RICE UNIVERSITY

FLUCTUATIONS OF AN ELECTRIC ARC IN A PLASMA GENERATOR

by

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ABSTRACT

Argon gas was expanded in a supersonic nozzle after being partially ionized by a high-energy electric arc. The frequency of arc voltage oscillation was found to be inversely proportional to the power input to the arc. This was probably due to the motion of the arc with the vortex flow in the arc chamber. When a parallel resonant circuit was inserted in series with the arc, significant oscillation occurred over a range of frequencies from 15 KC to 30 KC. The energy exchanged between the coil and capacitor of the parallel resonant circuit was calculated. Due to the small magnitudes of the oscillation energy and the relatively low frequencies, it was concluded that the magnetic induction of the coils used could not produce any detectable exitation of the gas.

ACKNOWLEDGEMENT

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INTRODUCTION

As a partially ionized gas expands at high velocity in the diverging section of a supersonic nozzle, recombination of ions and electrons occurs in the rapidly cooling gas at a rate predicted by equilibrium considerations. This recombination is a three-body process in which an ion and electron collide in the vicinity of a third body, for instance a neutral atom. K. N. C. Bray (1)* states that if the relaxation time of the gas, which is temperature dependent, is on the order of the time required for the flow to move through the nozzle, then frozen flow will occur. Frozen flow is the term given to flow with constant degree of ionization and is due to the decreased mobility of the gas particles in the rapidly cooling supersonic expansion. The flow downstream of the point where freezing occurs will remain frozen in the absence of any external heat addition to the frozen flow. An addition of energy in the divergent section of a supersonic nozzle by an external source would result in a reduction of the rate of temperature drop of the expanding gas. Under proper flow conditions, recombination could be adjusted and frozen flow avoided by this means. Conditions close to thermal equilibrium could then

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* Numbers in parenthesis indicate references listed at the end of the thesis.

be created in the expansion process. This would be desireable where the plasma jet is used to supply a high stagnation temperature flow for aerodynamic and heat transfer studies.

R. Weiss (2) states that the high-energy electric arc used to heat a gas to the plasma state has been found to extinguish and reignite with a frequency in the kilocycle range. In a configuration where the plasma flows through a ring electrode (see Figure 2), the electric arc is carried along with the flow until its length becomes so great that the voltage available is insufficient to sustain it. The arc then breaks, reignites at the ring electrode, and the process is repeated.

The purpose of this investigation was to determine the frequency of oscillations of the electric arc voltage for a particular gas and electrode configuration and to determine the possibility of utilizing these oscillations to produce a high-frequency self-induced electromagnetic field in the supersonic stream, thereby making possible the reduction of the cooling rate of the gas.

SYMBOLS

a	radial distance from the longitudinal axis of an induction coil to the center of the windings (see Equation 1), inches
b	longitudinal thickness of an induction coil (see Equation 1), inches
c	radial depth of the windings in an induction coil (see Equation 1), inches
C	capacitance, farads
E	voltage, volts
e	instantaneous value of a-c voltage, volts
I	current, amperes
i	instantaneous value of a-c current, amperes
L	self-inductance, henrys
n	number of turns in an induction coil (see Equation 1)
W_C	total energy stored in electrostatic field of a capacitor charged to a voltage E, watt-seconds
W_L	total energy stored in magnetic field of an inductor carrying a current I, watt-seconds

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Experiments were performed using a d-c arc heated plasma flow. A general schematic of the apparatus is shown in Figure 1. The power was furnished by a 540 KW d-c generator. The generator had a 7000 pound flywheel which maintained constant speed under load. The arc was initiated by a Miller high-frequency welding starter which initially ionized the gas in the arc chamber. Stagnation pressures used were on the order of 0.75 atmospheres while the pressure downstream of the nozzle was maintained at approximately 10^{-4} atmospheres (0.1 mm Hg). This low pressure was maintained by the use of a 1000 cubic foot vacuum tank. The plasma generation chamber was contained in a test stand which provided a system closed to the atmosphere when the stand was raised against the fixed piping to the vacuum tank. A pneumatically operated globe valve separated the vacuum tank from the test section of the system and was opened only after this section had been evacuated.

The arc chamber is shown in Figure 2. The upper and lower electrodes consisted of thoriated tungsten cylinders inserted into copper discs. The upper tungsten electrode (cathode) served as the converging section of the supersonic nozzle with an included angle of 12.1° and a 0.500 inch diameter cylindrical throat. The diverging section of the nozzle was formed by a heat resistant pyrex glass ring having the shape of a truncated cone with an included angle of 60°. A non-conducting material was used so as to give minimum distortion to the magnetic field of the coils described below. After approximately 30 tests, the section of the glass nozzle near the throat became severely eroded and the glass was replaced. The length of the converging section was 0.9 inches and that of the diverging section was 0.8 inches. The tungsten insert in the lower electrode (anode) contained a small longitudinal hole through which stagnation pressure was determined. A teflon insulator ring separated the upper and lower electrodes. The electrode gap was approximately 0.11 inches.

The tests were conducted using a mass flow rate of 4 grams per second of argon gas. Arc voltages between 60 and 80 volts were used, resulting in arc currents between 400 and 2000 amperes.

The working gas was injected into the arc chamber through a 0.073 inch diameter orifice. The pressure upstream of the orifice was always sufficient to maintain choked flow at the entrance to the arc chamber. The orifice was calibrated to determine the mass flow rate as a function of the upstream supply pressure using a flow meter. Room temperature was maintained at 75° F. The orifice was mounted in the teflon ring of the arc chamber and situated so that the gas was injected tangentially into the chamber. This created a vortex in the chamber which prevented severe damage to the lower electrode by moving the arc rapidly over the face of the electrode.

Due to the extreme temperatures involved, test durations were limited to approximately 0.30 seconds. The copper rings acted as heat sinks but when tests longer than 0.50 seconds were used, melting and evaporation of the lower electrode began, resulting in a flow of tungsten vapor in the working gas and coating of tungsten from the lower electrode onto the upper electrode. However, steady flow was reached in less than 0.1 seconds so the 0.3 second test duration was sufficient.

