Variation of control characteristics of power thyratron tubes with frequency
by H W Snyder

A THESIS Submitted to the Graduate committee In partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University
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Abstract:
A study was made of the variation in the control characteristics of three electrode thyratron tubes operation at frequencies up to 1080 cycles per second. Tests were made on thyratron tubes in half-wave rectification with magnitude d-c grid voltage control. The existence of two control characteristics, a starting control characteristic and an extinguishing control characteristic, at higher-than-power frequencies was confirmed. The starting control characteristic was determined to be dependent uoon frequency of spoiled anode voltage, lnterolectrode capacitance, and tube "dark" currents which are determined by geometry of electrode structures. Extinguishing control characteristic was found to be a tube deionization phenomenon.

VARIATION OF CONTROL CHARACTERISTICS OF
POWER THYRATRON TUBES WITH FREQUENCY

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H. W. SNYDER

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ABSTRACT

A study was made of the variation in the control characteristics of three electrode thyratron tubes operation at frequencies up to 1080 cycles per second. Tests were made on thyratron tubes in half-wave rectification with magnitude d-c grid voltage control. The existance of two control characteristics, a starting control characteristic and an extinguishing control characteristic, at higher-than-power frequencies was confirmed. The starting control characteristic was determined to be dependent upon frequency of applied anode voltage, interelectrode capacitance, and tube "dark" currents which are determined by geometry of electrode structures. Extinguishing control characteristic was found to be a tube deionization phenomenon.

VARIATION OF CONTROL CHARACTERISTICS OF POWER THYRATRON TUBES WITH FREQUENCY

INTRODUCTION

The industrial application of electric power at frequencies other than those normally employed for generation is increasing rapidly, especially for such specialized purposes as heating, brazing, soldering and melting of metals by induction, speed control of motors by frequency variation, servo-mechanism controls, radar modulators, and aircraft rectifiers and inverters. Power at the desired frequency of utilization is generally obtained from standard frequency power systems by means of frequency converting devices or generating devices which are more and more taking the form of circuits incorporating thyratron tubes. Generally the circuits used in these frequency converting or generating devices are well understood, but until recently the variations which might occur in the control characteristics of the thyratron tubes when subjected to higher-than-power frequencies were not known, though it was and is generally accepted that there are frequency limitations in the use of these tubes because of finite ionization and deionization times.

HISTORICAL SURVEY

As early as 1934 Berkey and Haller pointed out that
thyratron firing characteristics would depend on frequency
of applied voltage. It was indicated by W. G. Shepherd[1]
in 1943 that there were two control characteristics in
thyratron control phenomena which he classed as static and
dynamic characteristics. H. H. Wittenberg[2] in 1946 intro-
duced the concept of a starting control characteristic,
meaning first cycle starting as compared to successive cycle
firing, and an extinguishing control characteristic, meaning
failure to ignite on successive cycles, and showed that
though these characteristics are generally coincident at low
frequencies (60 cycles per second) they may become separate,
at least for the control type thyratron tubes, in the audio
range of frequencies. As the frequency is increased both
control characteristics exhibit shifts, the extinguishing
characteristic generally shifting most. It was pointed out
that the starting characteristic would tend to shift in a
negative direction because of coupling to the grid through
the anode-grid capacitance and also because of increased gas
pressure, while the extinguishing characteristic would also
tend to shift negatively with increase in grid resistance,
increase of anode current, increase in gas pressure, the
presence of and the amount of inductance in the anode
circuit, as well as increasing frequency. It was also noted

that the shift was more noticeable in those tubes with larger cross-sectional electrode area (or greater volume).

It was the purpose of this investigation to study the variation in the control characteristics of the larger power thyratron tubes of the single grid, mercury-vapor type because of the trend toward installations requiring more power than control type thyratron tubes can supply. One thyratron tube of the Mercury-vapor-inert-gas stabilized type was also tested. Tubes tested were FG-27A, FG-57, FG-67, 3C23, 967, UX973.

DESCRIPTION OF TEST EQUIPMENT AND PROCEDURE

Figure 1 shows a diagram of the circuit used for testing the tubes. The taps on the inverter provided adjustable anode voltage for the tube under test up to peak values of 850 volts. R_L was a variable resistor in the anode lead to limit the average anode current. Filament power was supplied from a 60 cycle per second source through a variac in order to keep the filament voltage constant as well as to provide some measure of control of the condensed mercury temperature of the tube under test. A small air blower was also used in this connection.

A sine wave of test voltage was used because wave shape does affect thyratron performance, and the sine wave not only gives results easier to analyze but is also most widely used of all wave shapes. Voltage wave shape was monitored by the cathode ray oscilloscope and checked by comparison of the readings of a rectifier type voltmeter and a radial vane type voltmeter. Frequency of the applied voltage was determined by means of the audio frequency oscillator and the Lissajous pattern on the screen of the cathode ray oscilloscope. Grid voltage was obtained from a 24 volt battery and the potentiometer. The tube undergoing test was fired at the crest of the anode supply voltage wave by magnitude control of the grid voltage and the firing point was monitored with the

cathode ray oscilloscope.

The source of the test voltage was a parallel inverter using a pair of FG-67 thyratron tubes. Output power was limited by the input voltage rating of the inverter transformer and the current rating of the inverter tubes. The inverter was chosen as being best able to supply the required variable frequency, variable voltage power source of good output wave shape. Other means of obtaining variable frequency, variable voltage power were studied[3,4,5,] but rejected as being too costly or of insufficient frequency range.

TEST RESULTS

STARTING CHARACTERISTICS

It was apparent as testing advanced that the two con-
trol characteristics found for the smaller tubes would
generally be found for the larger tubes also. The starting
characteristics would in general shift with the frequency
of the applied anode voltage as can be readily seen in
figures 2, 3, and 4, though the degree of shift might be so
slight as to be masked by experimental inaccuracies as evi-
denced by figures 5, 6, and 7 and also by the curve of
figure 4 taken at 76° C. condensed mercury temperature.

Figure 3 showing the shift of starting characteristic
with frequency in the type FG-67 thyratron tube was of
especial interest, since the shift here is shown in a pos-
itive direction where all other tubes exhibited, where
noticeable, a shift in the negative direction. Wittenberg,
as was noted previously, indicated that the negative shift
could largely be accounted for by the voltage induced into
the grid circuit through the anode-grid capacitance with
other factors such as d-c leakage currents and grid emission
also contributing.

Consideration of the equivalent circuit for a single
grid thyratron tube in half wave rectifier service with a
resistance load, source impedance negligible, leads to the

following expression for the voltage induced into the grid
circuit through the tube interelectrode capacitances in-
cluding tube base and socket: (See appendix I.)

$$e_g = j\frac{e_p R_g}{X_2} \tag{1}$$

This equation is, of course, valid only during non-conduc-
tion.   Figure 8 shows anode-grid coupling in a thyratron
tube (exaggerated for purposes of illustration) as calcul-
ated by equation 1.   It can be seen from figure 8 that the
effect of the voltage induced into the grid circuit by the
anode-grid capacitance coupling is to require more negative
d-c grid bias to prevent firing, though the necessary in-
crease in bias voltage will be less than the crest value of
the induced voltage.   Also, the induced voltage will tend
to fire the tube somewhat before crest anode voltage is
reached.

Because of the unusual behavior of the starting
characteristic of the type FG-67 thyratron, peak values of
induced grid voltages were calculated by means of equation 1
for all tubes used in this study and also for those tubes
used in the Wittenberg study and plots were made to determine
the amount of shift in starting control characteristic which
would be caused in each case.   The results of this work are
shown in table I in comparison with the shift in starting

control characteristic actually observed.

Table I also lists the anode-grid capacitances including tube base and socket as measured for those tubes tested in this study and also those values listed by Wittenberg in his study. It will be noted that the measured values are all greater than the figures published by tube manufacturers. This is because of the added capacitance from the tube base and sockets.

Examination of table I discloses that of the eleven tubes tested the starting control characteristic of one tube shifted in a positive direction. For four tubes no shift in starting control characteristic was observed, though this is not conclusive since the shift predicted for two of the tubes by consideration of anode-grid coupling is so slight as to be masked by experimental error and in the case of the other two tubes the predicted shift is zero. For the remaining six tubes the observed shift in starting control characteristic is substantially greater than that predicted from consideration of anode-grid coupling. In those instances of negative shift in starting control characteristic greater than predicted by anode-grid coupling a part of the added shift may be caused by d-c leakage currents over the stem press between the cathode and grid

TABLE I

COMPARISON OF CALCULATED* AND OBSERVED SHIFT OF STARTING CONTROL CHARACTERISTICS

Tube Type	Anode-Grid Capacitance Mmfd	Grid Resistance Ohms	Frequency	Crest Anode Volts	Crest Induced Grid Volts	Calculated Shift Volts	Measured Shift Volts	Difference
2D21 **	0.25	0.1 meg	3500	650	0.051	0.00	0.00	0.00
3D22 **	0.45	"	3500	650	0.643	---- ***	-0.20	----
2050	0.60	"	1500	1000	0.570	0.00	-0.90	----
2051	0.60	"	3500	650	0.791	---- ***	-1.70	----
884	6.40	"	700	300	3.43	-1.60	-4.0	-2.40
FG-27A	11.0	5000	1020	800	0.277	0.00	0.00	----
FG-57	11.0	2000	920	650	0.0897	0.00	-0.35	-0.35
FG-67	12.0	5000	1280	800	0.302	-0.05	+0.55	+0.60
3C23	10.0	5000	1020	800	0.265	-0.05	-0.20	-0.215
967	16.0	5000	1020	850	0.426	-0.05	0.00	0.05
UX973	13.0	5000	1020	800	0.347	-0.05	0.00	0.05

* Calculated values were computed from equation 1 and accurate plots of applied anode volts, induced volts, and critical grid voltages.

** Shield grid type thyratrons. All others are single grid type thyratrons.

*** Could not be accurately plotted.

Note: 2D21, 3D22, 2050, 2051, 884, data from Wittenberg's article. All other data from present study.

structures, and, in tubes which have been in use long
enough for cathode coating to have been deposited on the
grid structure, grid emission may account for a part of
the added shift. In the case of the type FG-67 thyratron
tube none of the foregoing serves to explain the observed
positive shift in starting control characteristic.

