EXPLORATORY STUDY OF THE IONOPHONE

by

BRUCE LOWELL CHRISMAN and GEORGE MOORE IRWIN

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Signature of Author.......................................

Department of Physics, May 19, 1964

Signature redacted

Signature of Author.......................................

Department of Physics, May 19, 1964

Certified by..

Thesis Supervisor

Signature redacted

Accepted by...

Chairman, Departmental Committee of Theses

Abstract

An exploratory investigation of the feasibility of the Ionophone as a plasma research tool is described. A series of plots of acoustic output versus ambient pressure in helium and argon at several different acoustic and ultrasonic frequencies is presented, and suggestions are made for further work with the device.

Table of Contents

Acknowledgments

The authors wish to thank Professor K. Uno Ingard for his helpful guidance in the project. We appreciated the kind cooperation and suggestions of Dr. L. W. Dean, Dr. George Maling, Dr. Herbert Willke, and Ken Gentle. Special thanks go to undergraduates Robert Hobbs, Kirby Smith, and Roy Harris. Finally, we wish to express our gratitude to Miss Clare Smith and to the RLE staff with whom we worked.

Introduction

This report summarizes some exploratory experimental work which was done in the Research Laboratory of Electronics at the Massachusetts Institute of Technology. The object of the investigation was a sound producing device called the Ionophone, which produces acoustic waves at audio and ultrasonic frequencies through audio-modulation of a compact radio frequency corona discharge.

The ionophone was invented by S. Klein in 1951 with the intention that it should be used as a loudspeaker, particularly in the high frequency range.[1] Later the device was extended to use in acoustic and biological laboratories, where, for example, it has been used in ultrasonic radiation experiments with animals.[2] The most significant systematic study of the instrument to date was conducted at Pennsylvania State University by Fujio Oda who plotted the frequency response curves and determined the high and low acoustic frequency cutoffs for several different designs at atmospheric pressure in air.[3]

The present investigation was made preliminary to incorporating the device into another experiment, where it will be used to excite traveling acoustic waves and pulses in plasmas. Although primarily exploratory in nature, the studies were guided toward obtaining a collection of curves which would reveal the pressure dependence of ionophone efficiency at several different acoustic frequencies. It is hoped that these curves will be useful not only in the adaption of the device to other experiments but might also point the way to a more thorough understanding of the parameter dependence of the acoustic coupling mechanism across the corona-neutral gas interface.

Experimental Configuration

The work involved the design and assembly of a three part system: (1) the ionophone which generates acoustic waves in a medium density corona, (2) a connecting tube in which the acoustic wave propagates from the corona carrier to a neutral gas carrier, (3) a microphone which receives the sound from the neutral gas and displays its intensity and frequency on an oscilloscope screen and permits measurements of relative sound intensity on a voltmeter. A vacuum system was provided as well as facilities to measure pressure in the tube and to introduce sundry gases. A few remarks about each of these elements are in order.

Figure (1) is a diagram of the ionophone unit. The instrument is substantially the same as one found favorable by Fujio Oda, with three exceptions: (1) a tungsten point was substituted for Oda's platinum one; (2) a cylindrical quartz-glass heat shield was inserted between the electrodes to protect the neck of the ionophone; (3) the mouth of the ionophone was equipped with a three inch circular flange to permit a tight seal to the wave propagation tube. A steady decomposition of the tungsten point limited the lifetime of a particular ionophone unit to 15-20 hours of use despite the employment of two cooling fans. The circuitry associated with the ionophone unit was also suggested in large part by Oda's paper. The R.F.

oscillator, designed to produce between 15 and 50 watts of 27 Mc power, was fed by a 0-20 watt audio modulating signal from a precision, push-button signal generator via a 35 watt McIntosh audio amplifier. Improper impedance matching between the amplifier and R.F. oscillator prevented transfer to the oscillator of a full 35 watts of modulating power, thus holding the modulation percentage below 25 per cent for most practical R.F. power settings. This limitation was not a serious handicap, however. Figure (2) shows the circuit diagram for the oscillator. The two pairs of coupling coils between the R.F. oscillator and the ionophone electrodes were hand wound to the specifications shown in Table (1); these specifications differ somewhat from those recommended for the purpose by Fujio Oda.

The microphone was mounted at the end of the pyrex connecting tube with a vacuum seal which proved to be somewhat unsatisfactory, in that air leaked into the evacuated tube through and around the microphone connecting cable, where it entered the tube. To minimize sound reflection from the microphone mounting back toward the source, a 1/2 inch layer of acoustically dissipative glass wool was placed around the microphone head. The microphone itself was a Brüel and Kjaer type 4133 condenser microphone with an Altec P518A power supply. Figure (3) shows the circuit diagram of the microphone preamplifier, which is of the authors' design. As circumstances and the press of time forced several hurried and makeshift changes of design (the entire transistor section was added as an afterthought), the preamplifier circuit is presented to aid in interpretation of the graphs, and not as a recommended design. The circuit features high attenuation for signal frequencies below 500 cps and above 1 Mc to eliminate the effects of room vibration and R.F. pickup, respectively. The presence of R.F. noise in the microphone circuitry necessitated the solution of special shielding problems. The R.F. oscillator and the ionophone had to be enclosed in metal cages, and many cables were replaced by better shielded ones. Finally, the earthing system for the different devices was carefully combed for unwanted R.F. ground currents. This problem was successfully met only after undue belaboring.

Although unable to use it for data taking, the authors also constructed an alternate microphone utilizing a lead zirconate crystal placed within a Lucite mount. A special threaded holder allowing 3" of longitudinal microphone displacement (variable) was permanently mounted at the end of the tube to accept this microphone. This unit could have provided an important check to the results of the condenser microphone had time permitted the elimination of R.F. noise from the circuitry. Experience with the condenser microphone suggested too late that the R.F. pickup might have been eliminated by replacing the one conductor coaxially shielded cable leading to the crystal microphone by a shielded two conductor cable, allowing isolation of both leads from ground.

A mechanical pump was used to achieve low pressures in the tube. An inlet pipe was provided, and hoke valves allowed rapid increase or decrease of pressure as required for the taking of data. Although the pump tended to be a bit slow, the evacuation system proved satisfactory, notwithstanding a slow air leak of less than 1 inch of mercury per 5 minutes at the lower pressures. As a mercury manometer would have been unclean, a thermocouple gauge and a mechanical pressure gauge reading in inches of mercury were mounted on the endplate. Of these the latter was used exclusively in the data taking, since the pressures considered were out of the range of the thermocouple gauge.

Technique of Data-Taking

Several series of data, relevant to the ionophone efficiency versus pressure (for a particular frequency) curves, were taken. The following description summarizes the conditions under which most runs were conducted.

Detailed lists of relative sound intensity, as measured at the voltmeter, versus ambient pressure in inches of mercury were desired. To check reproducibility, several runs were taken at each frequency; generally, identical frequency runs were taken in pairs, and consistency within such a couple might be reinforced by agreement between pairs taken often on different days or even with different ionophones. Within a particular run pressure and corresponding sound intensity readings were taken 0.5 inches of mercury apart within an absolute ambient pressure range of 30 inches ($\sim$1 atm.) to 0.5 inches. Thus each run was comprised of some 60 closely spaced readings. In order to monitor the power dissipated in the corona, the plate current in the R.F. oscillator tube, considered to be a measure of the power output from the oscillator, was also recorded each time a reading of pressure and sound intensity was made.

It became evident during the data taking process that the sound intensity-pressure curves took on two distinctly different forms depending on whether the run of 60 readings was taken for an ascending series or for a descending series of pressures. Data taken in the direction of ascending pressures, however, was characterized by a general incoherence, instability, and non-reproducibility. As this effect seemed in large part due to the slowness with which the new gas admitted into the tube for each new reading reached temperature equilibrium with the rest of the gas in the tube, a policy of taking data only in the descending pressures direction was adopted. It is believed that data taking in the ascending direction would have been feasible had the authors been willing to wait for the new gas to reach temperature equilibrium before taking each reading. Rapid ionophone decomposition and slowly leaking air demanded that each run be completed within 15 minutes, possible only in the descending pressures direction.

Data Presentation and Discussion

Curves of relative sound intensity versus ambient pressure in helium were taken at 5 Kc intervals in the range of 10 Kc to 40 Kc. Representative curves are presented in Appendix B-1. Although each plot evidences distinctive maxima and minima as well as suggestive slope behavior, confirmation runs (of which at least three were taken per acoustic frequency) showed that between 10 Kc and 30 Kc only the positions of certain of the maxima could be reproduced. These persistent maxima are labeled on the graphs. Above 30 Kc, moreover, the positions of the maxima varied radically among a plot and its corresponding verification curves. Inspection shows that for each frequency the representative curves have one or two "resonant" pressures within the pressure range considered.

Although a less thorough catalogue of curves was obtained for argon, plots for frequencies between 10 Kc and 30 Kc and for frequencies above 40 Kc showed behavior similar to the corresponding helium curves, respectively. Indeed, at 25 Kc the positions of the argon maxima were within 0.5 inches of mercury of the respective helium maxima for the same frequency. Argon curves are found in Appendix B-2.

It is evident from the graphs in Appendix B-1 that the helium curves for frequencies below 25 Kc all have a reproducible maximum between 1.0 in. Hg. and 2.5 in. Hg.