A parallel resonant (tank) circuit was connected in series with the d-c generator and the arc (Figure 3). Three coils were used with windings of 2, 8, and 32 turns. The value of the self-inductance of each coil was calculated by the following expression (3)

$$L = \frac{0.8\, a^2 n^2}{6a + 9b + 10c} \times 10^{-6}. \qquad (1)$$

For each series of tests, a coil was located concentric with the glass nozzle. In order to vary the resonant frequency of the tank circuit, 4 μfd capacitors were connected in parallel with the coil, the number of capacitors determining the resonant frequency of the tank. By interchanging the coils and varying the number of capacitors, the resonant frequency could be varied from 2.3 KC to 83 KC. An oscilloscope was connected to the tank circuit to indicate voltage across the coil and capacitor as a function of time.

The external triggering circuit for the oscilloscope is shown in Figure 4. When the arc was initiated, an 110 volt a-c signal was switched to the a-c relay solenoid in the triggering circuit. The closing of Circuit A by the a-c relay activated the solenoid of the d-c relay after a delay due to the time required to charge the 2000 μfd capacitor, thus opening Circuit B. The external trigger terminals on the oscilloscope were connected across the 50K ohm resistor and the oscilloscope was adjusted to trigger on the negative voltage slope when Circuit B was opened. Triggering of the oscilloscope produced a single sweep on the cathode ray tube screen. The two relays and the capacitor were used to insure a sufficient time delay after the arc fired before triggering occurred. This eliminated the possibility of any excitation of the parallel resonant circuit by the high frequency starter appearing on the oscilloscope screen and assured steady flow conditions at the time triggering occurred. Due to instabilities in the system, the oscilloscope trigger delay varied between 0.25 seconds and 0.29 seconds after the arc fired. The time delay of the oscilloscope trigger was recorded by the deflection of a galvanometer in the oscillograph described below. Horizontal sweeps of between 1 millisecond and 50 microseconds per cm were used on the oscilloscope.

Quantities recorded during each test were arc current, arc voltage, supply pressure, and stagnation pressure. They were automatically recorded on a Minneapolis-Honeywell oscillograph using light sensitive paper and reflecting galvanometers. The arc current was measured from the voltage output of a calibrated shunt. The arc voltage was measured between the electrodes. The supply pressure was measured using a Bourns differential pressure transducer located upstream of the orifice at the inlet of the arc chamber. A Statham strain gage pressure transducer was used to measure stagnation pressure and was connected to the space under the lower electrode by a flexible nylon tube.

The following procedure was used in carrying out the tests. After all components of the arc chamber, nozzle, and tank circuit were assembled, the test stand was raised against the fixed vacuum tank piping by a pneumatic lift.

A vacuum pump was used to evacuate the test section. The generator was started and the output voltage adjusted to the desired value. The working gas supply was adjusted to the proper pressure. The oscillograph and all transducers were excited. The delay timer and the test duration timer were each set for 0.3 seconds. The valve to the vacuum tank was opened and a zero reading was taken on all galvanometer traces. The shutter was opened on the Polaroid oscilloscope camera and the test sequence was initiated by a push button. During the 0.3 second delay time, the working gas began to flow through the arc chamber, the oscillograph began recording, and the full output voltage of the generator was applied across the electrodes. At the end of the delay time, the high frequency starter switched on and the gas in the chamber was ionized by the high frequency voltage superimposed on the generator output voltage. When the arc current began to flow, a current relay switched off the high frequency starter and activated the test duration timer. The current relay also activated the relay which supplied 110 volts a-c to the oscilloscope triggering circuit described above. At the end of the predetermined test duration, the timer interrupted the arc current circuit, stopped the oscillograph, closed the working gas supply line, and closed the valve to the vacuum tank. The shutter on the Polaroid camera was then closed and the picture was developed.

TEST RESULTS

An investigation of the output characteristics of the 540 KW generator was made. An electric heater was connected to the output lugs of the generator and load tests run at several generator output voltages. Oscilloscope pictures of the voltage waveform showed a 4 KC, 0.8 volt fluctuation for an output voltage of 150 volts. The heater was then connected to the voltage leads which normally furnished power to the arc chamber. The high frequency starter was then in the line between the generator and the heater. Tests made with the high frequency starter off and the generator output at 100 volts showed a 0.5 volt fluctuation at 4 KC. With the high frequency starter on and the generator output at 110 volts, the voltage supplied to the heater consisted of a 3.4 volt 60 cps signal and a 6 KC signal from the starter superimposed on the 100 volt generator output. A spark gap oscillator was used as the high frequency starter and the 60 cycle and 6 KC signals were from the output of the oscillator.

A series of tests were performed on the plasma jet without the parallel resonant circuit in the line. Since the maximum frequency response of the arc voltage galvanometer in the oscillograph was 1 KC, the oscilloscope was connected in parallel with the galvanometer to detect voltage fluctuations of higher frequencies. Tests were run at several values of power input and the frequency of arc voltage variation was determined from the oscilloscope pictures. Two representative pictures are shown in Figure 5. The results of these tests are given in Table I and are plotted in Figure 6. At the lower values of input power, small oscillations of lower frequency than the principal oscillation frequency were evident while at the higher power inputs these small oscillations were of higher frequency than the principal oscillation frequency. The voltage waveforms of the oscilloscope pictures were slightly irregular, making frequency analysis somewhat difficult.

A series of tests was run using the parallel resonant circuit shown in Figure 3. The oscilloscope was connected in parallel with the resonant circuit to record voltage fluctuations in the circuit. Again the voltage waveforms on the pictures were slightly irregular. Three representative pictures are shown in Figure 7. The largest voltage variation over the test range was approximately 5 volts. The data is tabulated in Table II and plotted in Figure 8. The method of calculation of the values plotted is described below.

