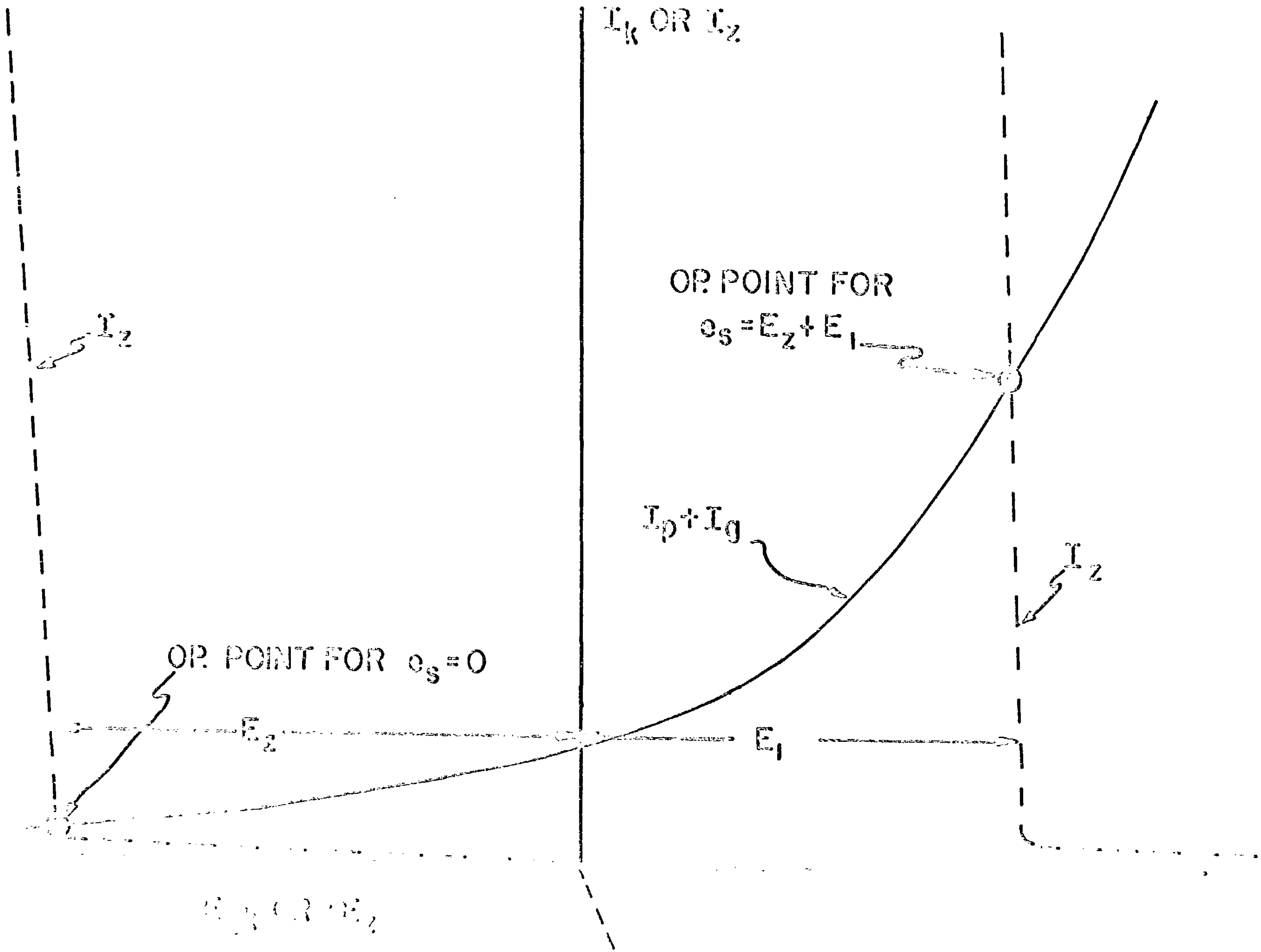


FIG. 5



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es = Ez + E1
Ip + Ig
Iz
OP. POINT FOR es = 0
Ez
E1