Curves taken at 12.5 Kc and at 17.5 Kc (not shown in Appendix B-1) also showed maxima in this position. One notices that although this peak is visible in all curves from 10 Kc to 25 Kc, the relative size of the peak increases progressively from an inconsequential bump in the 10 Kc plot to a large central feature on the 20 Kc curve, whereafter it drops swiftly back to a small protrusion on the 25 Kc curve and falls out of sight before 30 Kc. One recalls that above 30 Kc, the curves cease to be reproducible. The region between 25 Kc and 30 Kc, then, is a region falling between curves with the 1.0-2.5 in. Hg. peaks on the low frequency side and disorder on the high frequency side. Moreover, the 25-30 Kc region, represented by two curves at 25 Kc and 30 Kc in Appendix B-1 shows reproducible maxima at pressures other than 1.0-2.5 in. Hg.; this is the only region where such other peaks were found. The authors suggest that the 25Kc-30Kc range of frequencies be more closely surveyed for interesting peak behavior. Although the argon curves show a like evidence of 1.0-2.5 in. Hg. peaks, reproducible maxima at other pressures are found on both the 15 Kc and the 25 Kc plots. Further study of argon is recommended.

A few remarks on the visual appearance of the corona are in order. For all audio frequencies considered, the volume of the corona ranged from $\sim 1/8$ cm^3 at atmospheric pressure to between 3 cm^3 and 5 cm^3 (2 cm to 3.5 cm in axial length) at 0.5 inches of mercury. The helium corona consistently filled a relatively uniform red-blue glowing sphere or cylinder centered about the tungsten point, whereas the argon corona often took the configuration of a curvilinear blue arc for the upper half of the pressure range and a diffuse red-blue cylinder for the lower pressures.

It is worthy of mention that the position of the curve maxima appeared largely invariant to small ($<$ 1/4in.) longitudinal displacements of the brass ionophone ring electrode. The peaks resisted mild variants from the usual corona geometry as described in the preceeding paragraph, moreover. Progressive ionophone decomposition (corrosion of the tungsten point) appeared to have little effect on the positions of the maxima, despite its marked influence on the corona geometry.

Within any particular data-taking run, the R.F. oscillator plate current would decrease more or less monotonically from $\sim$200 ma at 1 atm. to $\sim$ 100 ma at 0.5 inches of mercury. Sample plate current behavior is shown on several of the helium and argon curves. As the plate current curves are considered an indication of the power dissipation in the corona for the various pressures, it is significant that seldom is positive correlation found between the plate current behavior and the sound intensity resonances at particular pressures. One notices also that these plate current curves are consistently flatter for the argon runs than for those of helium.

Error Discussion

If an association is to be drawn between the pressure resonance curves and the coupling between the ion-neutral gas interface, it must be ascertained that the resonance were not in fact due to one or more systematic causes. Four of the more plausible trivial causes are dealt with below.

It has been noted that the only check on corona power dissipation was rather indirect one, monitoring of the plate current in the oscillator tube. Although a test showed the r.m.s. voltage drop across the primary of the ionophone transformer to be substantially constant over a wide range of pressures in the tube, it is conceivable that the phase relation between voltage and current in the ionophone could have varied widely or in such a way as to, in fact, account for the apparent pressure resonances. Thus the plate current "normalization" curves provided in Appendices B cannot be considered a strictly comprehensive indication of power behavior. An inaccessibilityof high frequency phase measuring equipment prevented the authors from confirming their assumption of the essential constancy of phase with changing pressure.

An unknown pressure dependence in the response of the Bruel and Kjaer microphone could also have been responsible for the pressure resonances. As there was not time enough to perform a satisfactory calibration study of this microphone, the authors had to be content with the factory calibration result included with the unit. Factory calibration assured an "ambient-pressure coefficient of response" of below $\pm$ 5 percent within a static pressure range of 1.3 atm. to 0.7 atm. at 400 cps. Thus results obtained with this microphone for pressures below 0.7 atm. ($\sim$21 inches of mercury) should be interpreted with due caution. The fact that the pressure resonance peak positions were frequency dependent, however, would seem to justify the authors' interpretation of these peaks as due to more than microphone behavior. Again the crystal microphone could have provided an important check of this point.

Standing wave effects in the tube could have provided a third trivial cause of the observed effect. Probable as it is that the glass wool around the microphone head was really not preventing standing wave formation at all, the ways in which standing waves might have been connected with pressure resonances should be carefully considered. That the wavelength of sound in a gas is substantially independent of gas pressure indicates that, if standing waves are to be connected with pressure resonances, such an explanation must observe this constancy of acoustic wavelength with changing pressure. It was stated above that the axial length of the corona varied from less than half a cm in length at atmospheric pressure to sometimes over 3.0 cm in length at 0.5 inches of mercury. If this change in corona length were accompanied by a simultaneous axial displacement of the center of sound production, or even diffusion of the sound production throughout the expanded corona volume, it is apparent that the phase angle of the standing wave at the position of the microphone could undergo significant variation, even to the point of causing one or two apparent pressure resonances. This mechanism could also account for the non-reproducibility of peak positions for frequencies above 30 Kc. At 35 Kc the wavelength of sound in helium is $\sim$ 2 cm. This wavelength is on the order of the corona size at low pressures, so that the chief standing wave effect at these frequencies would be destructive interference of waves from different parts of the corona, rather than pressure resonances. However, the reproducibility of the lower frequency peak positions, in the face of the variations of corona geometry noted earlier, lead the authors to attribute the resonances to something other than standing wave effects.

It has been noted that the experiment was carried out in the face of an air leak of not greater than 1 inch of mercury per five minutes for low pressures. In addition to the disturbing influence which such a leak would have on the temperature equilibrium inside the tube, the effects of air pollution on the curves should not be underestimated. Since the data was taken in a descending pressures direction, air pollution would have had a greater influence at the lower pressures.

The discussion has considered possible systematic problems with the experiment. A representative random measurement error bracket for the graphs is shown on graph no. 1 and is based on error estimates of $\pm$ 0.5 inches of mercury of pressure measurement, $\pm$ 2 percent of the voltage reading for relative sound intensity, and $\pm$ 5 ma for R.F. oscillator plate current.

Conclusions

Some further use of the ionophone of the present design is anticipated. It is expected that the graphs presented in Appendices B of this report will be of use in maximizing the efficiency of the device in the specific contexts of further experiments.

The authors feel they have demonstrated the existence of the "pressure resonance" peaks and have indicated some trends in the behavior of these peaks. It is felt that the experiment has opened up possibilities for further and more detailed study for higher pressures and different gases.