DISCUSSION

Figure 6 and Table I show that the frequency of arc voltage oscillation is inversely proportional to the power input to the arc. This may be explained in the following manner: The pressure in the arc chamber (stagnation pressure) is a function of the power input to the arc, increasing with increasing power for a constant mass flow rate. Since the flow at the exit of the gas supply orifice in the arc chamber was at sonic velocity, the pressure in the exit plane of the orifice was approximately 30 psia. The pressure in the arc chamber near the orifice was approximately 18 psia. The resulting gas flow into the chamber was in the form of an under expanded jet (4), with the velocity of the flow in the arc chamber being greater for lower stagnation pressures. It was determined that the arc did not move continuously over the face of the lower electrode but rather moved in a jumping manner. This was evidenced by small burned spots on the face of the lower electrode which were visible upon disassembly of the apparatus after a test. If the vortex were not present, the arc would tend to remain in the same spot (5). Since an arc is sensitive to the movement of the surrounding gas (6), the vortex in the chamber causes the arc to elongate in the direction of the flow. This elongation of the arc results in an increase in the arc voltage due to the arc voltage gradient described by Suits (7). After the arc has reached a certain length due to the distending action of the vortex, the anode spot of the arc jumps to a new location, resulting in a shorter arc length and a lower voltage. This process is repeated as the arc moves around the chamber. Since the magnitude of the voltage variations was approximately independent of the power input and stagnation pressure, the length of the arc before a jump occurs must also be independent of the power and pressure while the frequency of the oscillations depends on the vortex velocity in the chamber.

Consideration was given to the possibility that the voltage variations might have been caused by the change in the electrical resistance of the anode due to the resistance heating of the electrode material. Since tungsten has a positive temperature coefficient of resistivity, the resistance of the electrodes would increase as they were heated by the arc current. It was thought that when the voltage drop in the anode material increased sufficiently due to the change in resistance, the arc would jump to a cooler spot on the anode and the process would be repeated. Using resistance heating equations (8, 9), the time required for the resistance to change sufficiently to give the measured voltage changes was calculated. However, this method of calculation indicated that the oscillation frequency would increase rather than decrease with higher power inputs.

Cobine and Burger (10) state that the anode spot of a high current arc is above the boiling temperature of the anode material and that this temperature is attained due to the power input at the anode surface by means other than resistance heating. They estimate the power input to be on the order of 10^5 watts/cm^2. This power input is several orders of magnitude greater than that calculated by the resistance heating method mentioned above. They also show that for an arc of short duration (1/120 sec.) that the depth of penetration of heat into the electrode is small compared to the size of the anode spot. This would indicate that the effect of the resistance change due to heating of the anode by the rapidly moving arc in the plasma chamber would be small.

Carbon, with a negative coefficient of resistivity, produces a hissing arc with voltage oscillations of approximately 1 KC and 50 KC (11). The 1 KC oscillations are due to the motion of the entire anode termination of the arc over the anode surface while the 50 KC oscillations are due to the motion, within the anode termination, of small "micro-burning-spots." Since this motion was evident with electrodes of negative coefficient of resistivity, the reasoning that the voltage variation and motion of the tungsten arc were due to the increase in electrode resistance seems invalid.

The total energy stored in the electromagnetic field of an inductor carrying a current I is given by the expression (12)

$$W_L = \frac{1}{2} L I^2. \tag{2}$$

The total energy required to charge a capacitor to a voltage E is

$$W_C = \frac{1}{2} C E^2. \tag{3}$$

If a direct current flows through a parallel resonant circuit (tank circuit), the voltage across the capacitor will be equal to the resistance drop across the coil and energy will be stored in the electromagnetic field of the coil and in the electrostatic field of the capacitor. When the source of d-c current is removed from the tank, the magnetic field of the coil will begin to collapse, inducing a current in the coil. This current will charge the capacitor until all of the energy formerly contained in the magnetic field of the coil has been transferred to the capacitor. Then the reverse process will occur with the charge leaving the capacitor in the form of a current flow to the inductor until all of the energy formerly stored in the electrostatic field of the capacitor is stored in the electromagnetic field of the coil. In the absence of energy losses, the total energy of the circuit is constant

$$\frac{1}{2} L i^2 + \frac{1}{2} C e^2 = \text{constant} \tag{4}$$

where e and i are the instantaneous values of voltage and current respectively. For this case of a d-c current initially flowing through the coil, the constant of Equation (4) is approximately equal to the energy stored in the electromagnetic field of the coil. If the d-c current source is removed, the energy stored by the coil is transferred to the capacitor, and the ratio of the energy in the capacitor at maximum charge to the constant in Equation (4) would be unity.

The results of the experimental investigation with the coil and capacitors in series with the arc circuit showed small amounts of oscillation of the tank circuit from about 10 KC to 30 KC. Using the data taken from the Polaroid pictures of the oscilloscope screen and data taken from the galvanometer traces, a comparison was made of the energy stored in the magnetic field of the coil and the energy of the capacitor at its highest charge. The ratio of these two quantities is tabulated in Table II and plotted versus frequency in Figure 8. As can be seen from the plot, W_C/W_L is a very small quantity over the entire range of frequency covered. This small value of W_C/W_L indicates that the arc in this plasma jet did not extinguish and reignite as Weiss has observed. If the arc had performed in the manner Weiss stated, the ratio of W_C/W_L would have been close to unity.

Due to the relatively small amount of oscillation energy, it was not possible to detect any heating or other effects on the gas due to the magnetic field of the coil. It can be concluded, therefore, that the use of a self-induced electromagnetic field to adjust the rate of recombination in the expanding gas is not practical.

As the value of arc current fluctuates, the degree of ionization of the gas in the vicinity of the arc must fluctuate. Thus the outflow of gas from the stagnation chamber consists of "slugs" of plasma of varying degrees of ionization. An externally powered high-frequency source could be used to excite a coil establishing an oscillating magnetic field in the diverging section of the nozzle. The small voltage fluctuations of the tank circuit could be used to vary the output power of the high-frequency source so that maximum output would occur when a slug of higher degree of ionization gas was present in the diverging section.

SUMMARY

It was determined that the voltage of the electric arc in the plasma generation chamber fluctuated with a frequency in the kilocycle range. This frequency was inversely proportional to the power input to the arc and was due to the movement of the arc with the vortex flow in the chamber.

When a parallel resonant circuit was placed in series with the arc, the amount of oscillation energy in the electromagnetic field of the coil was not sufficient to produce any detectable changes in the plasma stream. Thus self-induced high-frequency heating of the expanding plasma was not possible. However, these small voltage fluctuations might be used to control the output power of an external high-frequency source which could be used to excite the gas in the same manner as it was desired to use self-induced heating.