It is suggested that the positive shift in the start-
ing characteristic of the FG-67 thyratron may be caused by
relatively large "dark" currents [4,6,7,] in the grid circuit
just prior to firing. "Dark"current, the result of elec-
trons leaving the cathode with sufficient thermal acceler-
ation to reach the grid, is normally a function of cathode
temperature, grid potential, and anode potential, and may
be almost completely zero at high negative grid potentials
with low anode voltage. It is interesting to note from
figure 8 that the effect of the induced grid voltage is to
nullify the effect of the negative grid bias voltage so
that the "dark" current increases in magnitude as the
applied anode voltage begins to increase positively and
add its effect to that of the induced grid voltage to fur-
ther increase the magnitude of the "dark" current . Since
the direction of flow of this "dark" current is from grid
to cathode, a voltage drop is produced in the external grid
resistance of such polarity as to prevent the tube from

firing.

There is some experimental evidence in support of the foregoing. Attempts were made to measure the magnitude of the grid current in the FG-67 just prior to firing, a rather difficult task, since the large value of grid current flowing after firing may damage the instrument used for measurement of the "dark" current. It was determined that when a voltage with a frequency of 550 cycles per second and crest value of 560 volts was applied to the anode circuit of the tube the average d-c grid current, that is, "dark" current, prior to firing was at least 12 microamperes. This is probably well below the actual value of average grid current flowing at just the instant before firing because considerable caution was exercised for protection of the d-c microammeter used to measure the grid current. Also, the microammeter did not measure peak values of any pulsations which might be present.

"Dark" currents are particularly noticeable in the grid circuits of those thyratron tubes where the grid baffle is effectively interposed in the path of the arc-stream. It can be seen from figure 12 that the type FG-67 thyratron is of such construction as to be in this class. The type 967 and type UX973 also are in this class, though here the grid baffles do not lie so completely in the path of the arc-

stream. In the case of these last two types no shift in starting characteristic could be observed experimentally, though a slight shift was predicted by consideration of anode-grid coupling. It seems probable that in these types the grid "dark" current was of sufficient magnitude to just counteract the negative shift caused by anode-grid coupling and other effects.

In the case of such thyratron tube types as the FG-57, figure 12 shows that the hole in the grid baffle is as large as the cathode emission hole and so the grid cannot be said to be "interposed" in the path of the arc-stream. It would be expected that grid "dark" current in this case would be small in magnitude and of negligible importance as far as affect of the starting control characteristic is concerned and such is actually the case, no measureable grid "dark" currents being found for this tube.

Attempts were made to measure leakage currents and leakage resistance values in the tubes under test with completely negative results. As an example; the type FG-57 thyratron would require a cathode-grid leakage current of 175 microamperes to account for the difference between the observed and predicted shift in starting control characteristics. No measureable leakage currents were found with

negative grid voltages as great as 24 volts. From this it
may be conclude that the effect of leakage currents in
shifting the starting control characteristic negatively is
as small or smaller than the direct effect of grid voltage
induced through anode-grid coupling.

The following theory is offered in explanation of the
shift in starting control characteristics of three element
thyratron tubes:

In any hot cathode tube a certain number of electrons
leave the cathode with sufficient thermal acceleration to
reach either the grid baffle or the grid-anode space unless
the grid is made sufficiently negative relative to the cath-
ode to repel all these high speed electrons. Those electrons
reaching the grid baffle surface find their way back to the
cathode by way of the grid circuit and produce the grid
"dark" current previously mentioned. Those electrons which
pass through the grid holes and reach the grid-anode space
produce ionization in this region when the anode is at a
positive potential. The positive ions produced in the grid-
anode space are attracted to the grid and start forming a
positive space charge near the grid which tends to nullify
the effect of the negative grid bias and so permit more
electrons to enter the grid-anode region to produce greater
ionization. Unless the grid is made sufficiently more

negative to repel all electrons the tube will ignite.

As the frequency of the applied anode voltage is in-
creased the magnitude of the voltage induced in the grid
circuit by anode-grid coupling becomes appreciably large.
It was pointed out previously that this induced voltage
cannot of itself produce all the observed shift in starting
control characteristic. It is so phased, however, as to be
particularly effective in reducing the effect of the negative
grid bias voltage. This will cause the starting control
characteristic to shift strongly in a negative direction in
those negative-grid thyratron tubes with a single large
opening in the grid baffle because the weakened grid field
will permit ionizing electrons to pass through the large
hole in the grid baffle and reach the grid-anode space. In
those negative-grid thyratron tubes with a medium size hole
in the grid baffle some electrons may pass through the hole
and others strike the baffle resulting in some ionization
in the anode-grid region and at the same time, some "dark"
current in the grid circuit. The net result may be a
slight negative shift, no shift, or a slight positive shift
in the starting control characteristic depending upon the
size of the hole in the grid baffle. In those negative-
grid thyratron tubes constructed like the FG-67 with a grid
baffle consisting of a disk with many small holes the weak-

ening of the grid field by the induced grid voltage will
cause the grid "dark" current to increase and so shift the
starting control characteristic in a positive direction.
The starting control characteristic of all positive-grid
thyratron tubes should shift in the positive direction.

According to the above theory an increase in frequency
should cause the starting control characteristic of the
negative-grid thyratron tubes with single large hole in the
grid baffle to shift more negatively. Positive-grid thy-
ratron tubes and those negative-grid thyratron tubes with
grid baffles made as a disk with many small holes will
exhibit a shift of the starting control characteristic in
the positive direction. The shift of starting control
characteristic of those negative-grid thyratron tubes with
a moderate size single hole in the grid baffle will be in-
determinate. Increase of grid resistance should produce the
same effect as increase of frequency.

Data was taken for each tube at two different values of
condensed mercury temperature in order to determine the eff-
ect of temperature on starting control characteristic shift.
It was expected that at higher temperature the shift would
be more negative, since increased temperature effectively
increases the gas pressure. Actually the increase in pres-
sure would be about 8% (See Appendix II) which probably would

not noticeably affect results. There is some slight experimental evidence that the shift at the higher values of condensed mercury temperature is less than at the lower values of condensed mercury temperature, but this variation in shift is so very slight that it can be charged to experimental error and so should not be considered as being in any manner conclusive. This was especially true in the case of 3C23 which is the mercury-vapor inert-gas-stabilized tube. Here the experimental determination of the starting characteristic at the higher value of condensed mercury temperature became quite difficult, any slight change in filament voltage being instantly reflected in a change of emission and so of starting characteristic. Indeed, at condensed mercury temperatures of 80° C. and above the starting control characteristic becomes so erratic as to be classed as a random phenomena.

EXTINGUISHING CHARACTERISTICS

It was unfortunate that the extinguishing character-
istics could not be fully investigated, but power limita-
tions and the inherent unbalanced load presented to the
inverter by the test circuit made complete experimental
study of the extinguishing characteristic impossible.

At power frequencies of 60 cycles per second the
grid can control the average anode current by controlling
the point on the positive voltage wave at which the tube
fires. This feature is lost at audio frequencies, for
here the residual ionization is such that the grid can
provide only on-off control of the anode current, at least
when only magnitude d-c control is used on the grids.

Tests were made up to the limit of the test equipment
which in general seemed to indicate a negative shift of the
extinguishing characteristic. The average anode current of
these tests was only 0.1 amperes compared to the rated aver-
age anode amperes of from 1.25 amperes to 2.5 amperes and so
these results can show little more than a trend. Figure 9
shows the measured shift in extinguishing characteristic at
1000 cycles per second frequency applied anode volts for 0.1
ampere average anode current, resistance load, for the type
FG-57. Figure 10 shows the measured shift in extinguishing
characteristic for the 3C23 at 0.1 average anode amperes,

resistance load. In the case of the FG-57 only 4% of
rated average anode current is being passed and yet the
extinguishing control characteristic has shifted nega-
tively by 10.9 volts at 600 peak anode volts. Part of
this shift may be caused by the inductance of the in-
verter transformer which, by prolonging anode current
flow into the time of negative anode voltage, decreases
the time available for tube deionization.

Wittenberg has found that a linear relationship
exists between average anode amperes and grid voltage
required to extinguish a given tube at a given frequency
and peak anode voltage. Expressed as an equation this
would be

$$e_g = -(K_1 I + K_2) \qquad (2)$$

where K_1 would be a constant depending upon electrode
geometry, frequency of applied anode voltage, and gas
pressure, and K_2 would be the grid voltage intercept.
It has been shown [6] that under static conditions tube
deionization time may be calculated from the empirical
relation

$$t = \frac{0.0012 p I^{0.7}}{e_g^{3/2} x} \qquad (3)$$

where p is the gas pressure in dynes per square centimeter,
I is the arc current, x is the distance between grid and
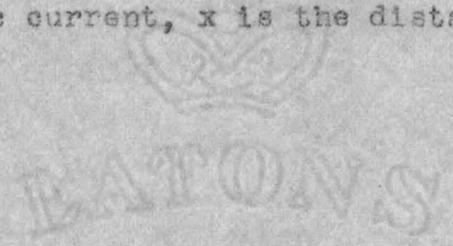
anode, and e_g is the potential of the grid relative to the surrounding space. Operating on equation 3 algebraically to find the grid potential required to deionize a given electrode structure in a given time for various values of arc current results in equation 4.

$$e_g = KI^{0.467} \qquad \qquad (4)$$

Plotting equation 4 will show that beyond a certain point the function seems linear in nature. It is possible that Wittenberg did not investigate low current values and so missed this relationship. The present study included only these low current regions and the curvature is plainly seen in figure 11. Because of limited output power available from the inverter it was impossible to carry the tests to high enough current values to be able to predict grid voltage needed to extinguish the tube when passing rated average anode amperes.

Wittenberg has stated that the shift in extinguishing control characteristic is a deionization phenomena and nothing in these present tests is contradictory of that statement.