Appendix A

Circuits and Diagrams

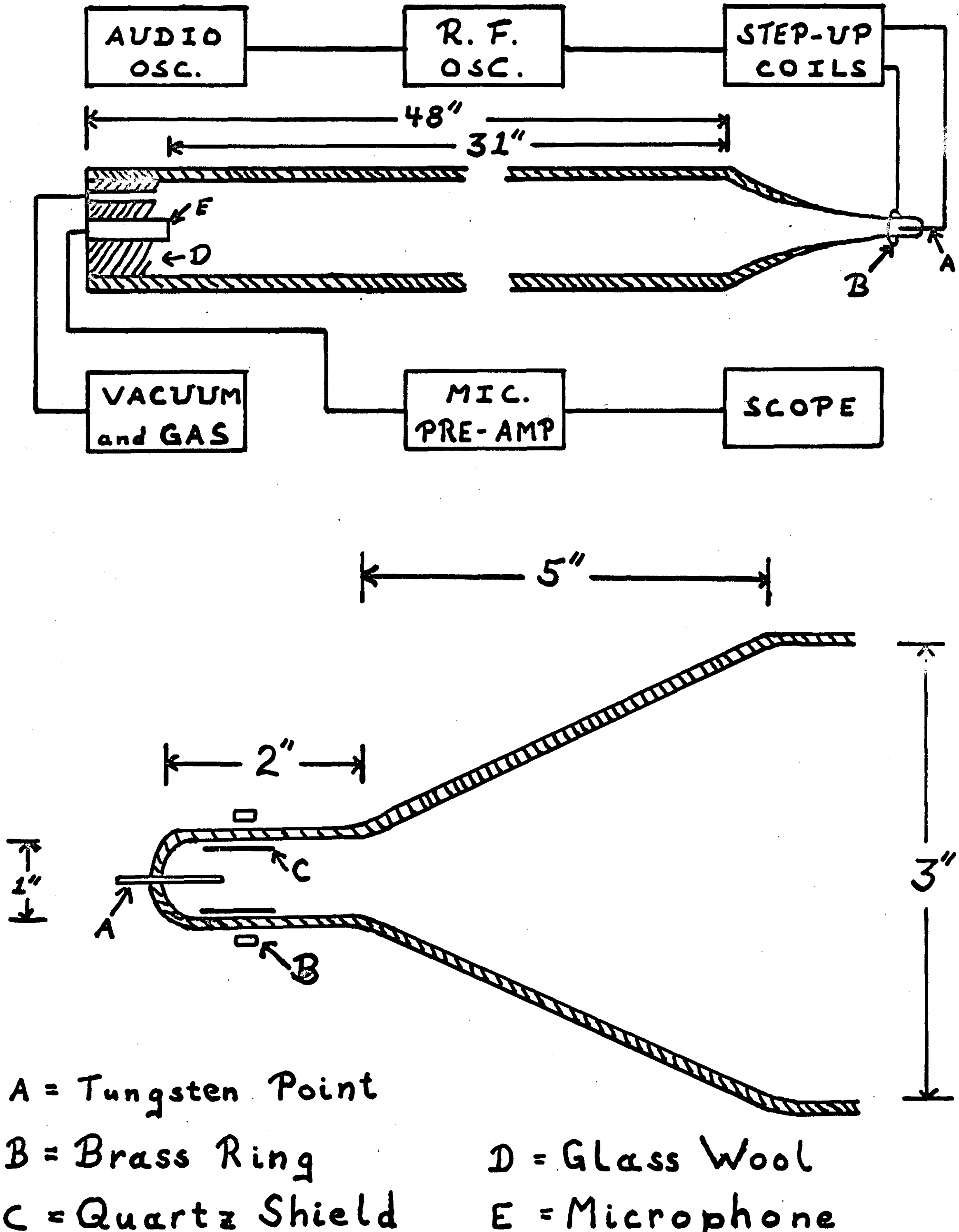


Fig. 1 — Block Diagram and Ionophone

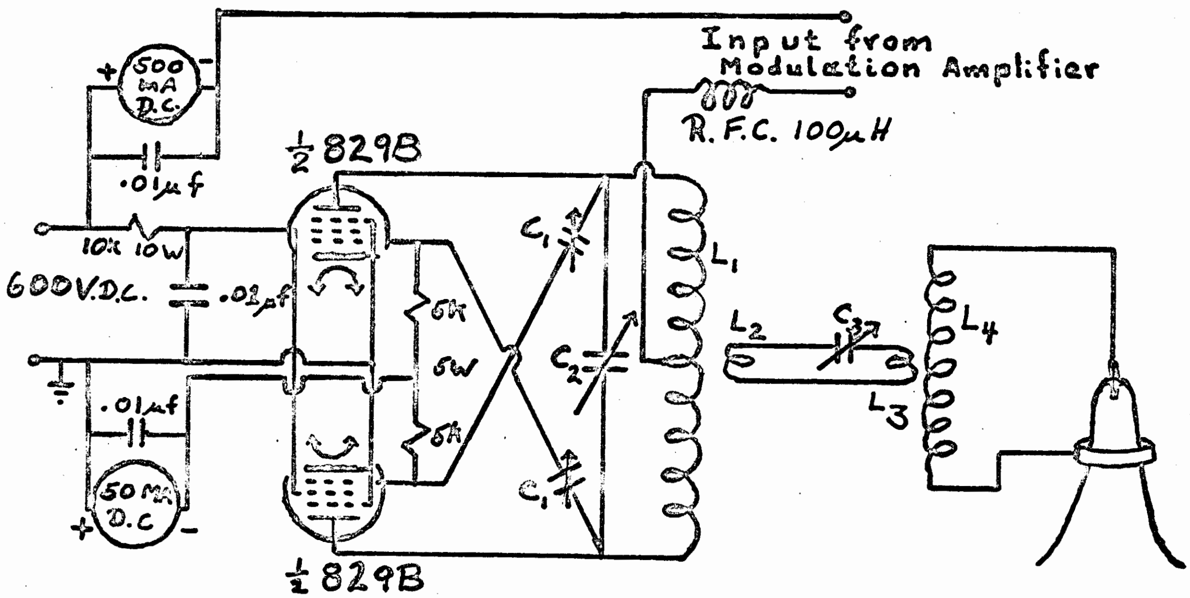
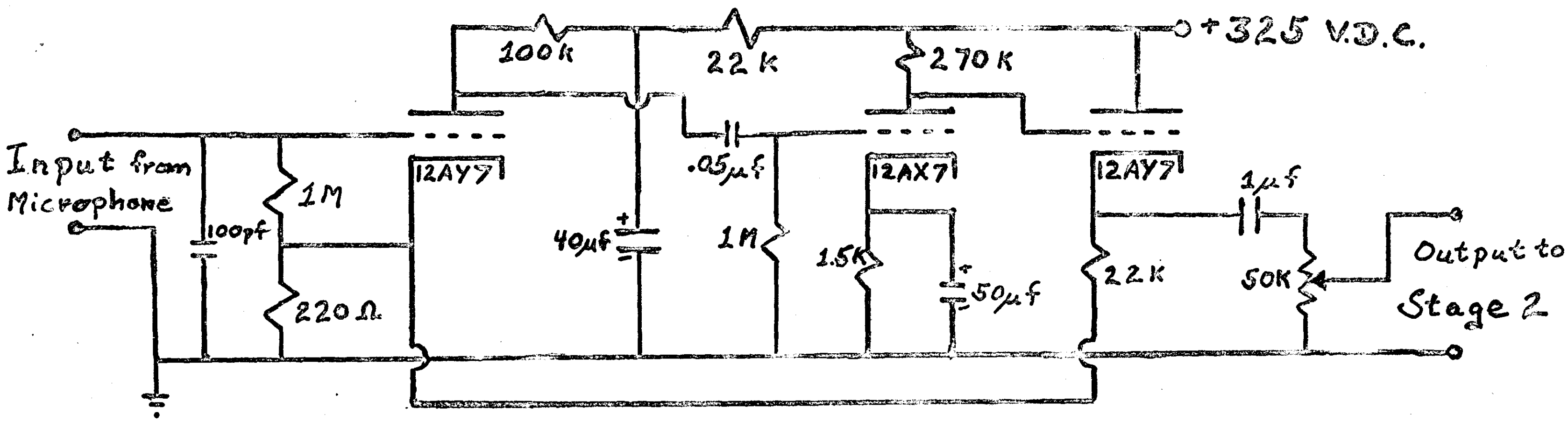


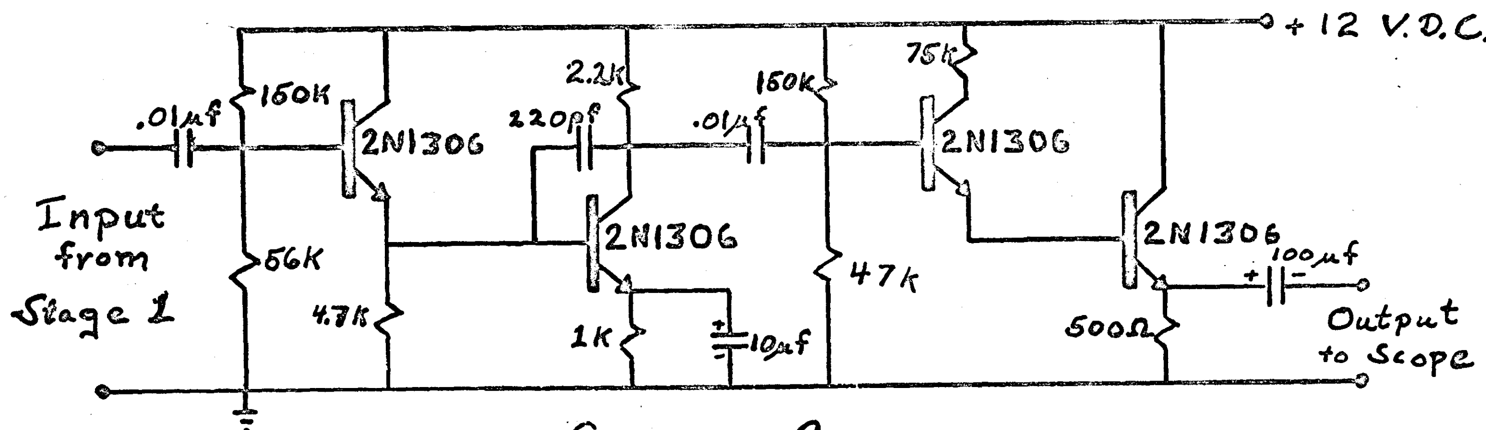
Fig. 2 — RF Oscillator Circuit Diagram

	Number of Turns	Diameter of Coil	Length of Winding	B. S. # of Wire
L_1	8	1.75"	3"	#10
L_2	2	1.5"	0.25"	#10
L_3	3	1.25"	2"	#10
L_4	44	1"	4"	#12
C_1 3~5 μμf	C_2 6~50 μμf	C_3 10~100 μμf		