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TABLE I

Test No.	Arc Voltage volts	Arc Current amperes	Power Input KW	Stagnation Pressure atm.	Frequency KC	Voltage Fluctuation volts
158	60.0	555	33.3	0.388	55	0.4
173	57.2	704	40.2	0.421	50	0.3
166	56.2	1430	80.3	0.628	35	0.4
167	56.8	1703	96.9	0.678	32	0.5
170	56.5	1765	99.7	0.721	30	0.5
163	68.8	1740	120.0	0.700	50	0.2
164	59.6	2080	124.0	0.735	25	0.6
171	61.5	2180	134.0	0.800	7	0.8

TABLE II

Test No.	C	Polaroid Pictures		Arc Current	W_C	W_L	W_C/W_L
					x 10^6	x 10^2	x 10^6
	μfd.	volts	KC	amperes	watt-sec.	watt-sec.	
102	52	1.0	2.86	370.2	26.0	594	4.38
105	40	1.0	3.33	357.9	20.0	554	3.61
106	36	1.5	3.50	370.2	40.5	594	6.82
107	32	1.0	4.16	382.5	16.0	632	2.53
108	28	1.0	3.50	382.5	14.0	632	2.22
109	24	1.5	4.20	431.9	27.0	805	3.35
110	20	2.0	4.24	444.2	40.0	852	4.69
111	16	1.5	4.28	444.2	18.0	852	2.11
112	12	1.0	4.28	691.0	6.0	2070	0.29
113	8	1.0	6.04	308.5	4.0	412	0.97
114	4	5.0	2.50	259.1	50.0	290	17.24
115	56	1.0	9.13	493.6	28.0	71.0	3.94
116	52	1.0	8.78	987.2	26.0	283	9.19
117	48	0.8	17.2	518.3	15.4	80.3	19.2
119	40	0.5	10.5	604.7	5.0	107	4.67
120	36	0.8	12.5	555.3	11.5	89.6	12.8
121	32	0.5	13.2	617.0	4.0	111	3.62
122	28	0.8	15.4	567.6	9.0	93.6	9.56
123	24	1.8	16.1	505.9	38.9	74.5	52.2
124	20	2.3	17.4	308.5	53.0	27.7	191.5

Test No.	C μfd.	Polaroid Pictures volts	KC	Arc Current amperes	W_C x 10^6 watt-sec.	W_L x 10^2 watt-sec.	W_C/W_L x 10^6
125	16	2.5	18.5	431.9	50.0	54.2	92.3
126	16	2.5	21.0	370.2	50.0	39.9	125.3
127	12	2.2	23.0	431.9	29.1	54.2	53.7
128	8	2.8	22.2	370.2	31.4	39.9	78.7
129	4	3.0	33.4	431.9	18.0	54.2	33.2
130	56	0.5	21.8	925.5	7.0	39.2	17.9
131	52	0.4	17.5	1011.9	4.2	46.9	8.9
132	48	0.5	20.8	962.5	6.0	42.4	14.2
133	48	0.3	22.2	592.3	2.2	16.0	13.5
134	44	0.4	23.4	962.5	3.5	42.4	8.3
135	40	0.4	20.0	888.5	3.2	36.1	8.9
136	36	0.5	25.6	987.2	4.5	44.4	10.1
137	32	0.6	28.0	530.6	5.8	12.9	44.7
138	28	0.3	29.1	555.3	1.3	14.2	8.9
139	24	0.1	33.0	530.6	0.12	12.9	0.93
140	20	0.1	32.4	530.6	0.23	12.9	1.7
141	16	0.2	37.5	925.5	0.32	39.2	0.82
143	8	0.3	50.0	567.6	0.36	14.8	2.4
144	4	0.2	54.0	567.6	0.08	14.8	0.54