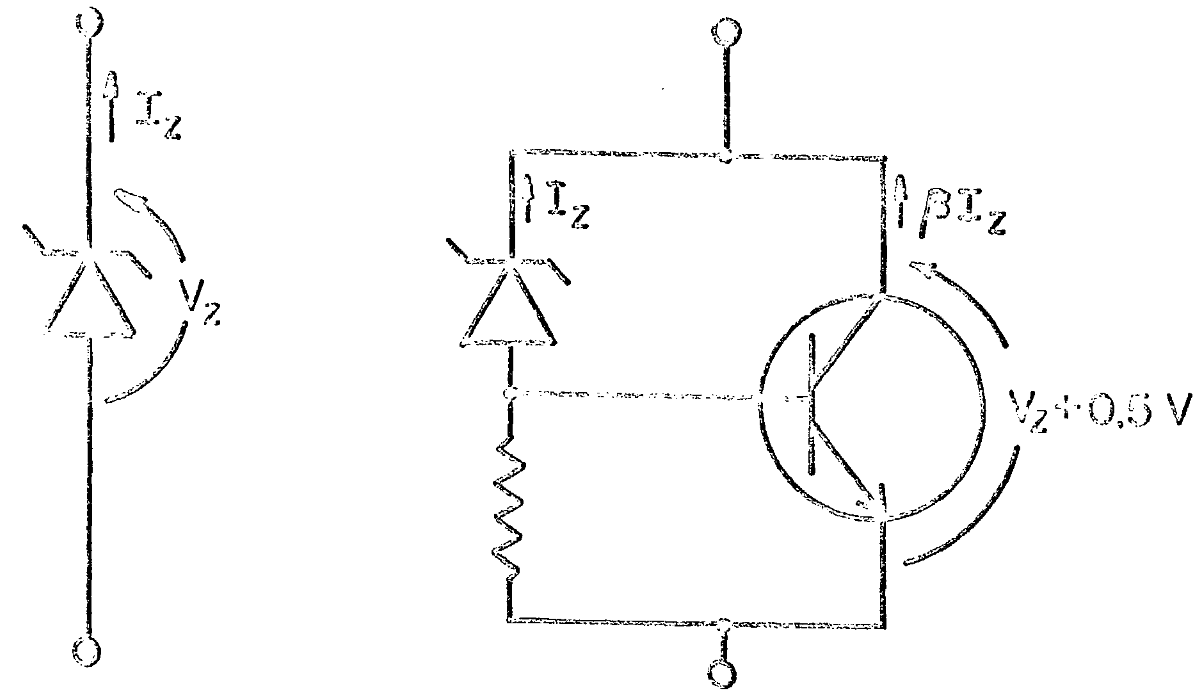
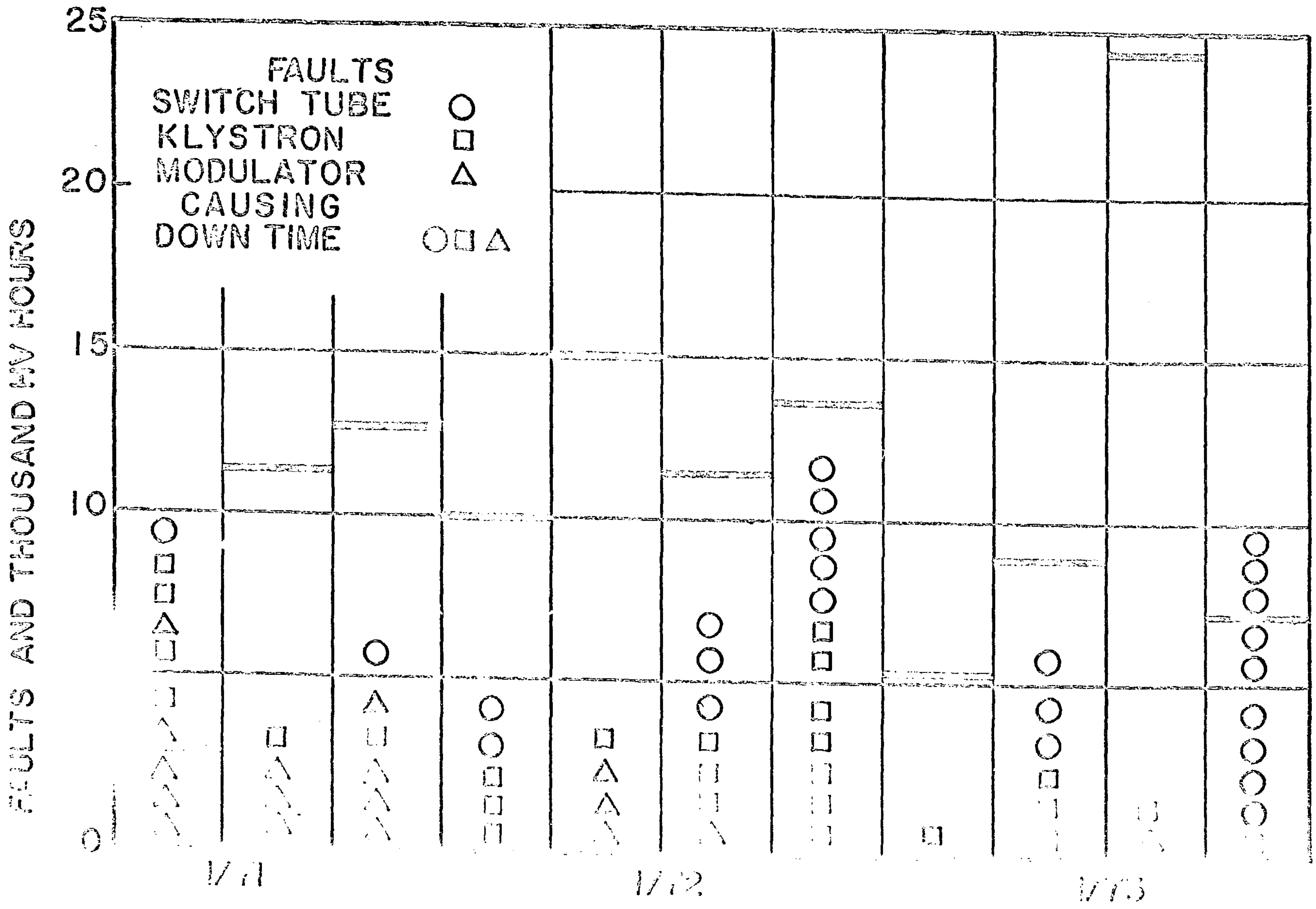
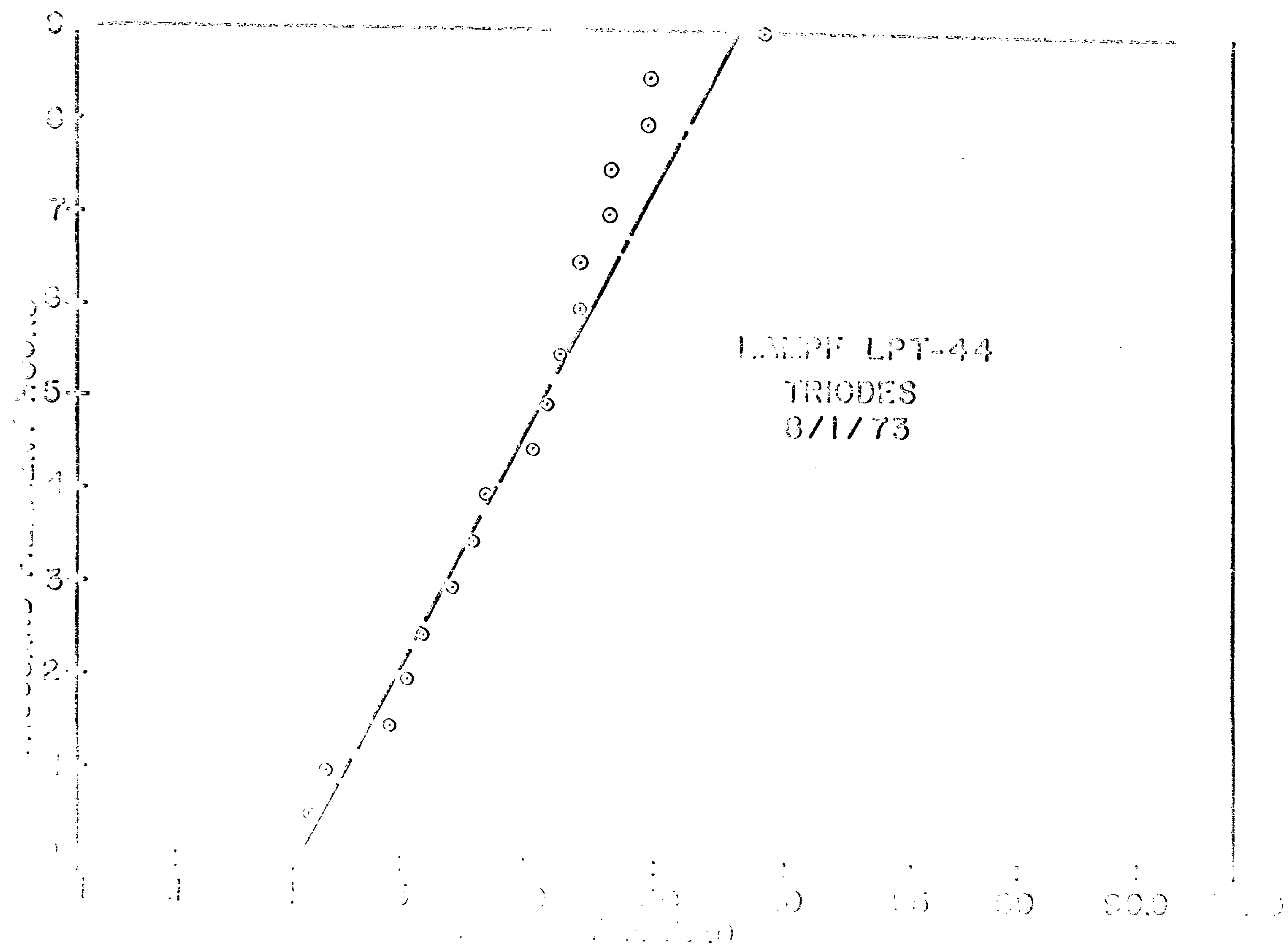


FIG. 7


FAULTS
SWITCH TUBE ○
KLYSTRON □
MODULATOR △
CAUSING
DOWN TIME ○□△
25
20
15
10
0
FAULTS AND THOUSAND HV HOURS
1/71
1/72
1/73


LAMPF LPT-44
TRIODES
8/1/73