Table 1 — Coil and Capacitor Specifications



Microphone Preamplifier - Stage 1

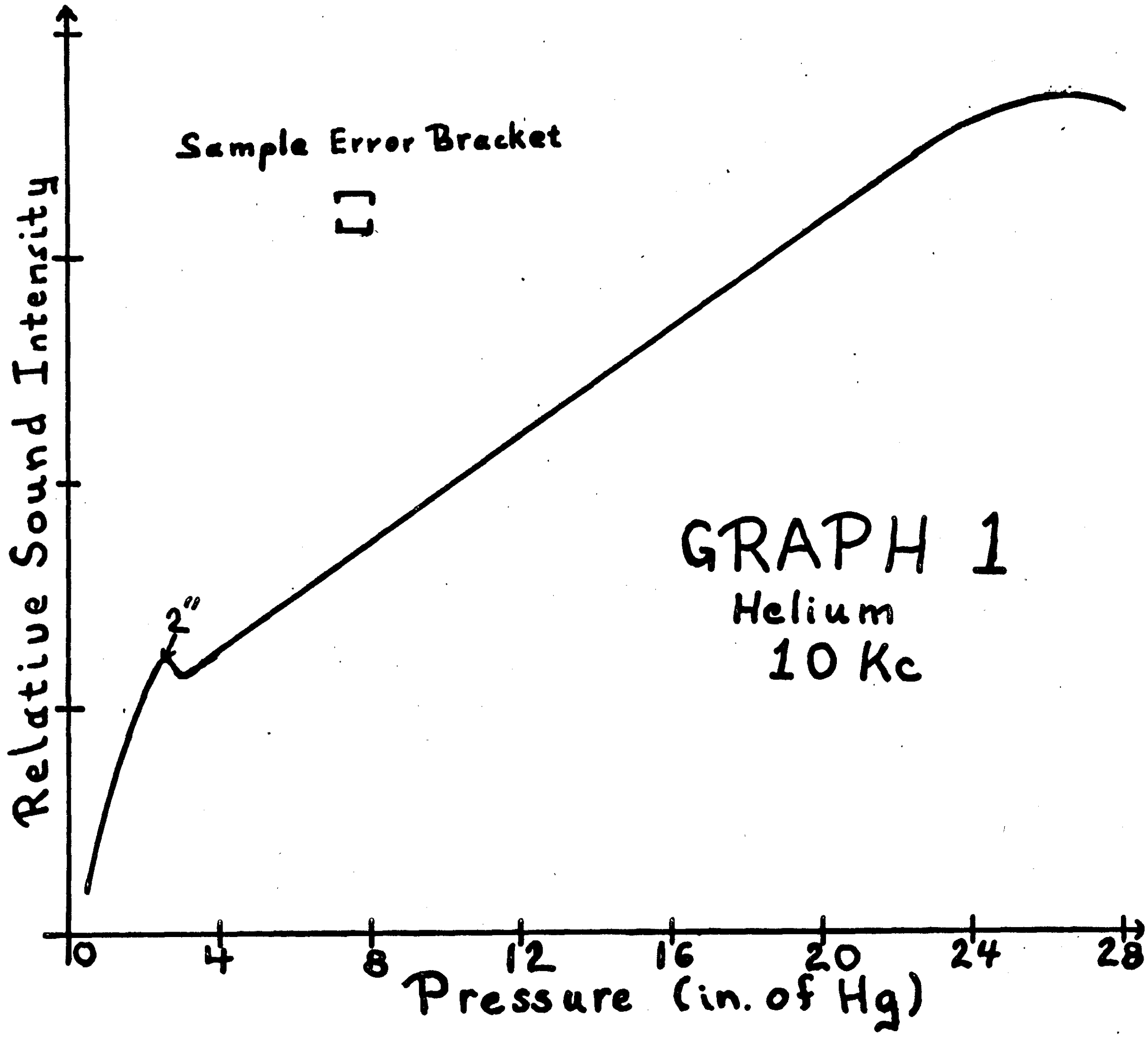


Stage 2

Fig. 3 – Microphone Preamplifier

Appendix B-1

Helium Curves


Sample Error Bracket
Relative Sound Intensity
2"
GRAPH 1
Helium
10 Kc
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

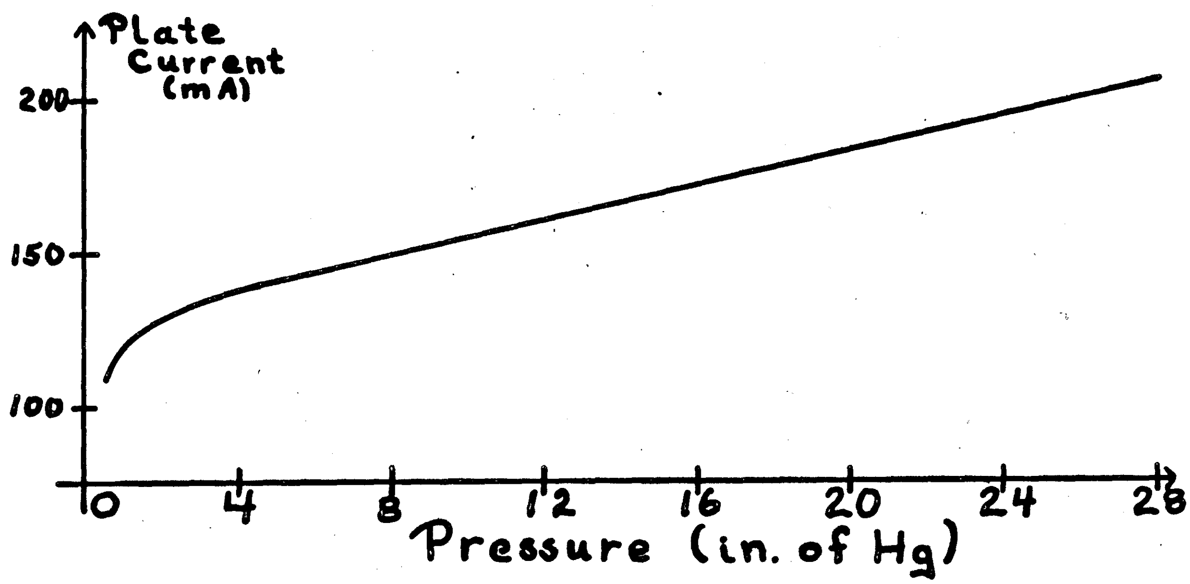
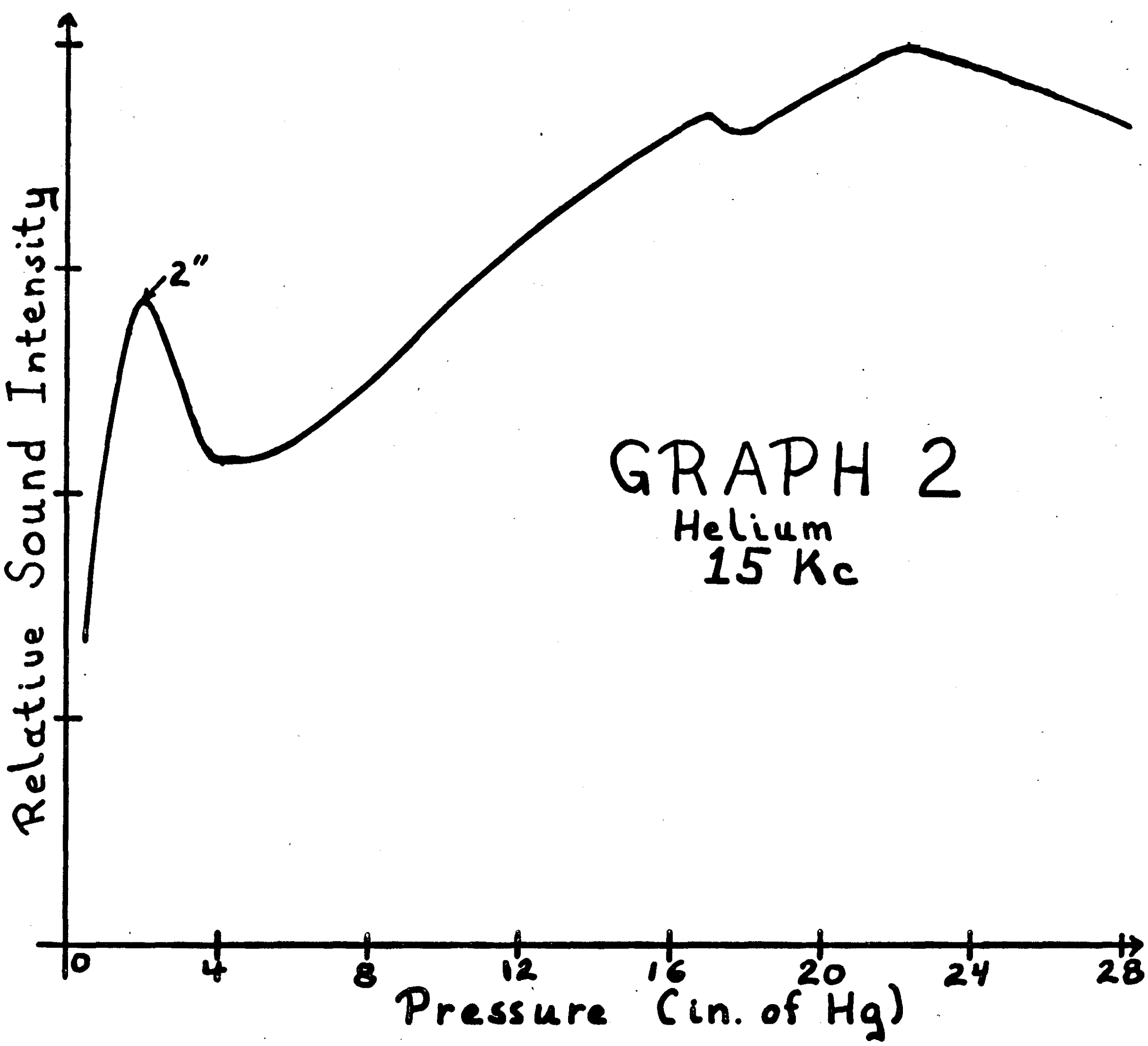