A series of calculations was made to determine the effect of transient current and voltage surges on tube deionization. These calculations showed that though respectable peak values of surge voltages would be developed,

the damping factor was such that these voltages become negligible in less than one microsecond and so their effect could be ignored.
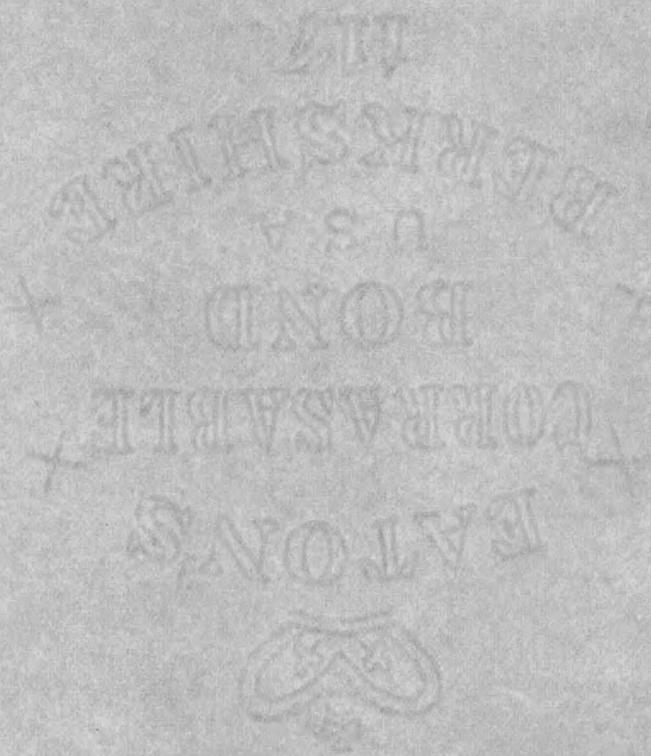
CONCLUSIONS

As a result of this study the following conclusions
are drawn regarding the variation in the control character-
istics of three element thyratron tubes at higher-than-power
frequencies:

1. There will in general be two control characteristics,
   a starting, or first cycle firing, control characteris-
   tic and an extinguishing control characteristic.

2. The extinguishing control characteristic will generally
   shift negatively with increasing frequency.

3. The direction and amount of shift in starting control
   characteristic with increasing frequency will be depend-
   ent upon electrode geometry as follows:

   a) A negative shift will be found for those thyratron
   tubes in which the grid baffle hole is of equal or
   greater diameter than the hole in the cathode heat
   shield.

   b) A positive shift will be found for positive-grid
   thyratron tubes and also for those negative-grid thyra-
   tron tubes where the baffle has many small holes but no
   single large hole.

   c) Direction and amount of shift will be indeterminate
   for those thyratron tubes in which the diameter of the
   grid baffle hole is less than that of the hole in heat

shield.

4. The shift in starting control characteristic is a
    function of tube "dark" currents. High values of grid
    "dark" current will cause a shift in a positive dir-
    ection while high values of anode "dark" current will
    cause a shift in a negative direction.

5. The extinguishing control characteristic shifts nega-
    tively with increasing anode current.

Further study of this subject is indicated to try and
provide answers to the following questions:

1. How will the starting control characteristic of three
    electrode thyratron tubes behave with combined negative
    d-c and phase shifted a-c voltages applied to the grid?
    "Spike"or "pulse" firing?

2. Tube deionization is a function of grid voltage. In-
    creasing value of negative grid voltage will shorten
    deionization time (see equation 3, page 21 and reference
    6). With this in mind, can upper limits of operating
    frequency be established for conventional thyratron
    tubes like those studied here?

3. More complete investigation should be made of the ex-
    tinguishing control characteristic to determine whether
    factors other than tube deionizing characteristics play

any part and if so, how great a part.

4. From these studies can a desireable electrode geometry for high-frequency thyratron operation be deduced?

-24 VOLTS D-C

110 VOLT, 60 ~
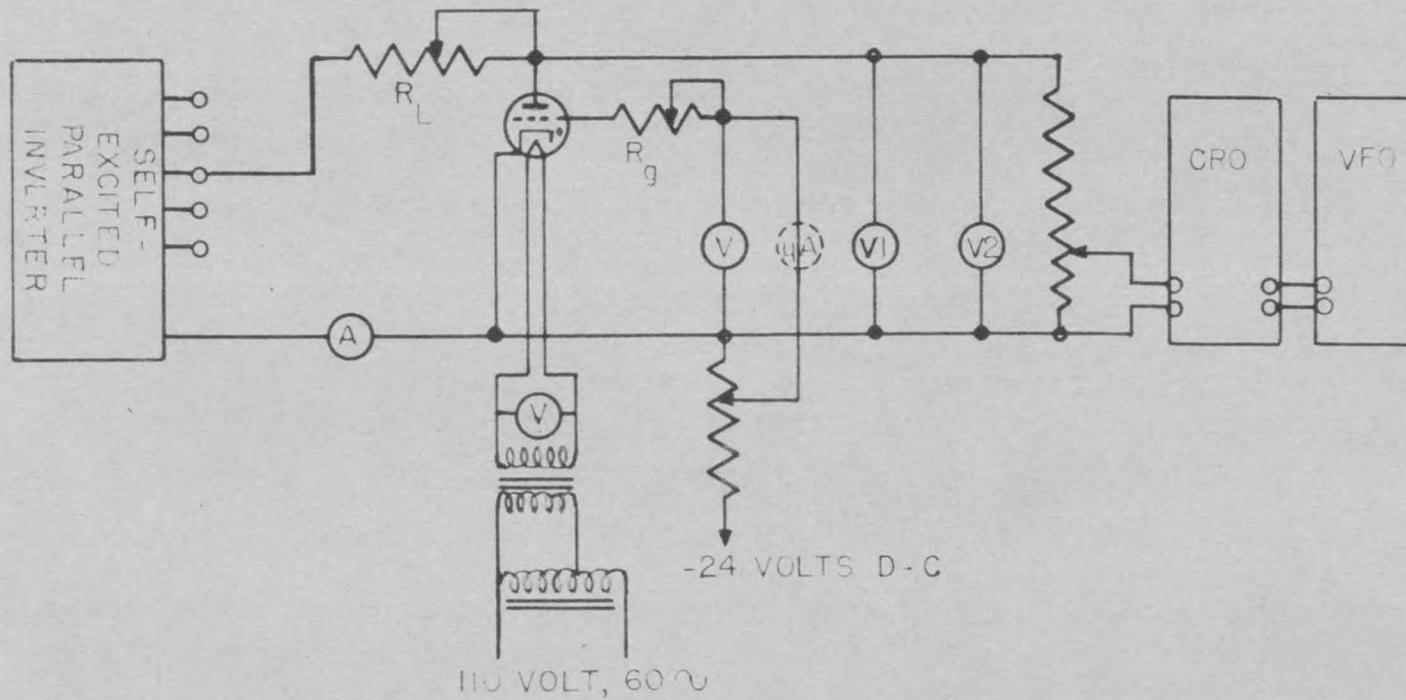
V1 = RECTIFIER TYPE A-C VOLTMETER
V2 = RADIAL VANE A-C VOLTMETER
VFO = VARIABLE FREQUENCY AUDIO OSCILLATOR