Test Nos. 102 - 114: 32-turn coil

Test Nos. 115 - 129: 8-turn coil

Test Nos. 130 - 144: 2-turn coil

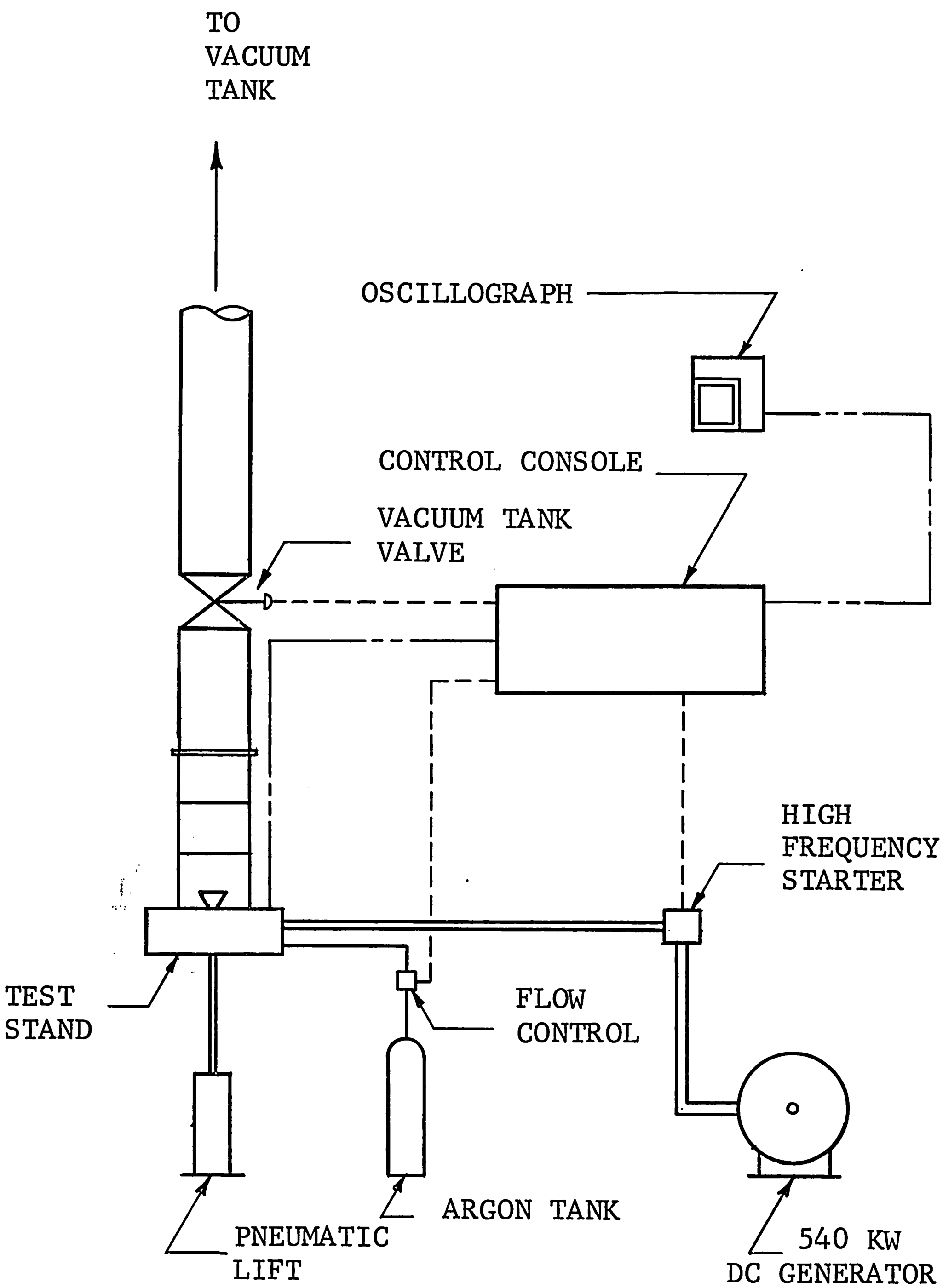


FIGURE 1
GENERAL SCHEMATIC DRAWING OF THE APPARATUS

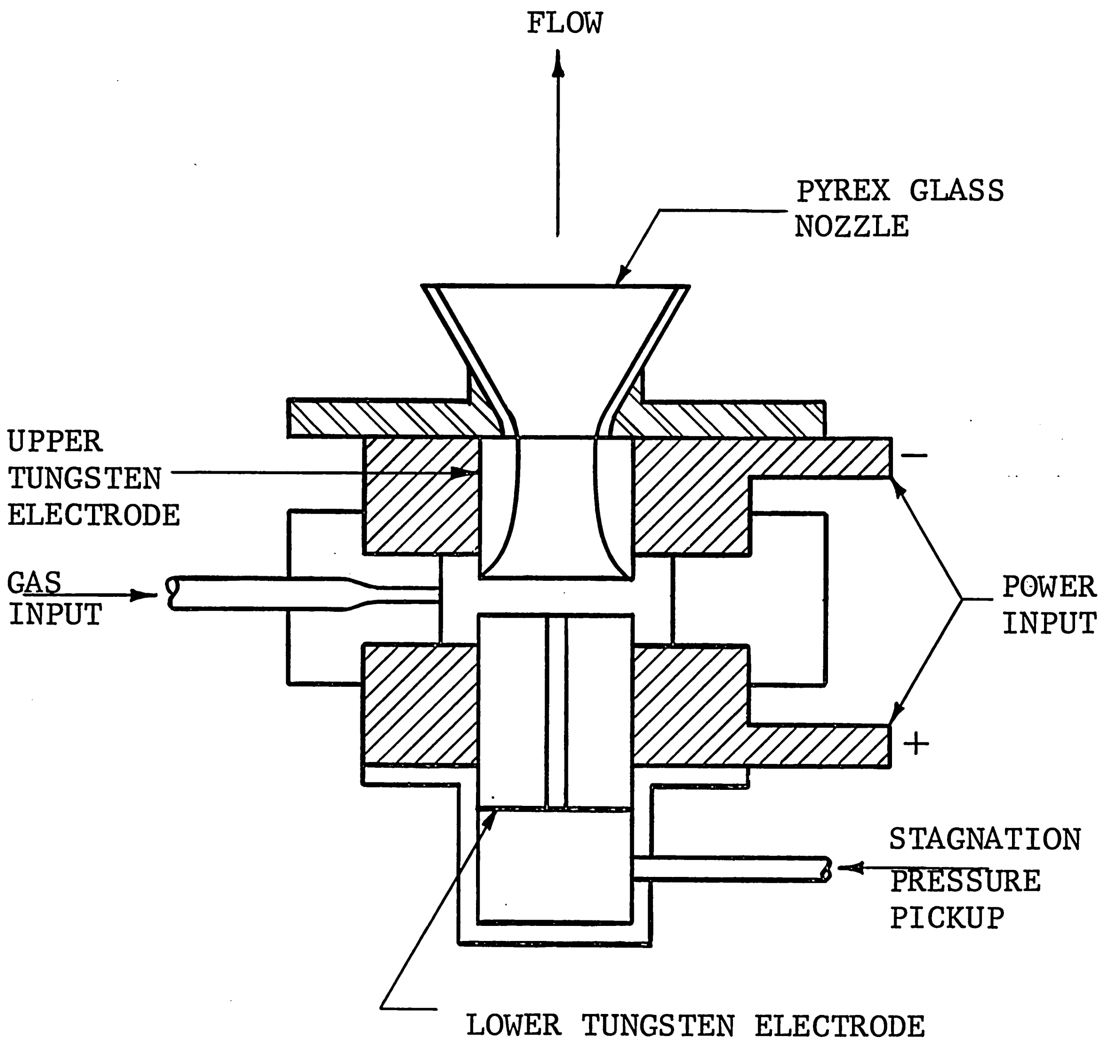