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


2"
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)
GRAPH 2
Helium
15 Kc

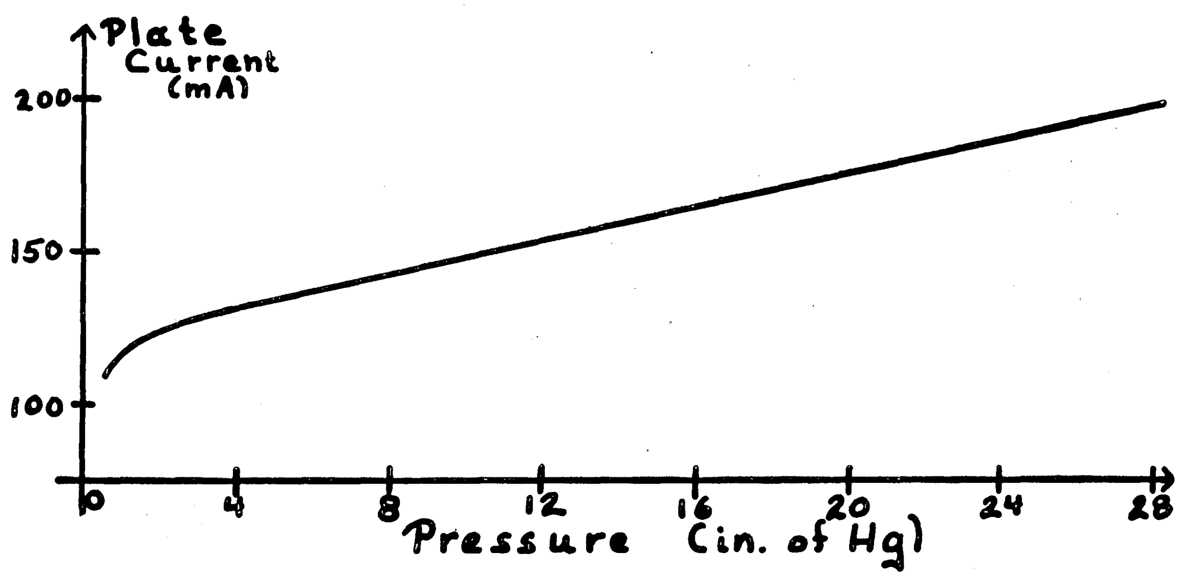
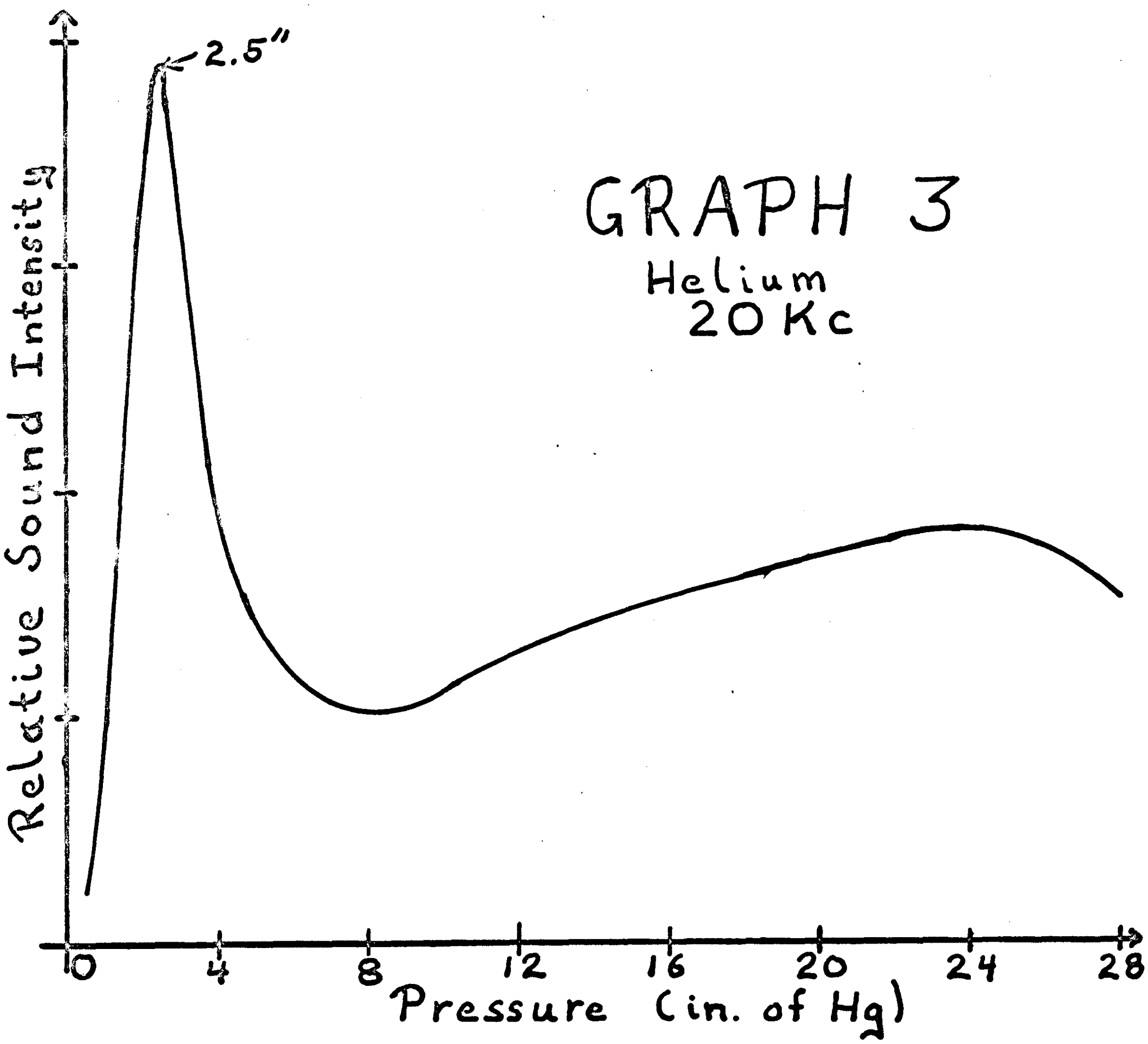


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


GRAPH 3
Helium
20 Kc
2.5"
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

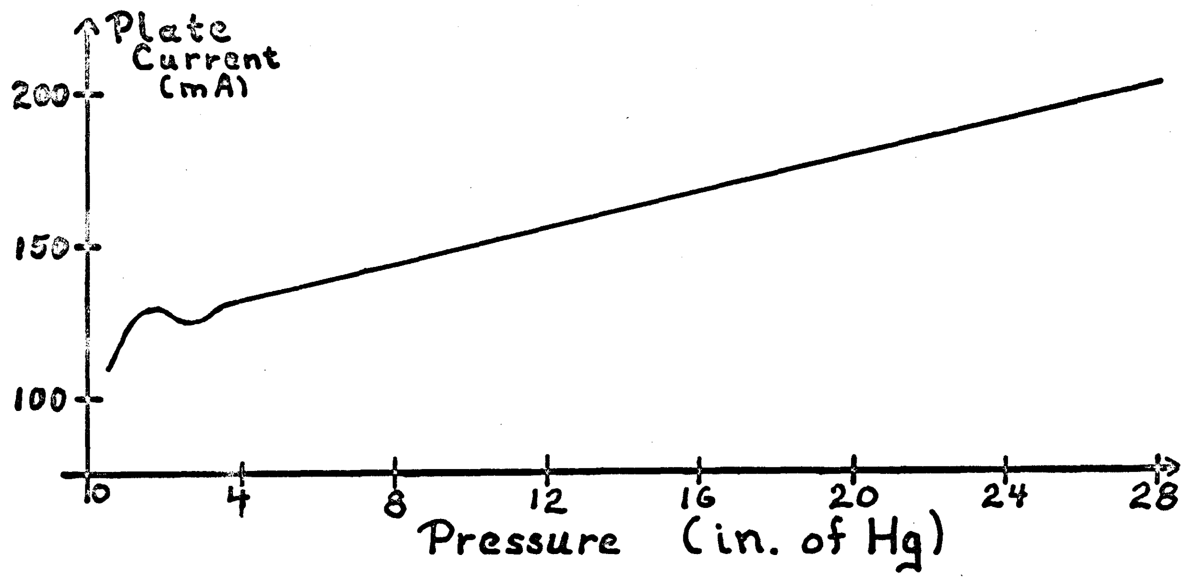
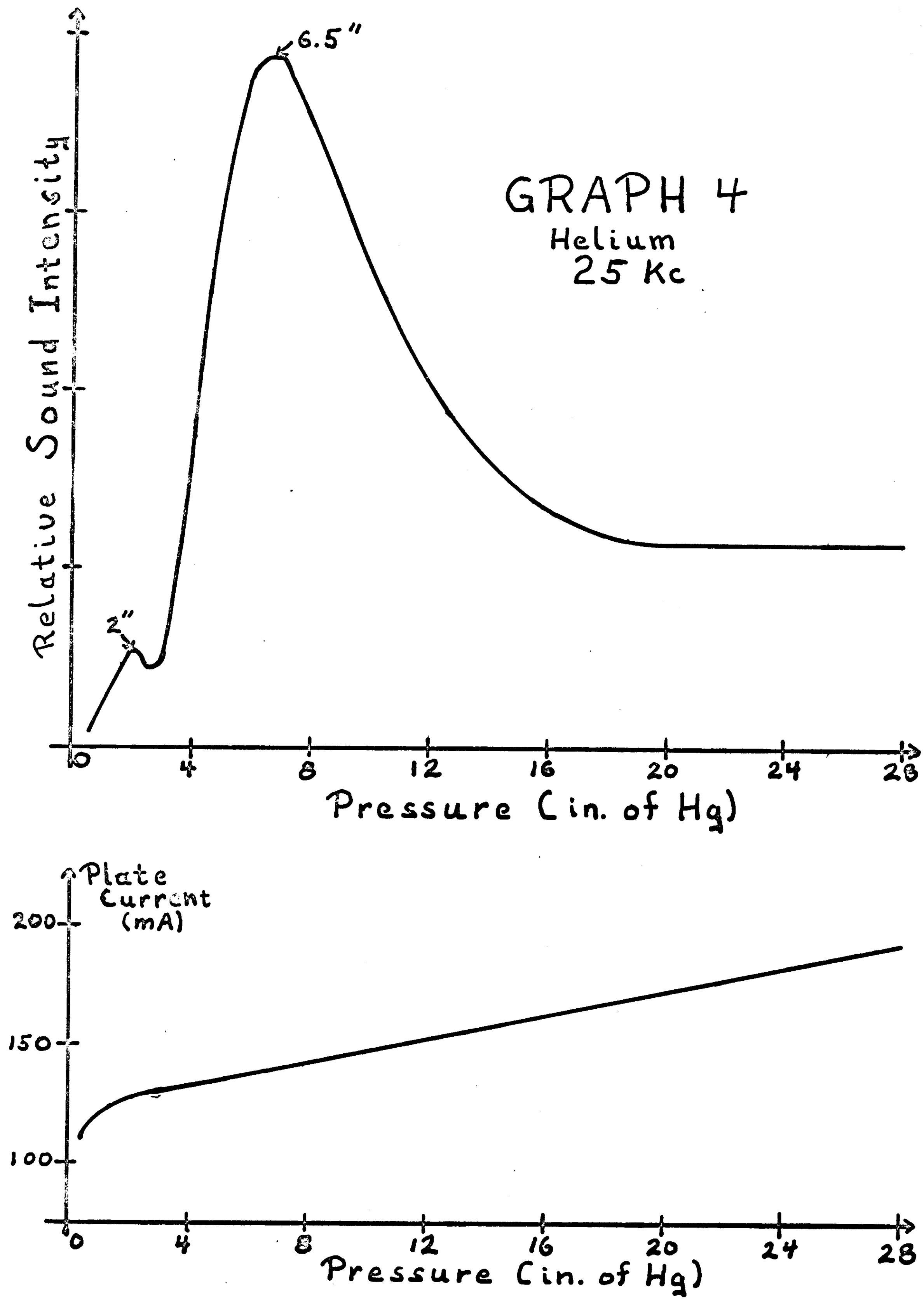
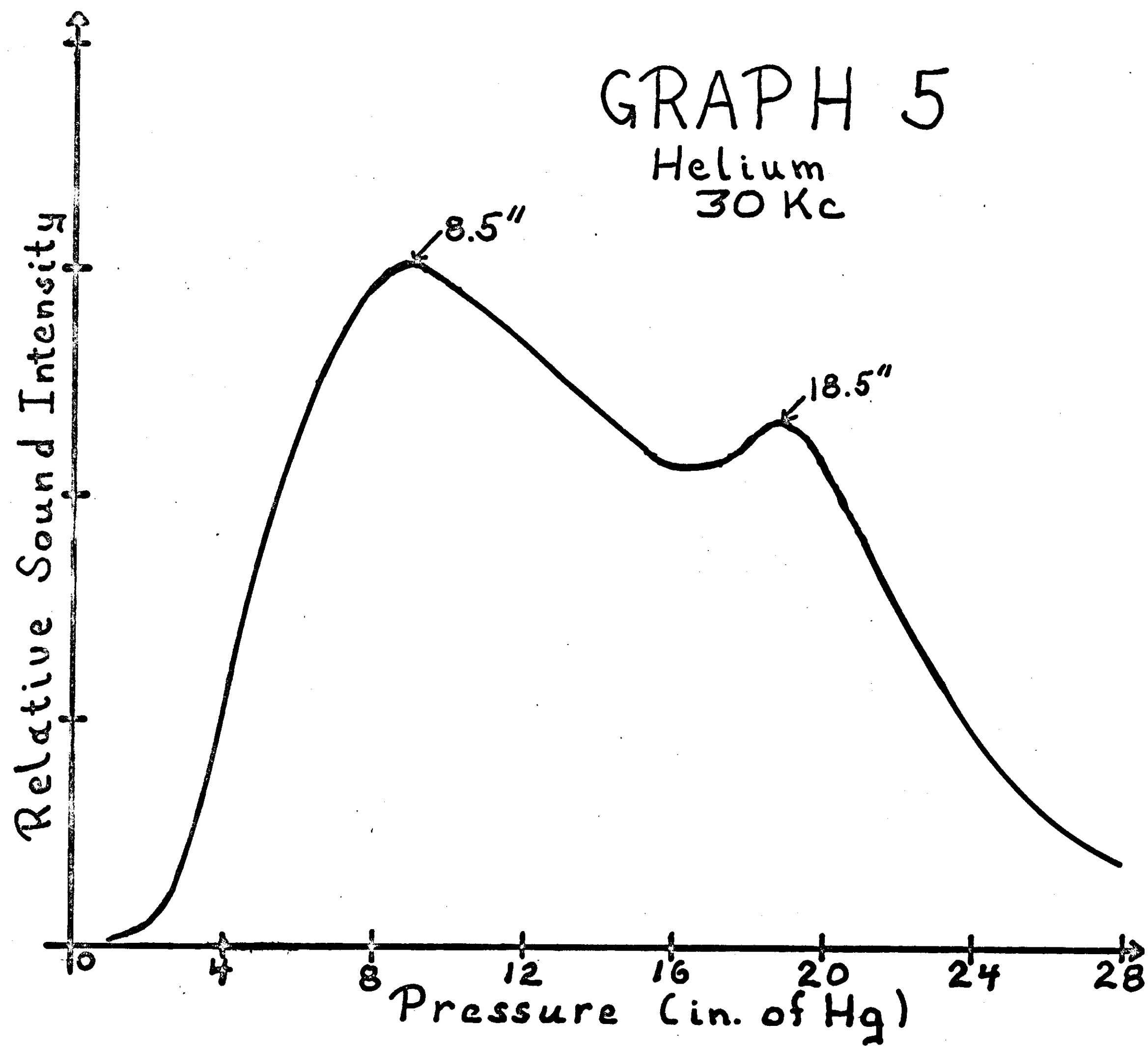