FIGURE 1. DIAGRAM OF CIRCUIT FOR TESTING THYRATRONS
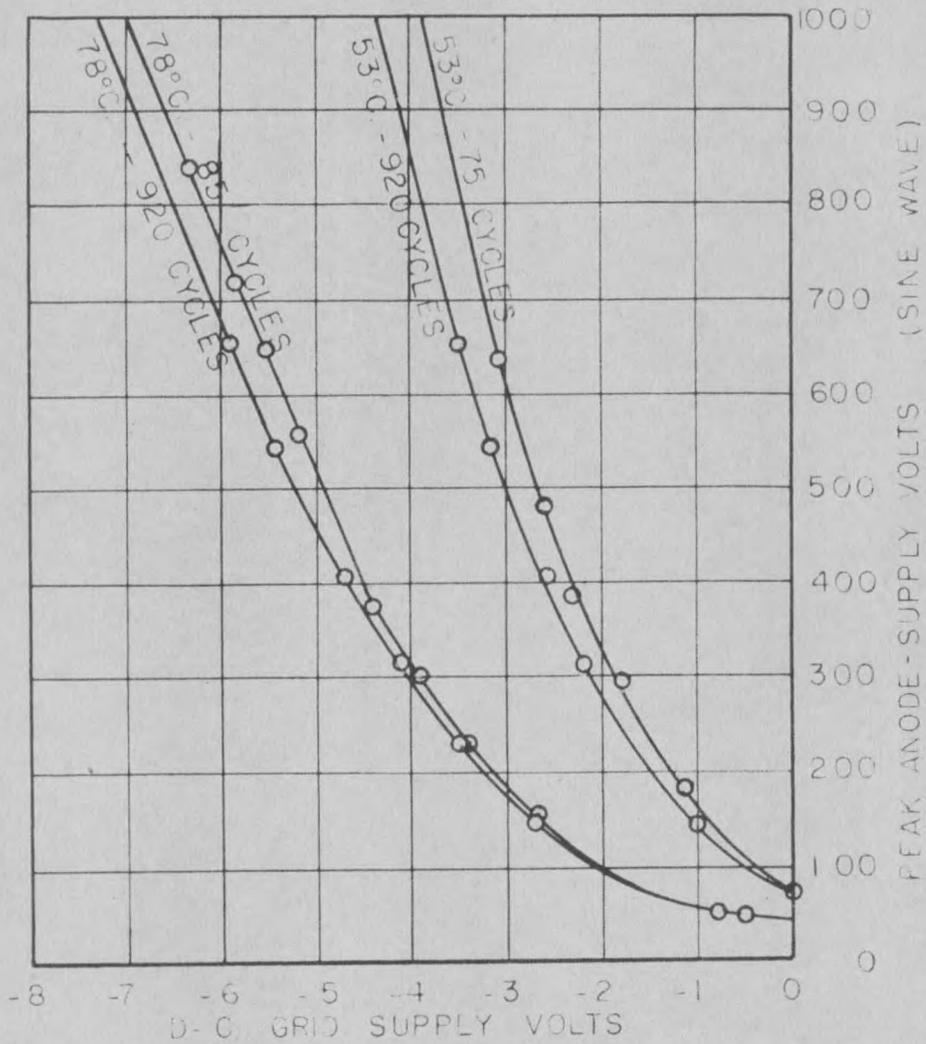
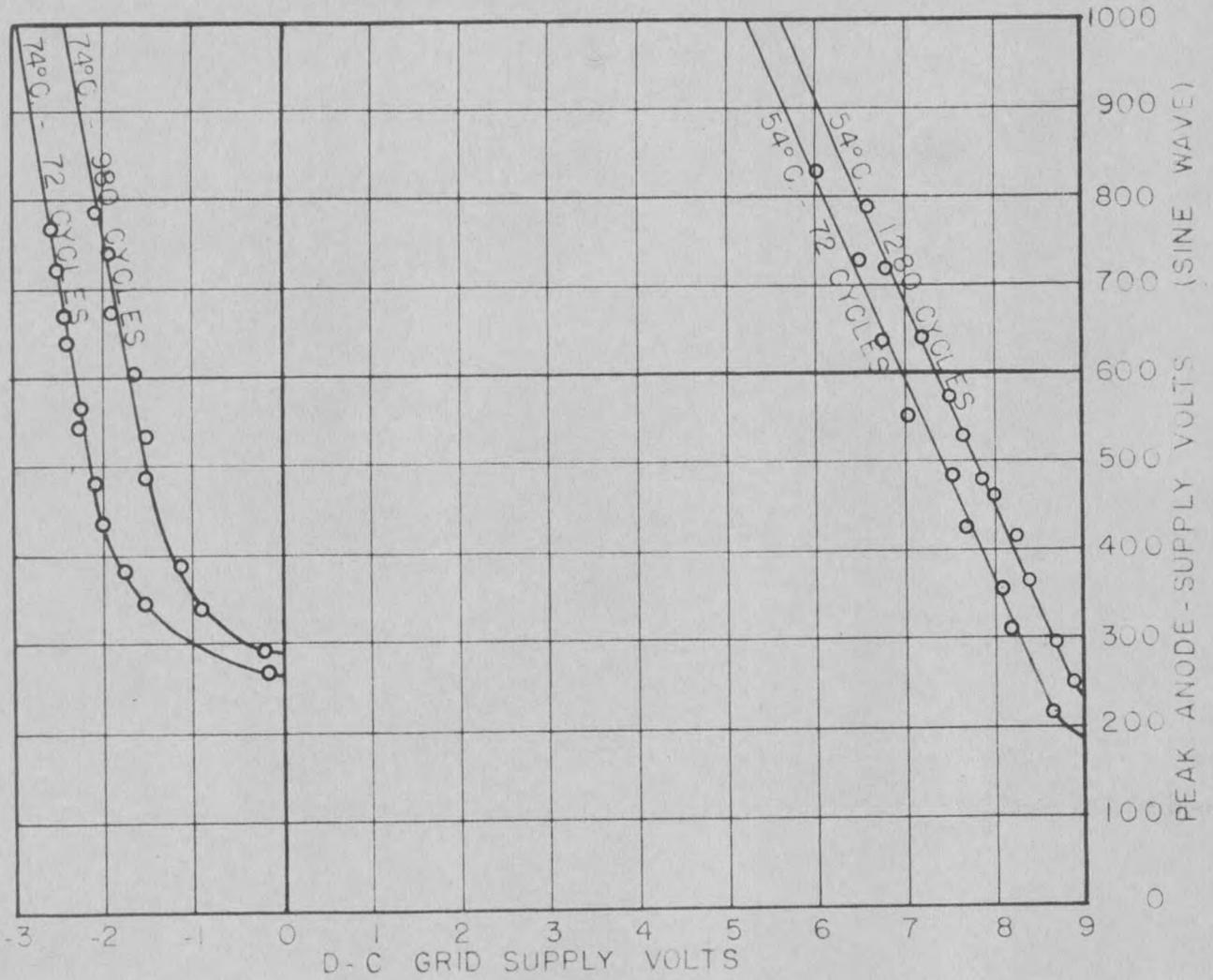FIGURE 2. STARTING CHARACTERISTICS OF
TYPE FG-57 THYRATRON