FIGURE 2
ARC CHAMBER AND NOZZLE

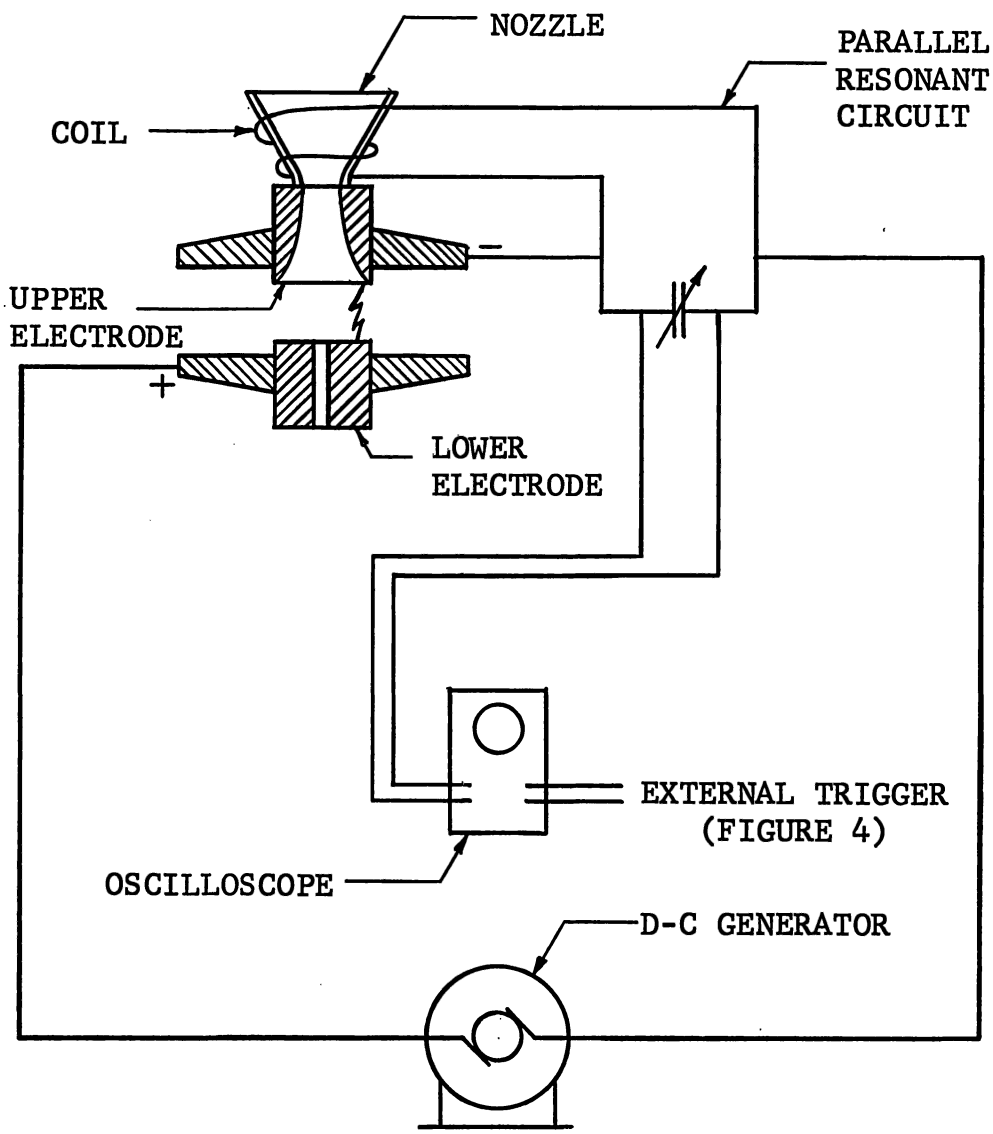


FIGURE 3
SCHEMATIC ARC CIRCUIT DIAGRAM

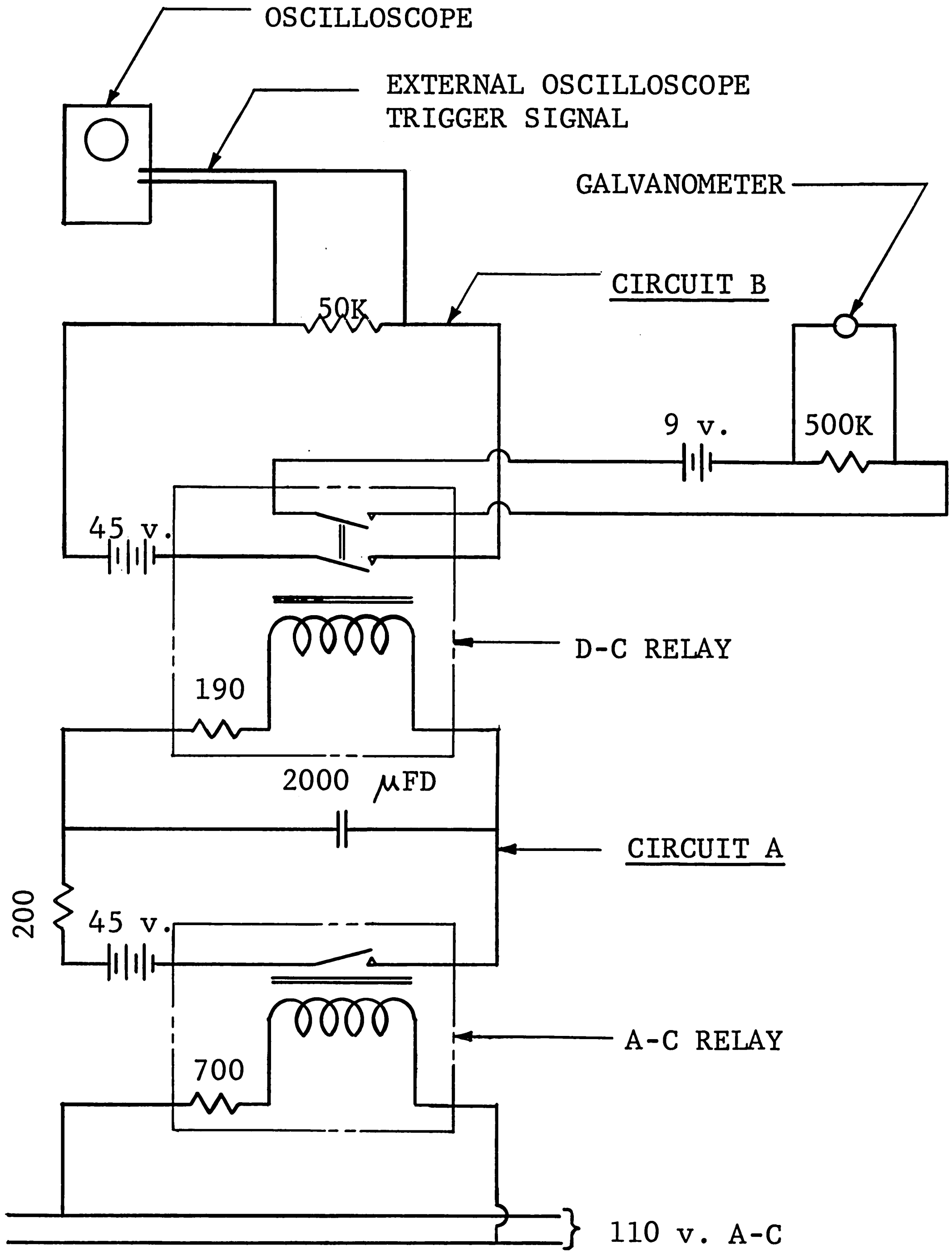
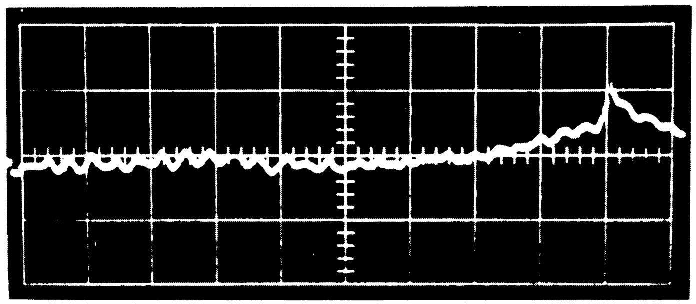
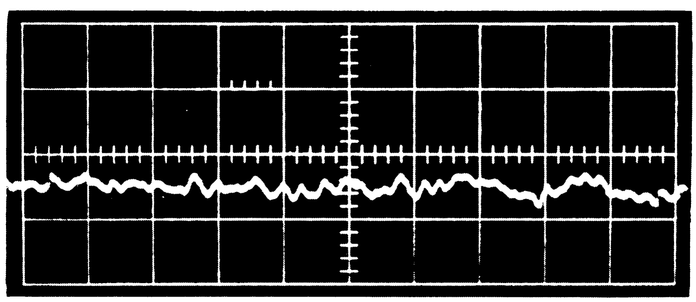