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


6.5"
2"
GRAPH 4
Helium
25 Kc
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)
Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


GRAPH 5
Helium
30 Kc
8.5"
18.5"
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

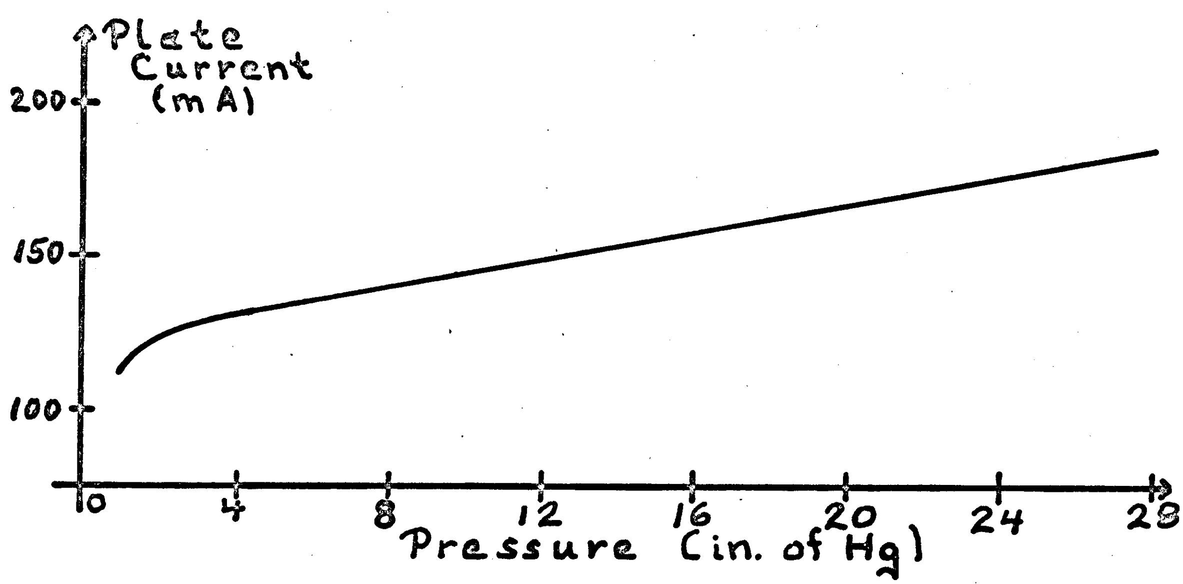
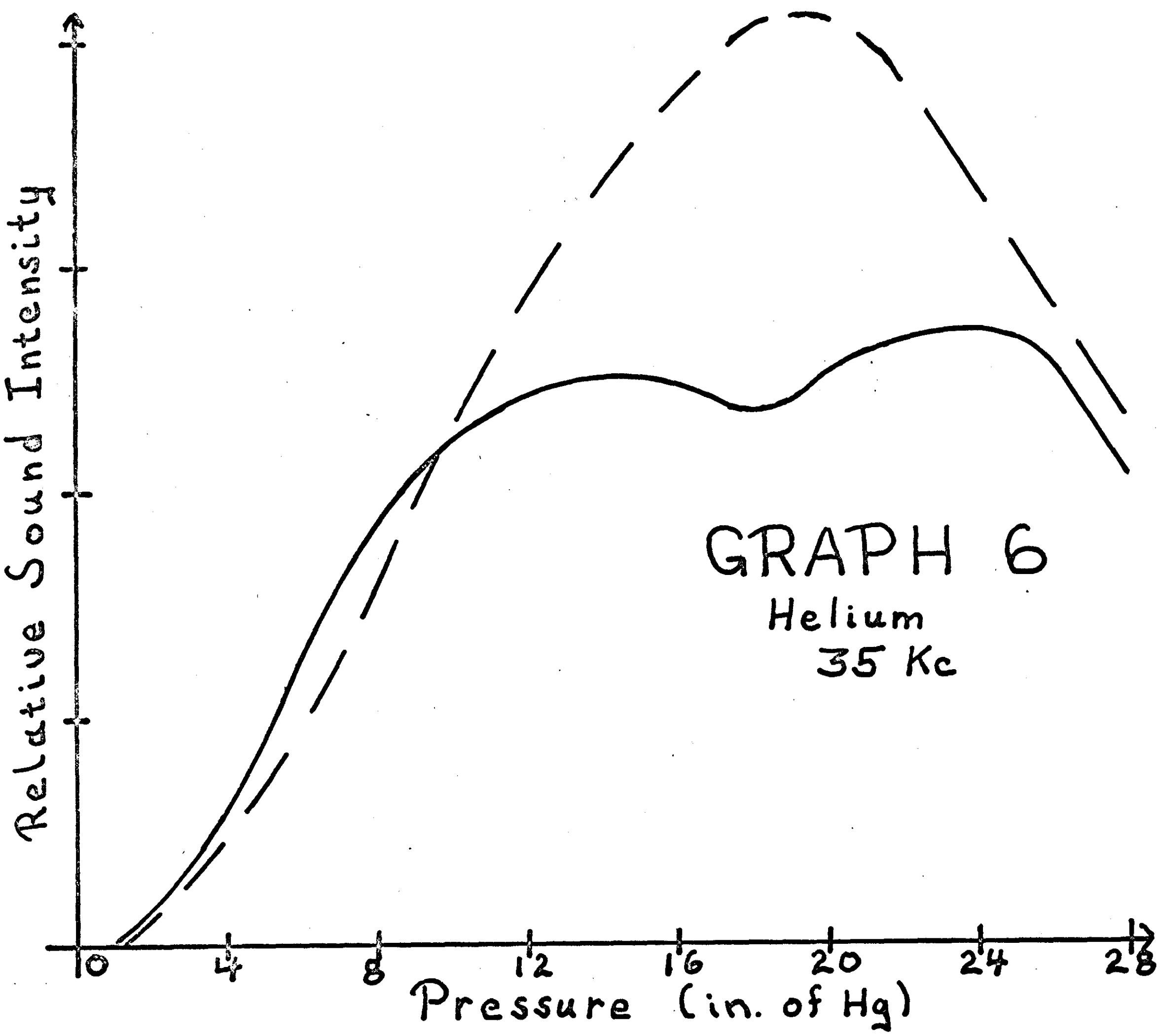