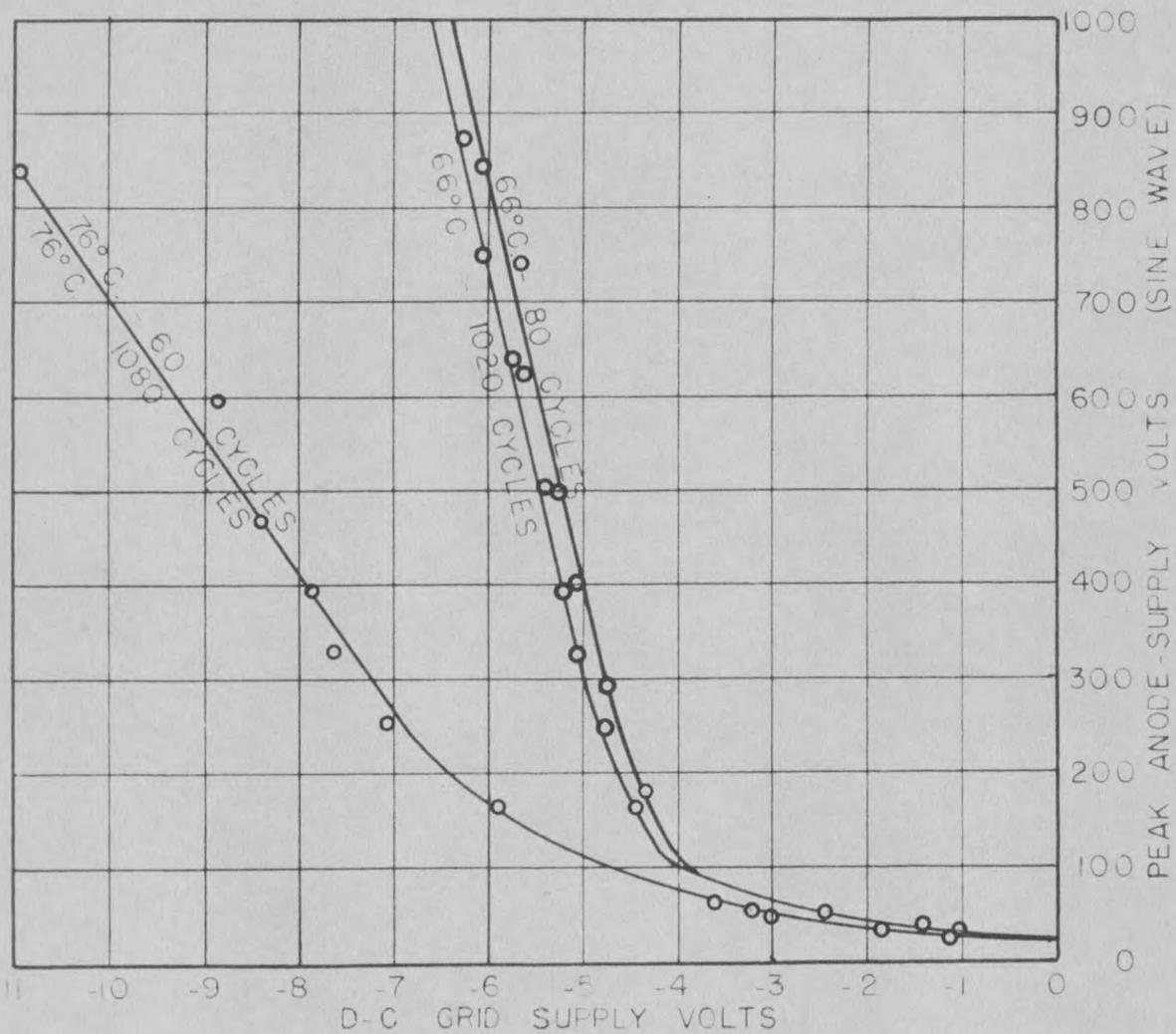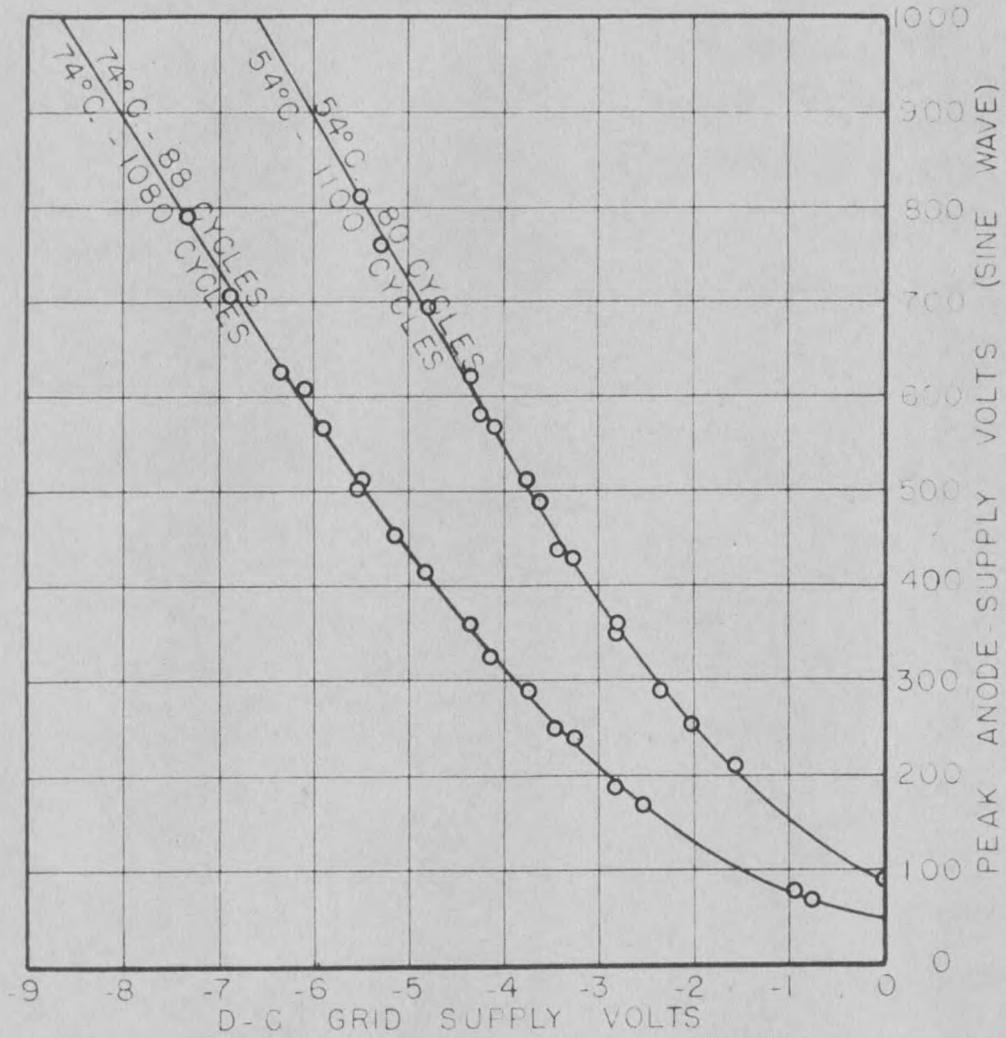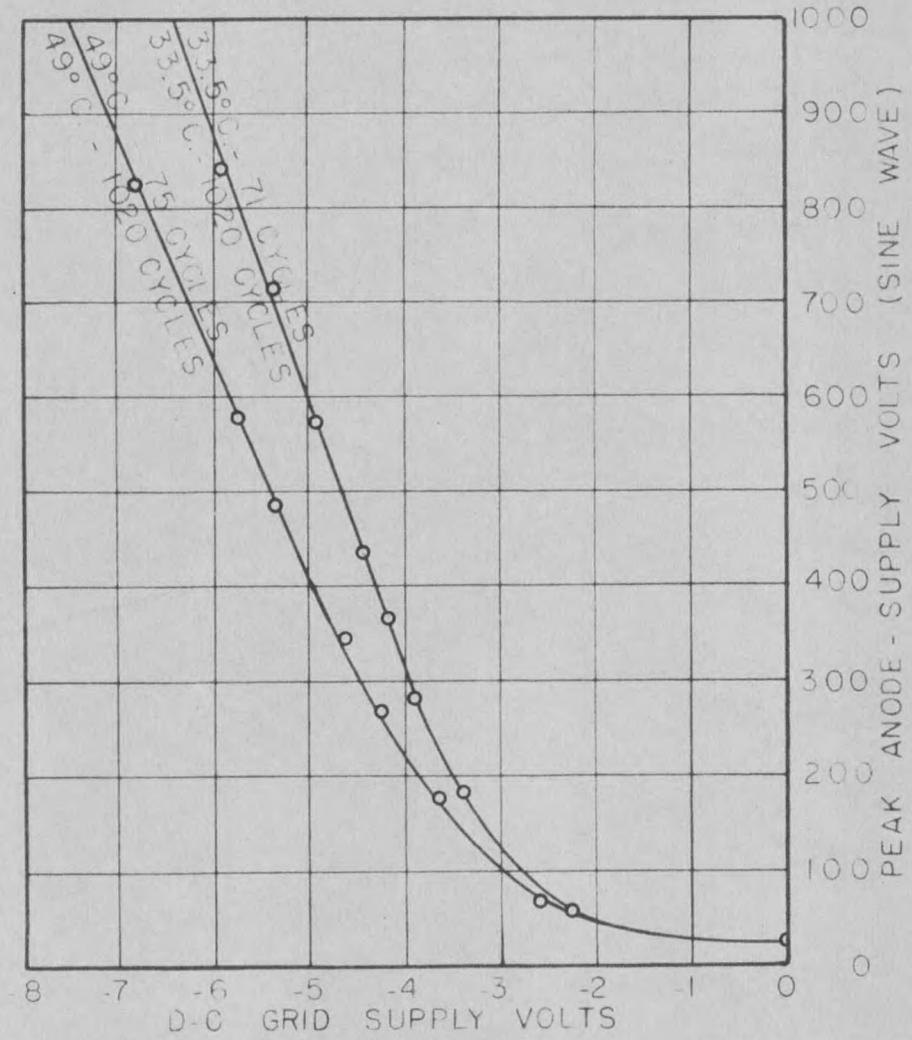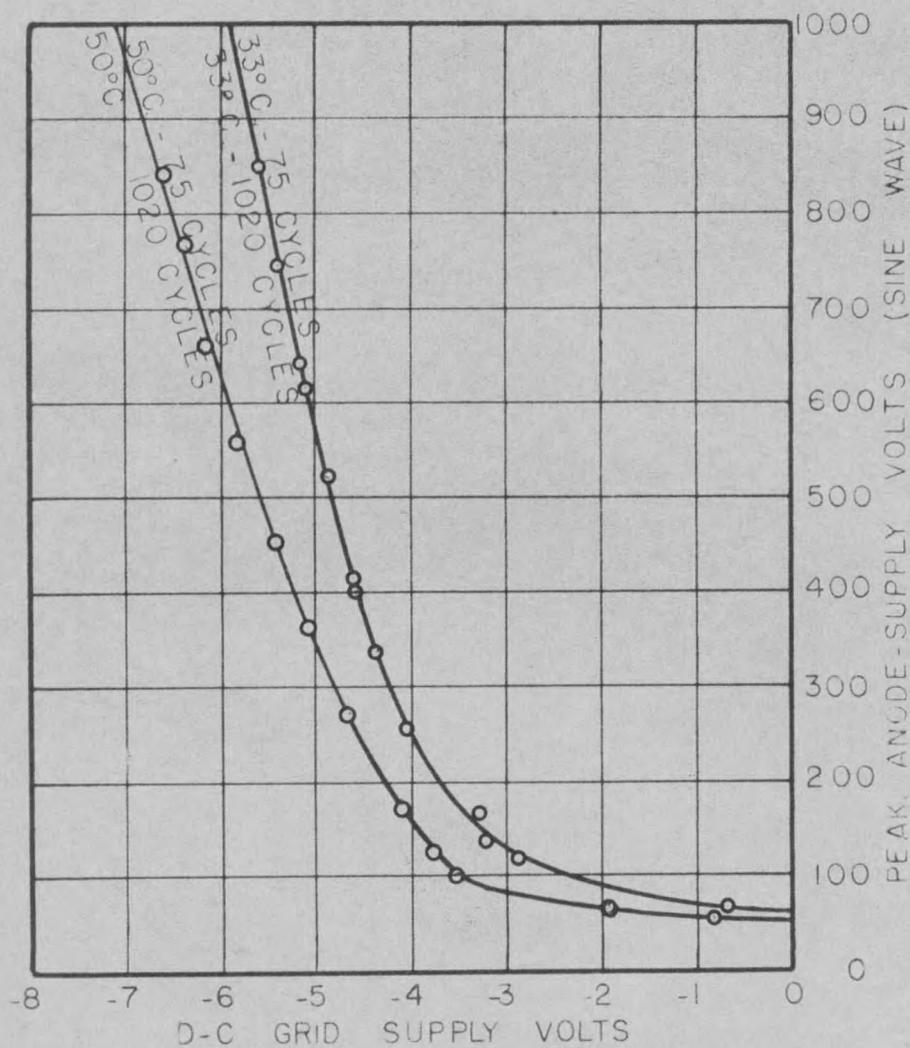FIGURE 3.   STARTING CHARACTERISTICS OF TYPE FG-67
THYRATRON