FIGURE 4
OSCILLOSCOPE TRIGGERING CIRCUIT



TEST NO. 158



TEST NO. 170

FIGURE 5
ARC VOLTAGE OSCILLATION
WITHOUT PARALLEL RESONANT CIRCUIT

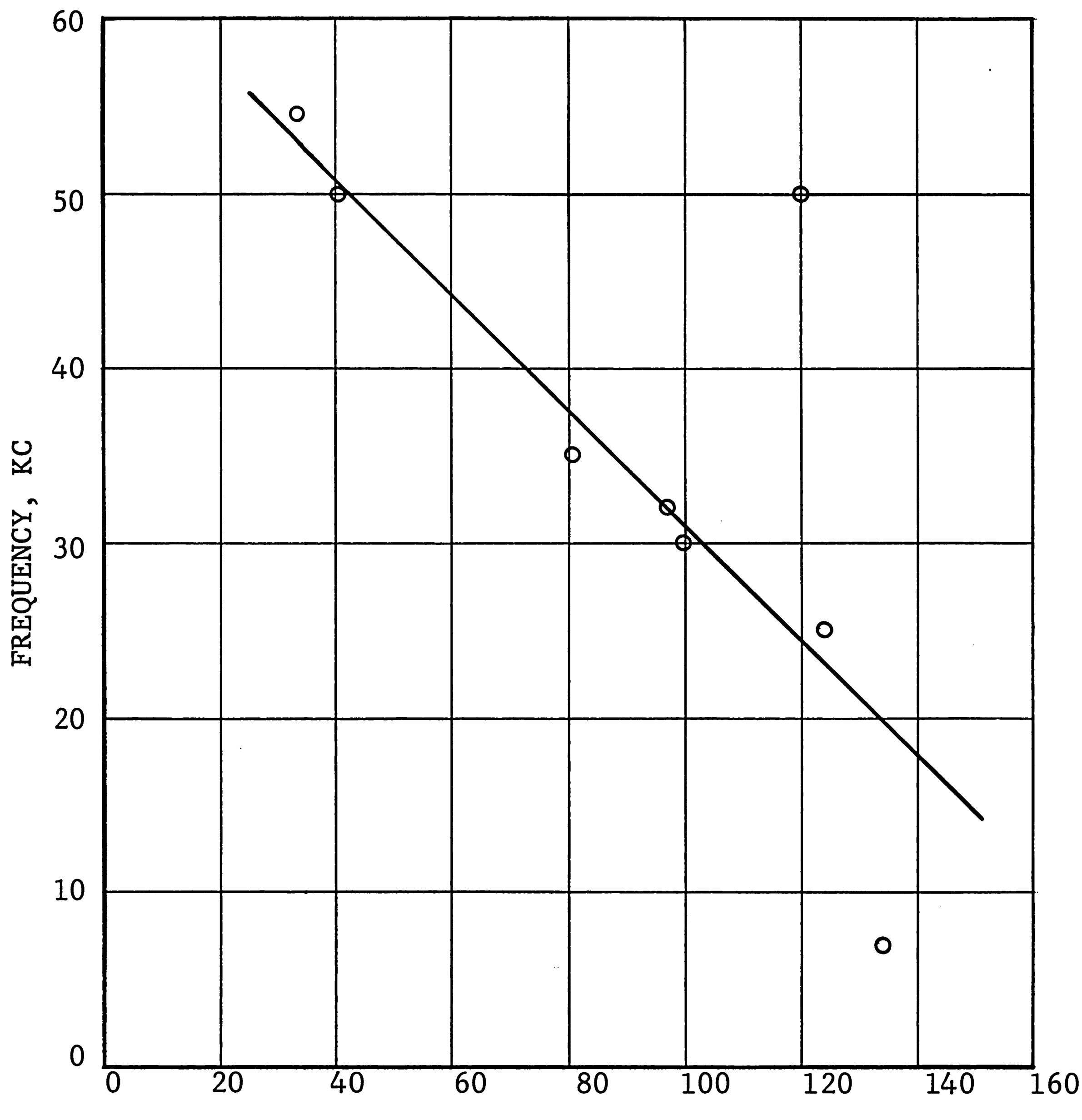
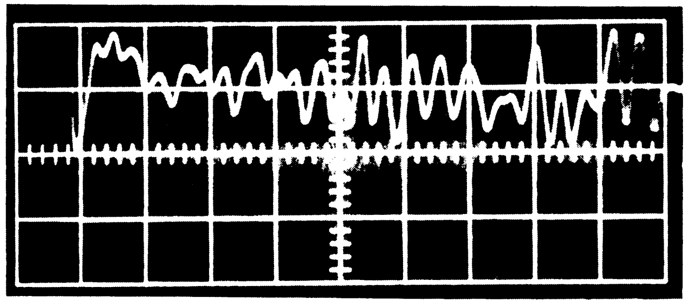