Plate
Current
(mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


Relative Sound Intensity
GRAPH 6
Helium
35 Kc
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

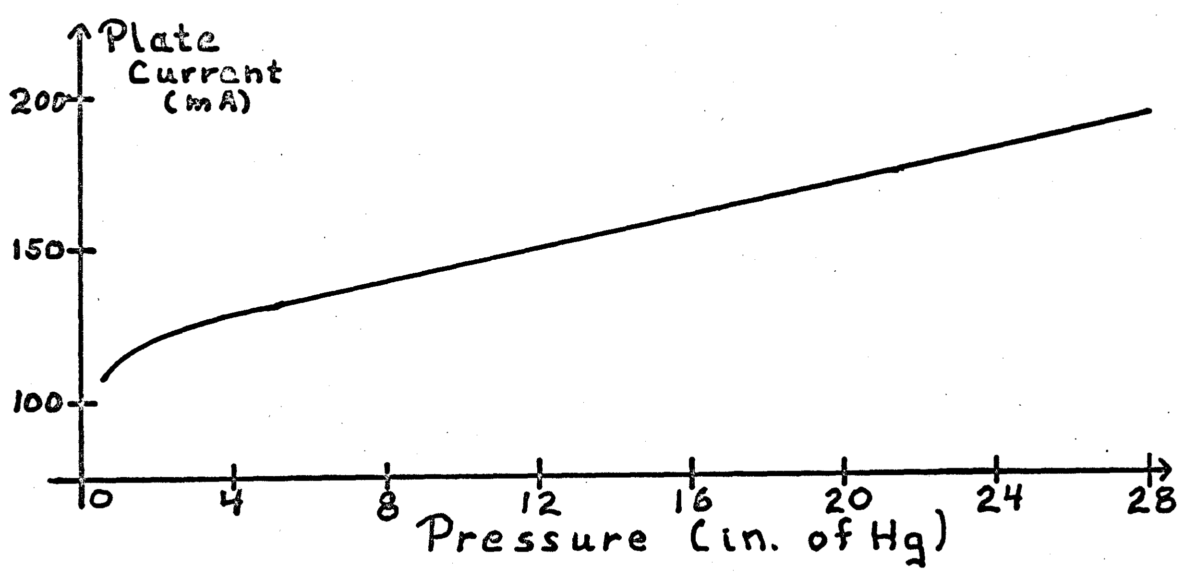
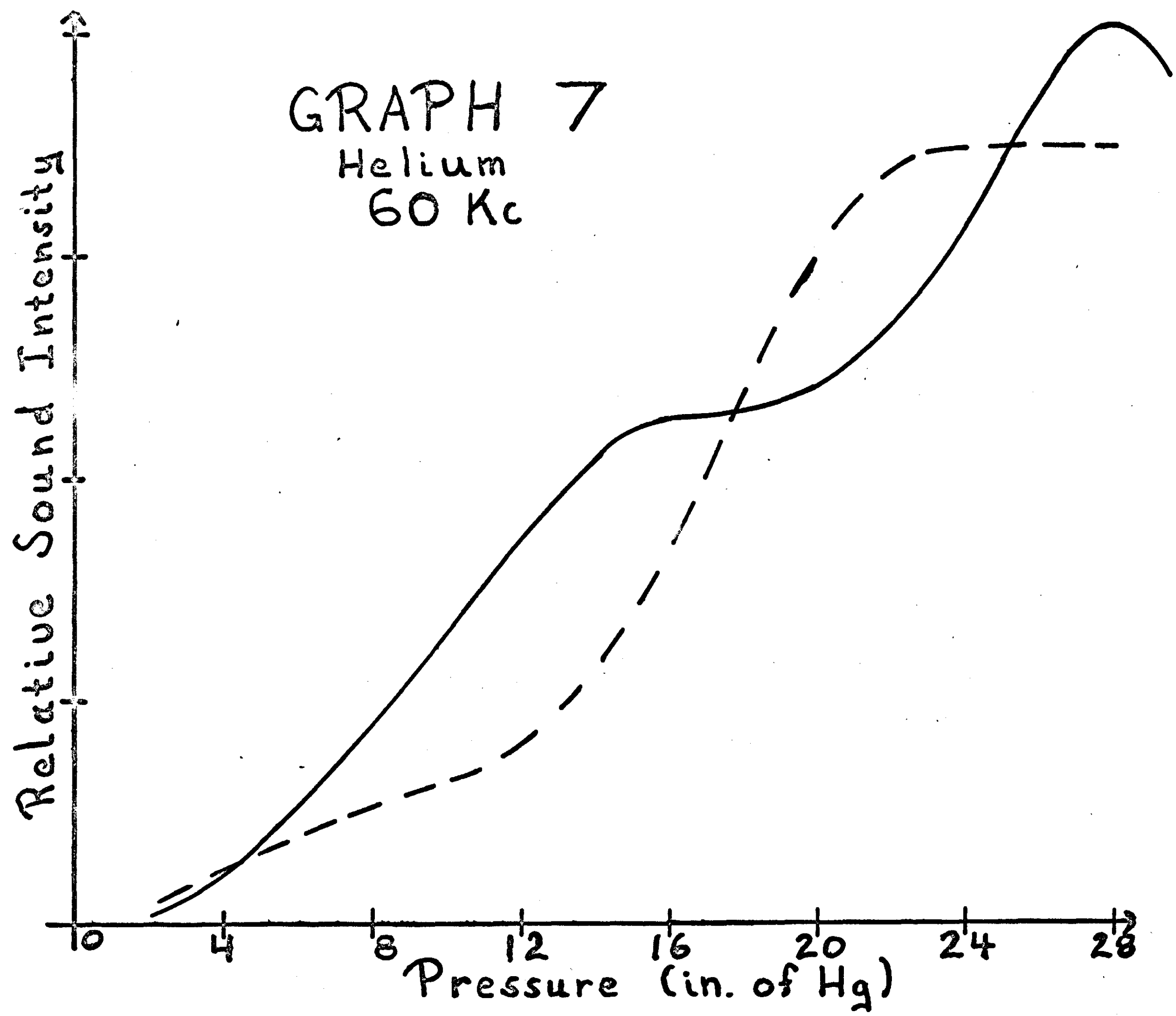