FIGURE 4. STARTING CHARACTERISTICS OF
TYPE 3C23 THYRATRON

FIGURE 5. STARTING CHARACTERISTICS OF
TYPE FG-27A THYRATRON

FIGURE 6. STARTING CHARACTERISTICS OF
TYPE 967 THYRATRON

FIGURE 7. STARTING CHARACTERISTICS OF
TYPE UX973 THYRATRON
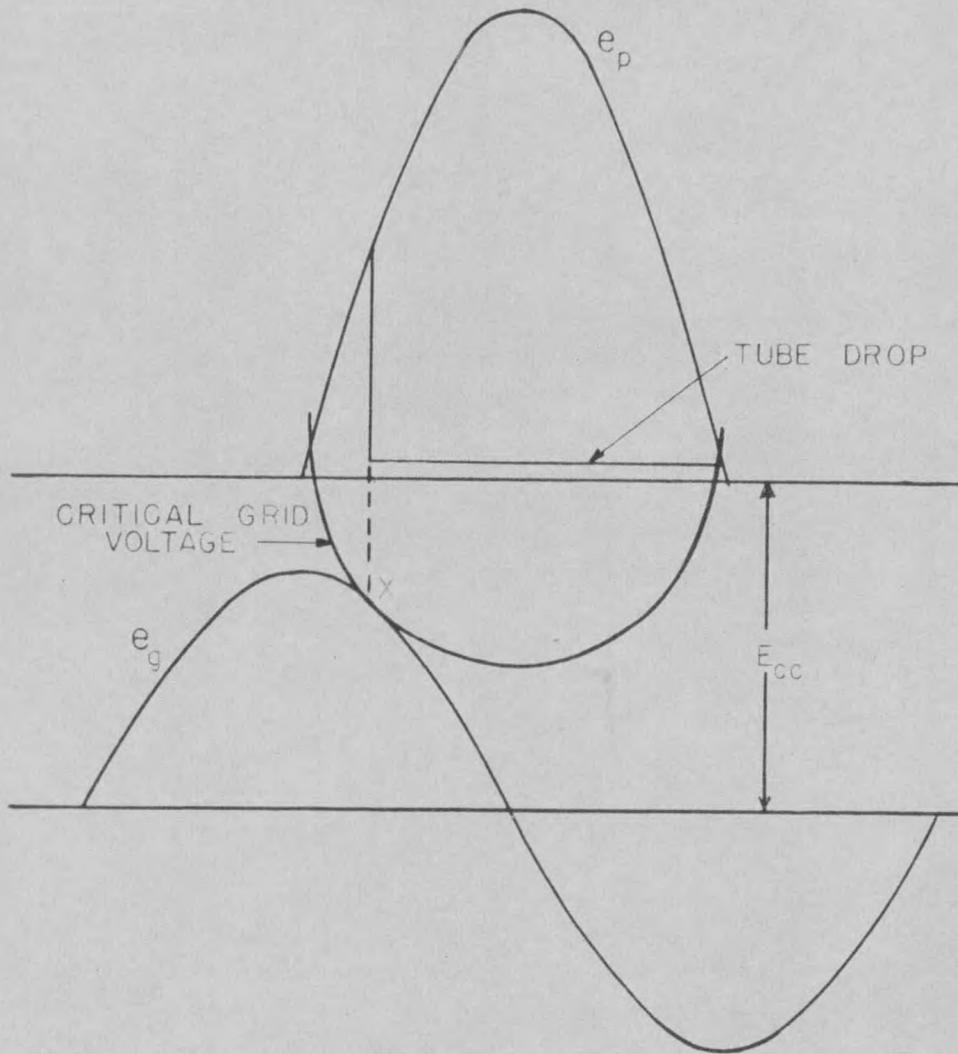
e_p = APPLIED ANODE VOLTAGE
e_g = INDUCED GRID VOLTAGE
E_{cc} = D-C GRID SUPPLY VOLTAGE
X - TUBE FIRES
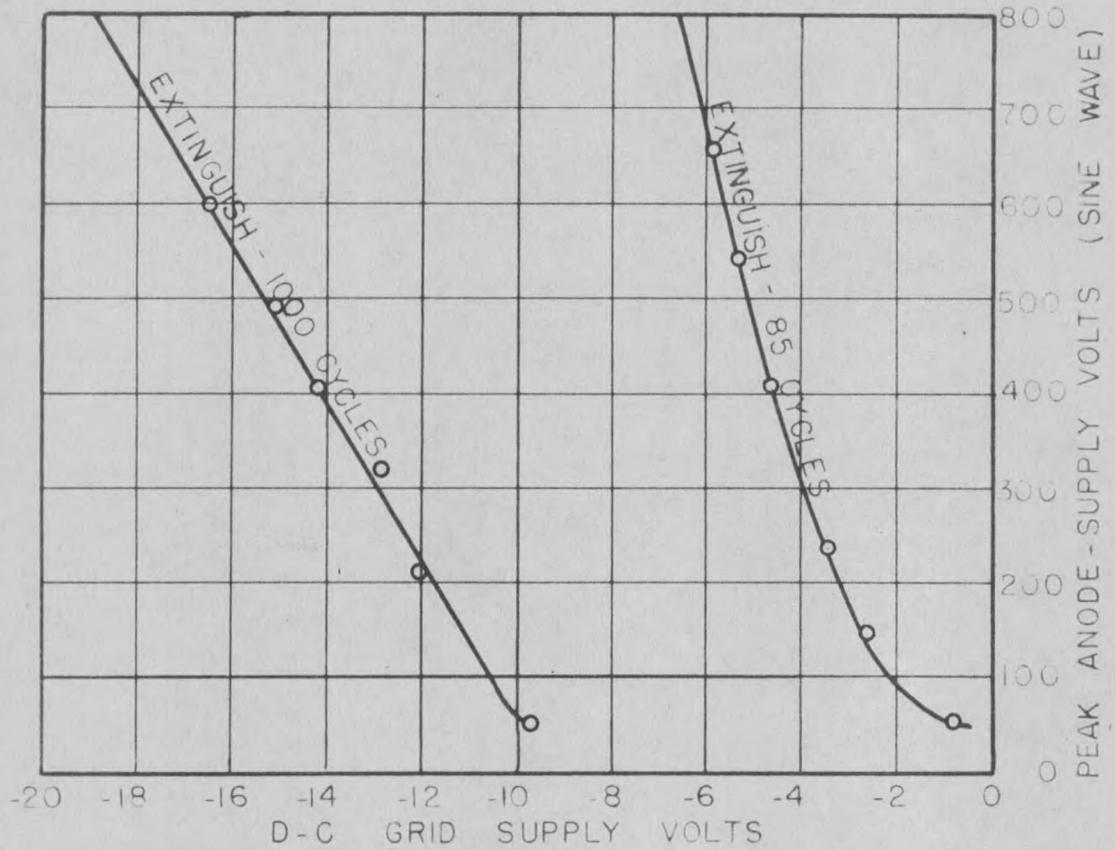
FIGURE 8. ANODE - GRID COUPLING IN THYRATRON

FIGURE 9. EXTINGUISHING CHARACTERISTIC OF TYPE
FG-57 THYRATRON
78° CONDENSED MERCURY TEMPERATURE.
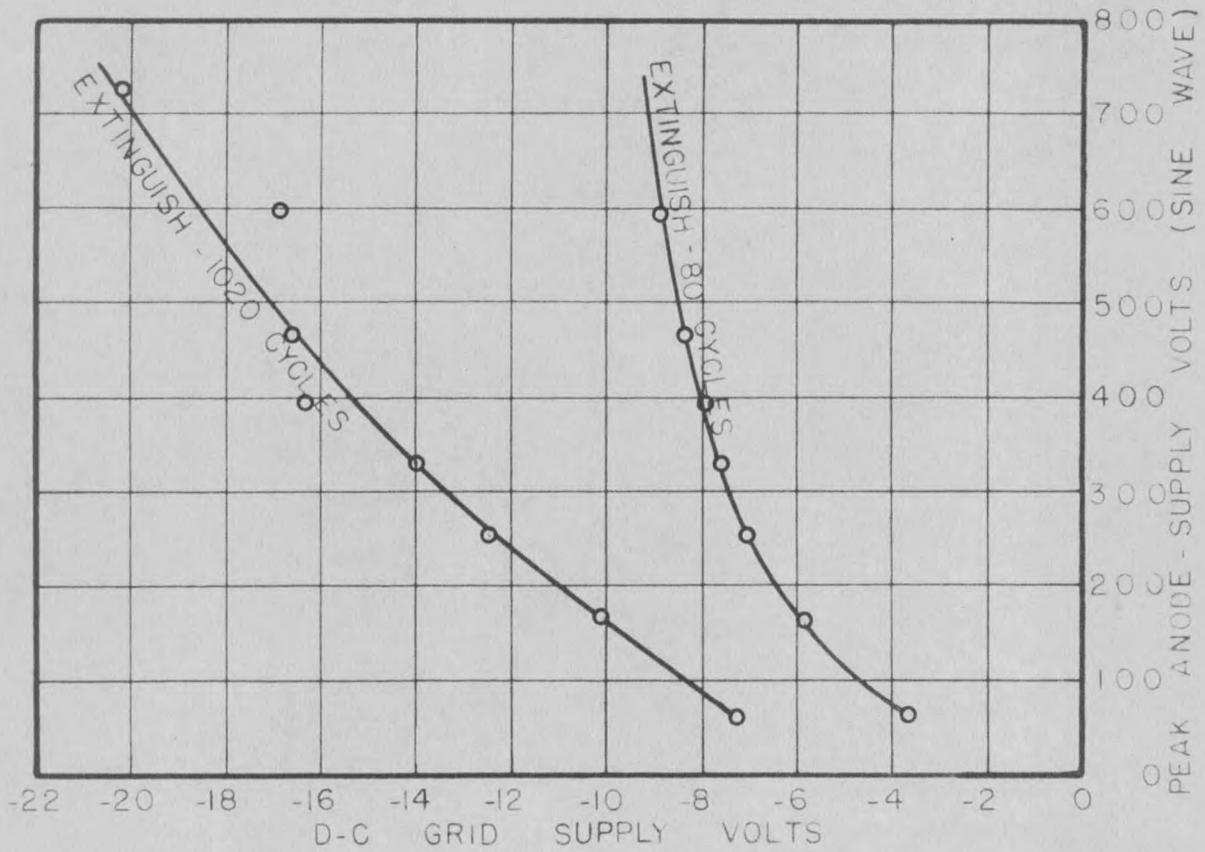0.1 AMPERE AVERAGE ANODE CURRENT.
f = 1000 CYCLES PER SECOND.