FIGURE 6
ARC VOLTAGE OSCILLATION



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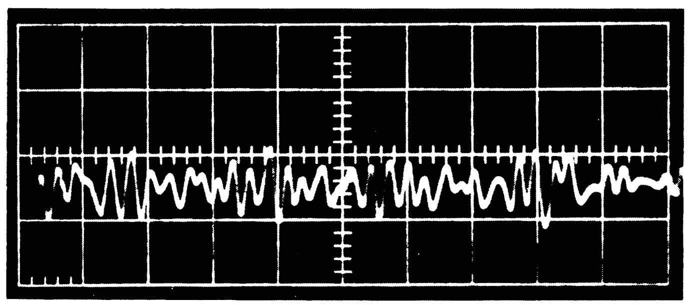

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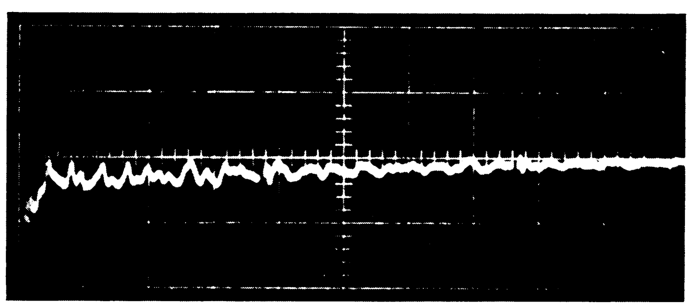

TEST NO. 144

FIGURE 7
OSCILLATION IN PARALLEL RESONANT CIRCUIT

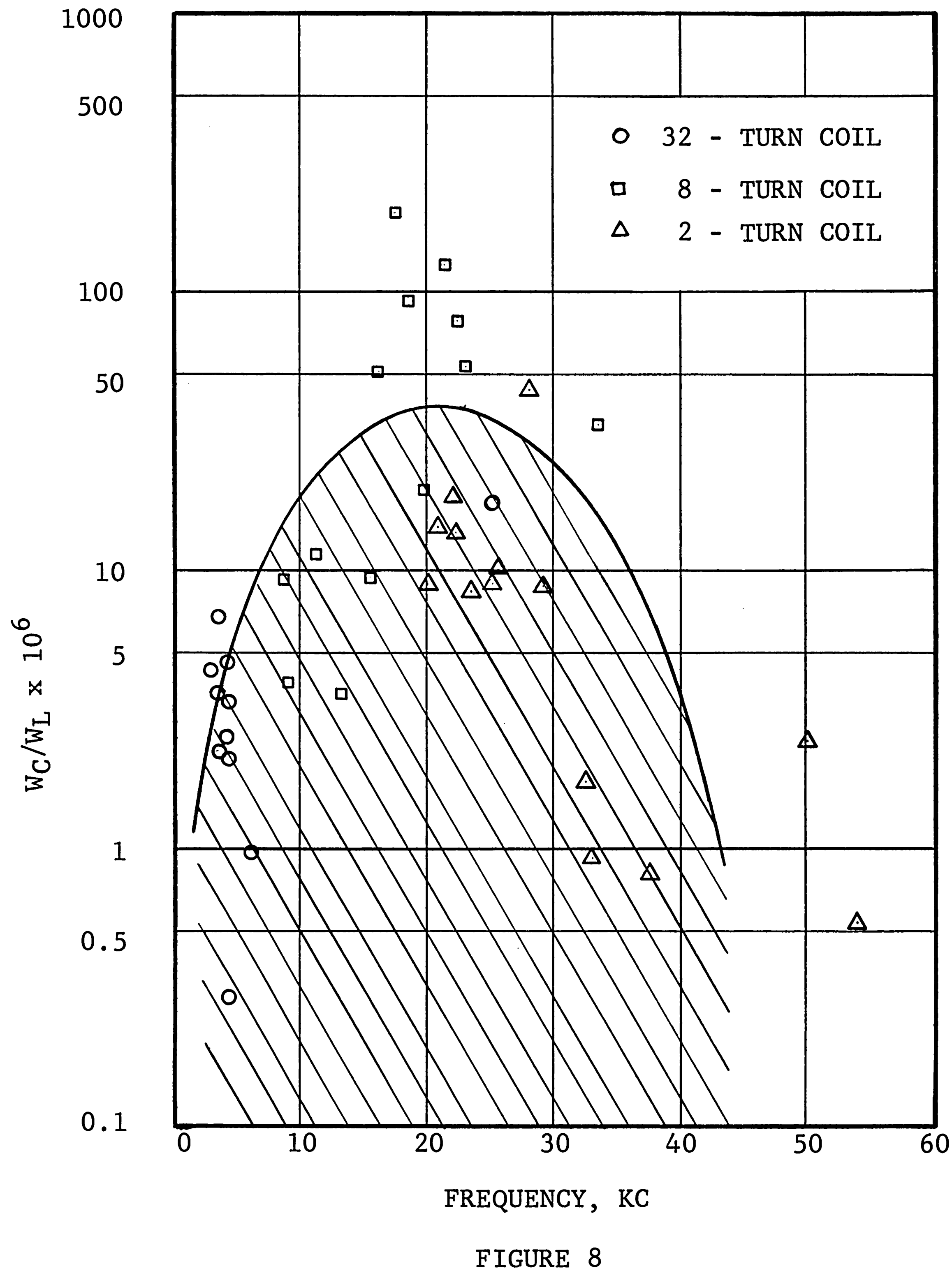

FIGURE 8
OSCILLATION IN PARALLEL RESONANT CIRCUIT