FIGURE 10. EXTINGUISHING CHARACTERISTIC OF TYPE
3C23 THYRATRON

76°C. CONDENSED MERCURY TEMPERATURE

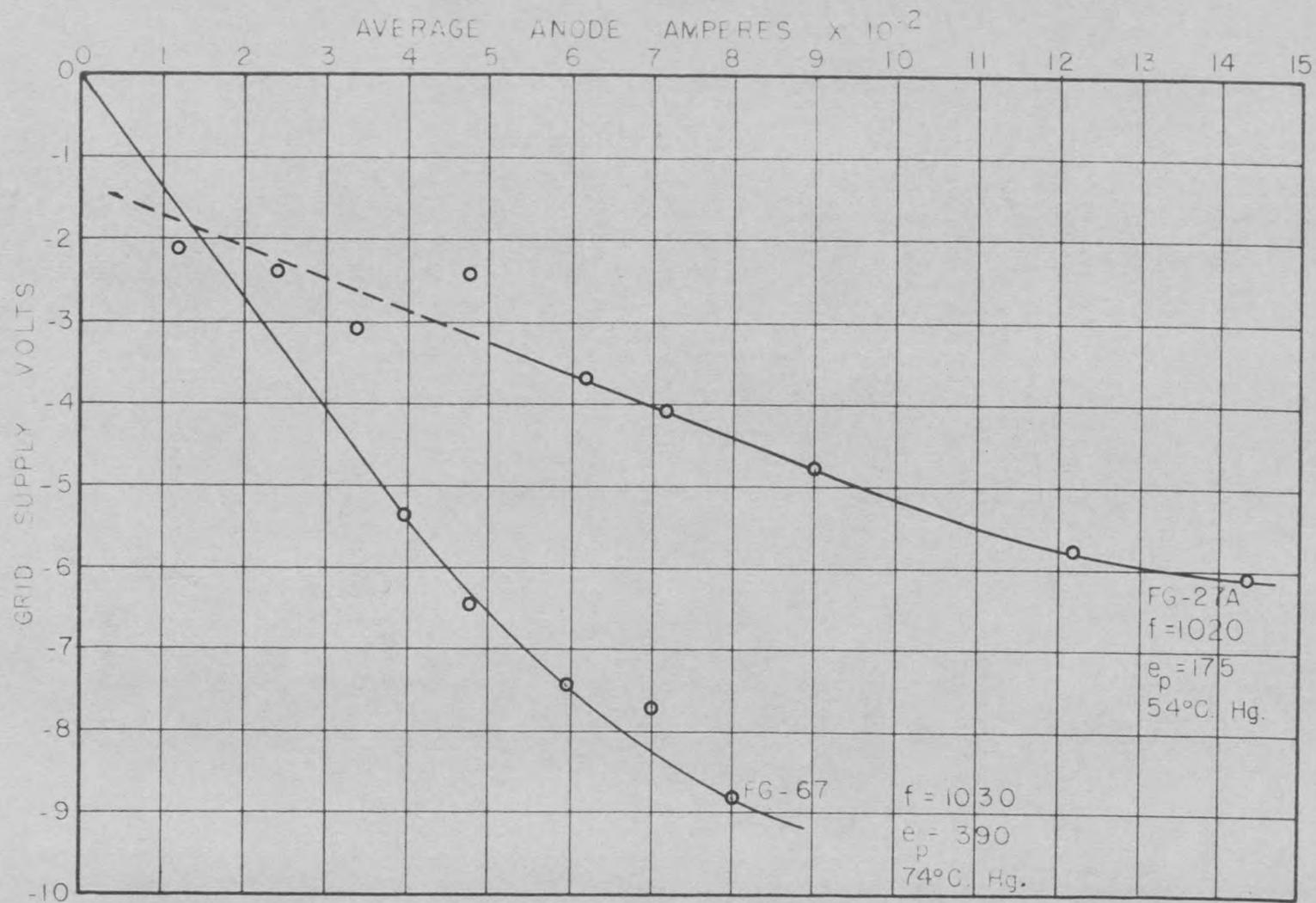0.1 AMPERES AVERAGE ANODE CURRENT

f = 1020 CYCLES PER SECOND

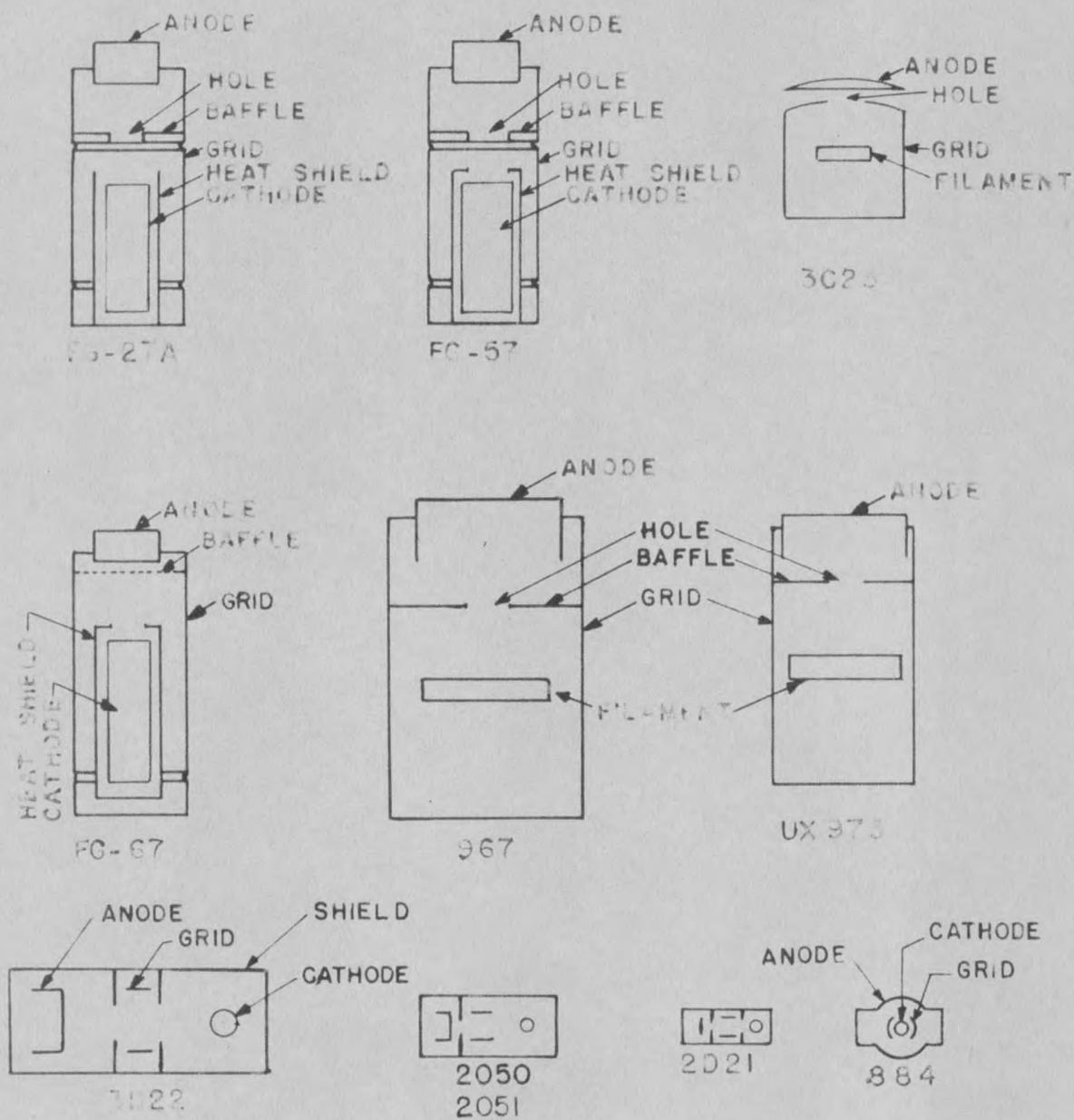FIGURE II. EXTINGUISHING GRID VOLTS VERSUS AVERAGE ANODE CURRENT

FIGURE 12. ELECTRODE CONSTRUCTION OF THYRATRONS

APPENDIX I

It can be shown [8] that in any parallel network of impedances the current $\dot{I}_A$ in any branch A of the network may be calculated by the equation

$$\dot{I}_A = \dot{I}_o \frac{\dot{Z}_B}{\dot{Z}_A + \dot{Z}_B} \tag{1}$$

where $\dot{I}_o$ = the total current to the two parallel branches A and B.

$\dot{Z}_A$ = the impedance of branch A

$\dot{Z}_B$ = the impedance of branch B

The equivalent circuit of a three electrode thyratron tube in rectifier service, tube non-conducting, grid bias voltage zero, can be represented as shown by figure 13
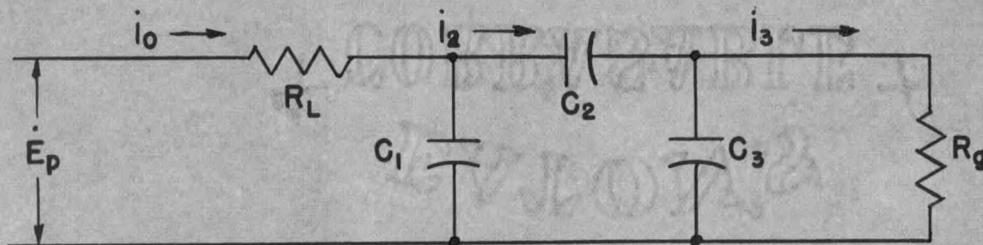

Figure 13.   Equivalent circuit of thyratron .

where R_L = load resistance

C_1 = anode-cathode capacitance

C_2 = anode-grid capacitance

C_3 = grid-cathode capacitance

E_O = rms anode supply voltage

R_g = grid resistance

Using the principles outlined in the reference cited, and assuming sinusoidal voltages and currents:

$$\dot{i}_3 = \dot{i}_2 \frac{-jX_3}{R_g - jX_3}$$

$$\dot{i}_2 = \dot{i}_0 \frac{-jX_1}{-j\left[X_1 + X_2 + \frac{R_g X_3}{R_g - jX_3}\right]} = \dot{i}_0 \frac{X_1(R_g - jX_3)}{(X_1 + X_2 + X_3)R_g - jX_3(X_1 + X_2)}$$

$$\dot{i}_0 = \dot{E}_p \frac{1}{R_L - \frac{jX_1\left[-jX_2 - \frac{jX_3 R_g}{R_g - jX_3}\right]}{-j\left[X_1 + X_2 + \frac{R_g X_3}{R_g - jX_3}\right]}}$$

$$= \dot{E}_p \frac{R_g(X_1 + X_2 + X_3) - jX_3(X_1 + X_2)}{R_L R_g(X_1 + X_2 + X_3) - X_1 X_2 X_3 - j[R_L X_3(X_1 + X_2) + R_g X_1(X_2 + X_3)]}$$

$$\dot{i}_2 = \dot{E}_p \frac{X_1(R_g - jX_3)}{R_L R_g(X_1 + X_2 + X_3) - X_1 X_2 X_3 - j[R_L X_3(X_1 + X_2) + R_g X_1(X_2 + X_3)]}$$

$$\dot{i}_3 = \dot{E}_p \frac{-jX_1 X_3}{R_L R_g(X_1 + X_2 + X_3) - X_1 X_2 X_3 - j[R_L X_3(X_1 + X_2) + R_g X_1(X_2 + X_3)]} \tag{2}$$

The voltage drop over the grid resistance is

$$\dot{E}_g = \dot{i}_3 R_g = \frac{-j\dot{E}_p R_g X_1 X_3}{R_L R_g(X_1 + X_2 + X_3) - X_1 X_2 X_3 - j[R_L X_3(X_1 + X_2) + R_g X_1(X_2 + X_3)]} \tag{3}$$

The grid resistance R_g is in parallel with the capacitance C_1, the grid-cathode capacitance, and the potential drop will be the same over each of these elements. Replacing the rms voltages by the instantaneous voltages in equation 3 results in the following equation for the instantaneous voltage induced into the grid circuit of the thyratron by interelectrode capacitances

$$e_g = \frac{-je_p R_g X_1 X_3}{R_L R_g (X_1 + X_2 + X_3) - X_1 X_2 X_3 - j[R_L X_3 (X_1 + X_2) + R_g X_1 (X_2 + X_3)]} \tag{4}$$

Since the interelectrode capacitances are very small, generally only a few micro-microfarads, their reactances will be very large and so equation 4 may be approximated with very little error by

$$e_g = j \frac{e_p R_g}{X_2} \tag{5}$$

APPENDIX II

According to Gay-Lussac's law for perfect gases at constant volume

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

where P_1 = pressure at temperature T_1

P_2 = pressure at temperature T_2

and T_1, T_2 are in absolute degrees.

Assuming that the mercury vapor in a thyratron tube will obey the perfect gas law, then the per cent increase in pressure (since volume is constant) as the condensed mercury temperature is increased from 53° C. to 78° C. (or 326° A. to 351° A) will be

$$\frac{351 - 326}{326} \times 100 = \frac{2500}{326} = 7.97\%$$

APPENDIX III

The starting of parallel inverters designed to oper-
ate self-excited in the audio-frequency range is often
rather difficult. Simply closing the d-c supply voltage
switch does not as a general rule provide a transient
grid voltage of sufficient magnitude and duration to ini-
tiate inverter action. To assure easy and certain starting
of the inverter used in this study the circuit shown below
was invented on August 17, 1948, built up and tested by
March 2, 1949 and operated satisfactorily throughout the
experimental work conducted thereafter.

The operation of the starting circuit is as follows:
the positive terminal of the d-c grid bias supply voltage
is connected to the cathodes of the inverter tubes through
a normally closed contact of the "Start" push button. The
potentiometer tap is connected to the center tap of the
secondary winding of the grid transformer and provides a
means of varying the d-c grid bias voltage of the inverter
tubes. Pressing the "Start" push button then does the
following:

1.) Disconnects the positive terminal of the d-c grid
bias supply voltage from the cathodes of the
inverter tubes.

2.) Connects the negative terminal of the d-c grid bias

supply voltage to the cathodes of the inverter tubes.

3.) Connects the series arrangement of starting resistance and starting inductance to the d-c bias supply voltage.

4.) Connects the junction of starting resistance and starting inductance to the grid of inverter tube T2.

As a result of step 3 above a d-c transient is produced in the "starting" circuit, the duration of which is determined by the relative values of R_s and L_s. This transient, through the connection described in step 4 above applies a high positive pulse of voltage to the grid of inverter tube T2 and so initiates operation of the inverter.

Releasing the "Start" push-button causes the "starting" circuit to be disconnected from the inverter and reconnects the potentiometer for usual negative grid bias variation.
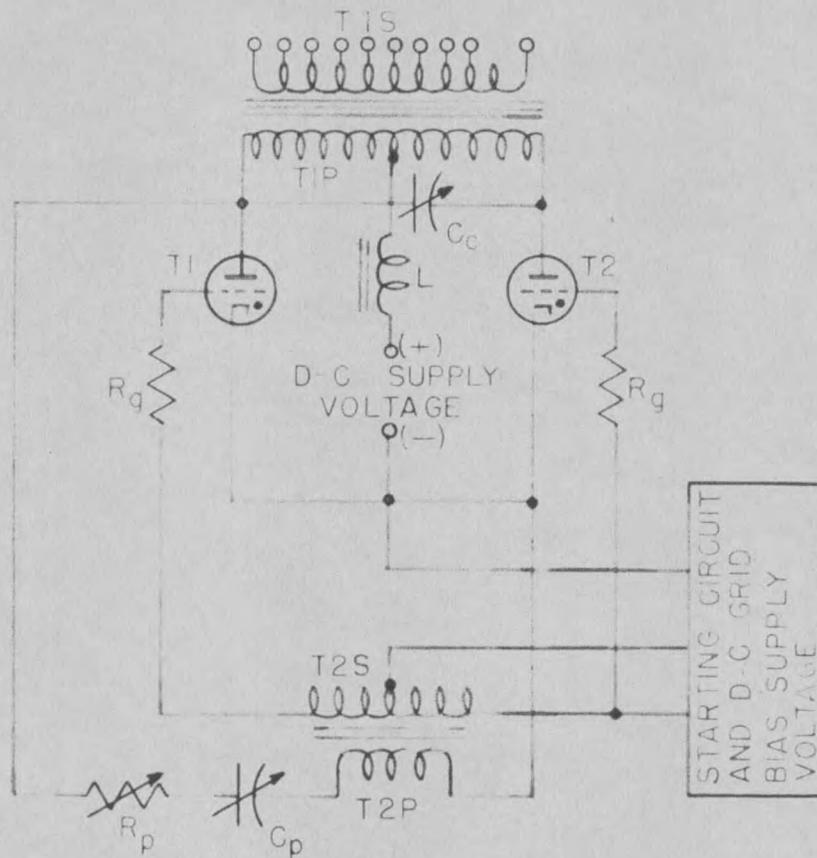
T1, T2 = INVERTER TUBES (FG - 67)
R_g = GRID RESISTOR (2000 OHM)
L = D-C CHOKE (0.2 HENRY)
C_c = COMMUTATING CAPACITANCE (0.1 - 5 mfd.)
R_p = GRID PHASE-SHIFT RESISTANCE (0 - 200 OHMS)
C_p = GRID PHASE-SHIFT CAPACITANCE (0.02 - 3 mfd.)
T1P, T1S = INVERTER TRANSFORMER
T2P, T2S = GRID TRANSFORMER
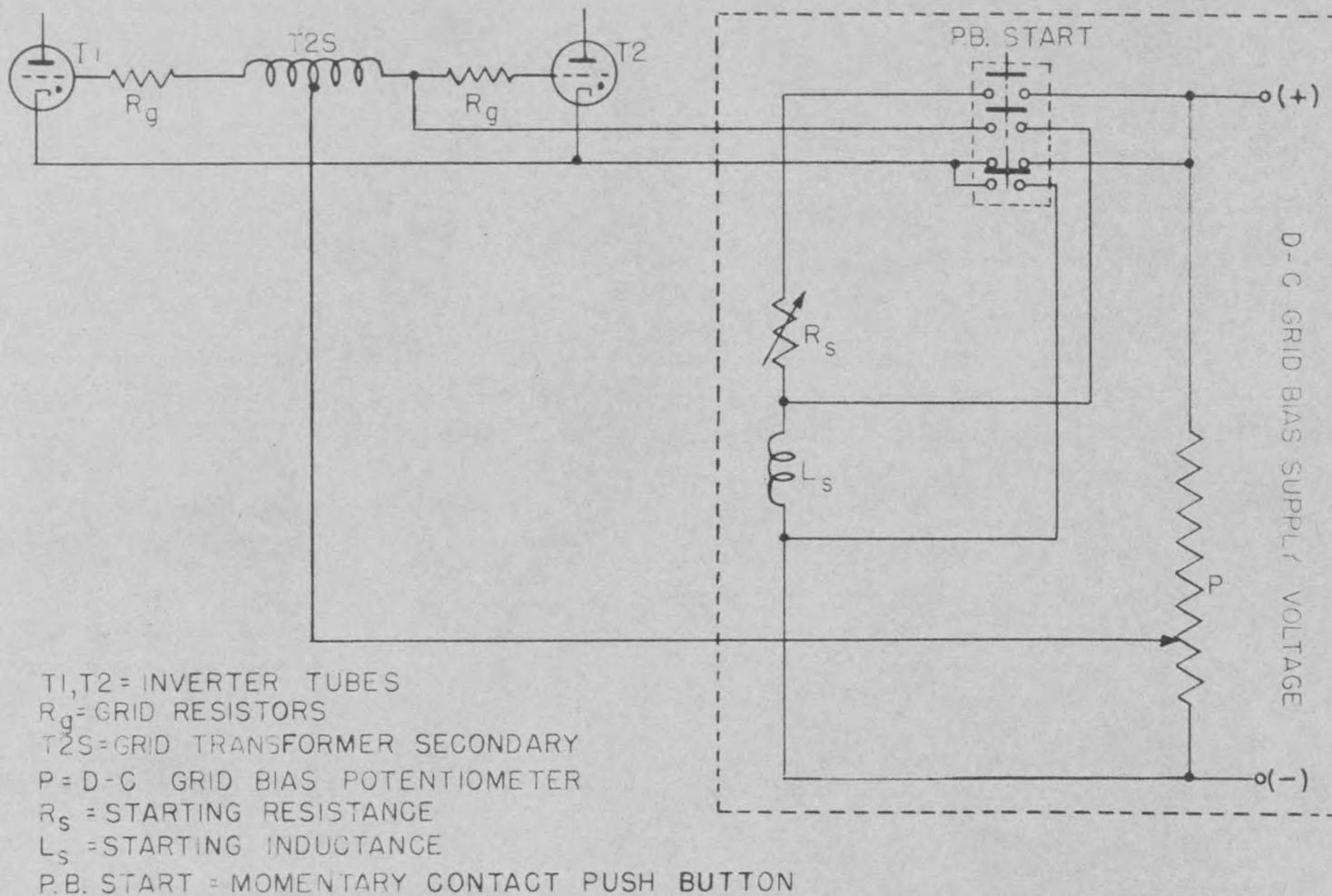
FIGURE 14   SELF-EXCITED   PARALLEL   INVERTER.

TI,T2 = INVERTER TUBES
R_g = GRID RESISTORS
T2S = GRID TRANSFORMER SECONDARY
P = D-C GRID BIAS POTENTIOMETER
R_s = STARTING RESISTANCE
L_s = STARTING INDUCTANCE
P.B. START = MOMENTARY CONTACT PUSH BUTTON

FIGURE 15 INVERTER STARTING CIRCUIT

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