Plate
Current
(mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


GRAPH 7
Helium
60 Kc
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

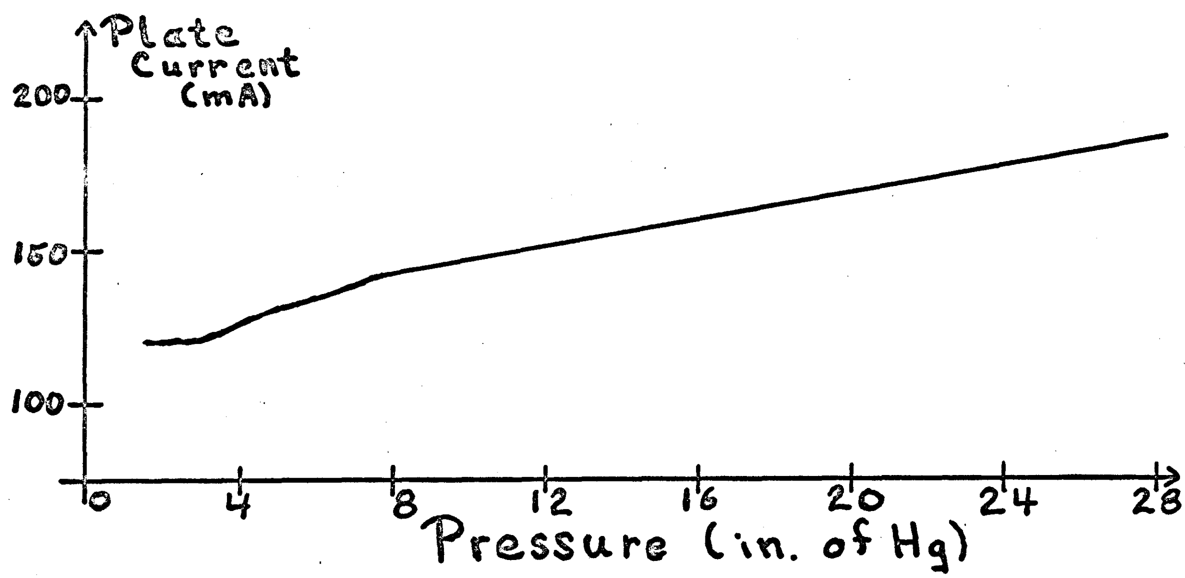
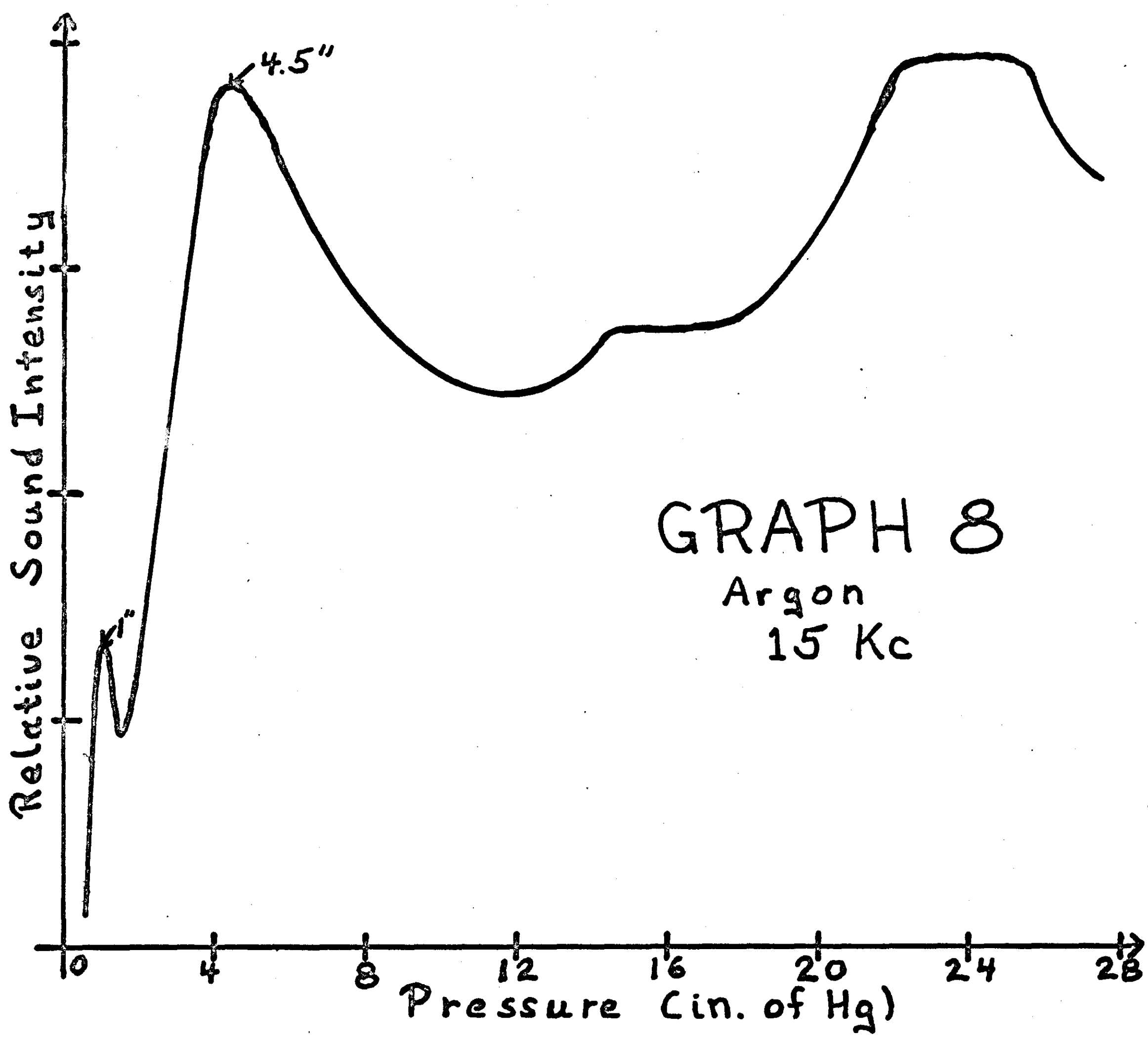


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

Appendix B-2

Argon Curves


4.5"
1"
Relative Sound Intensity
GRAPH 8
Argon
15 Kc
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

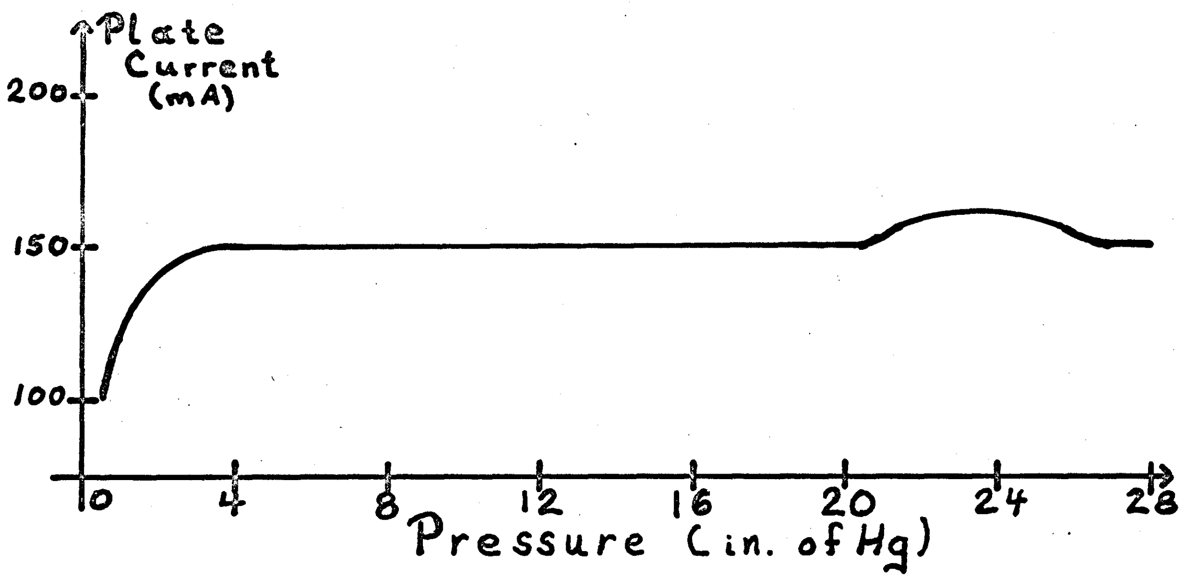
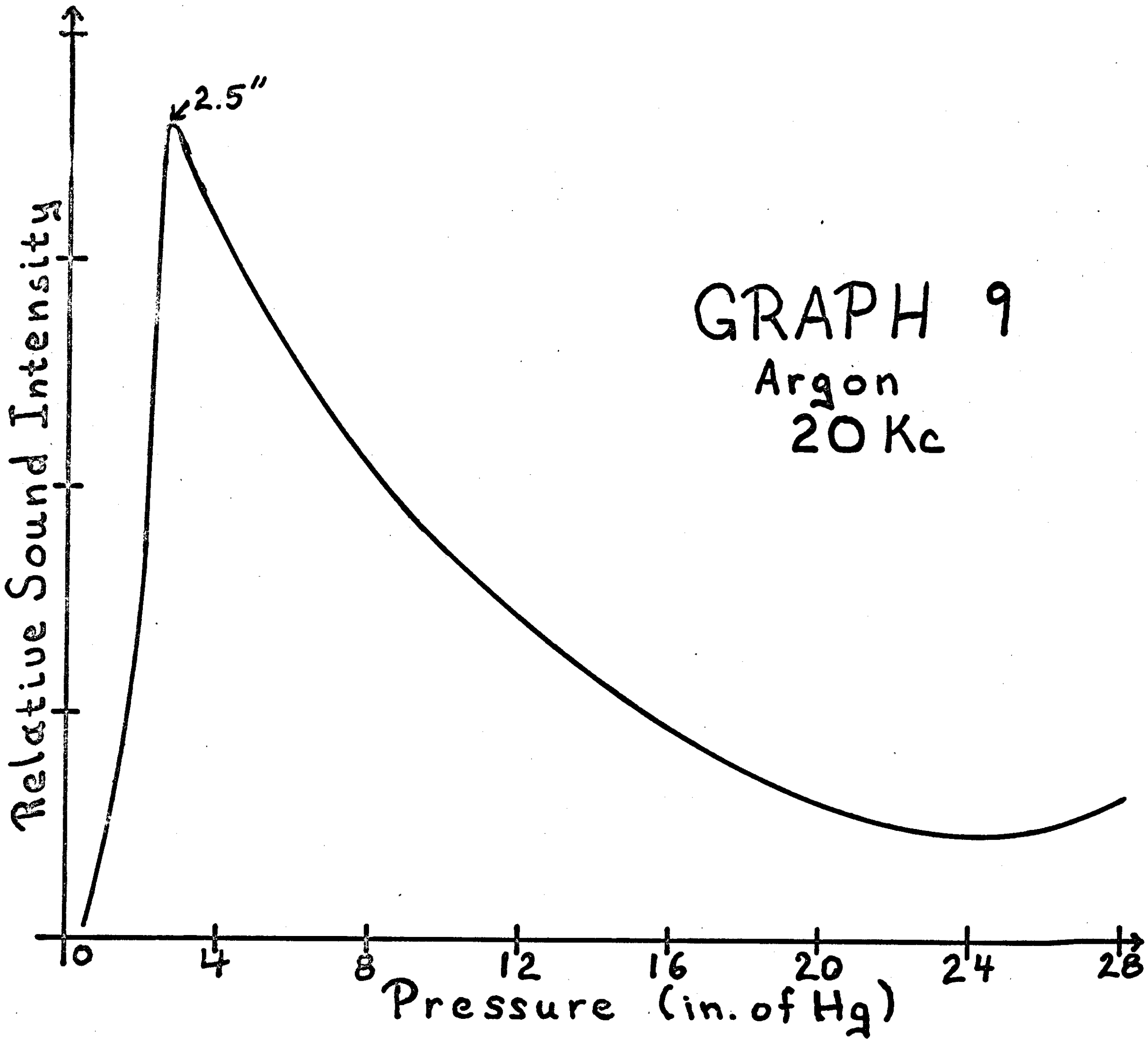


Plate
Current
(mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


GRAPH 9
Argon
20 Kc
2.5"
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

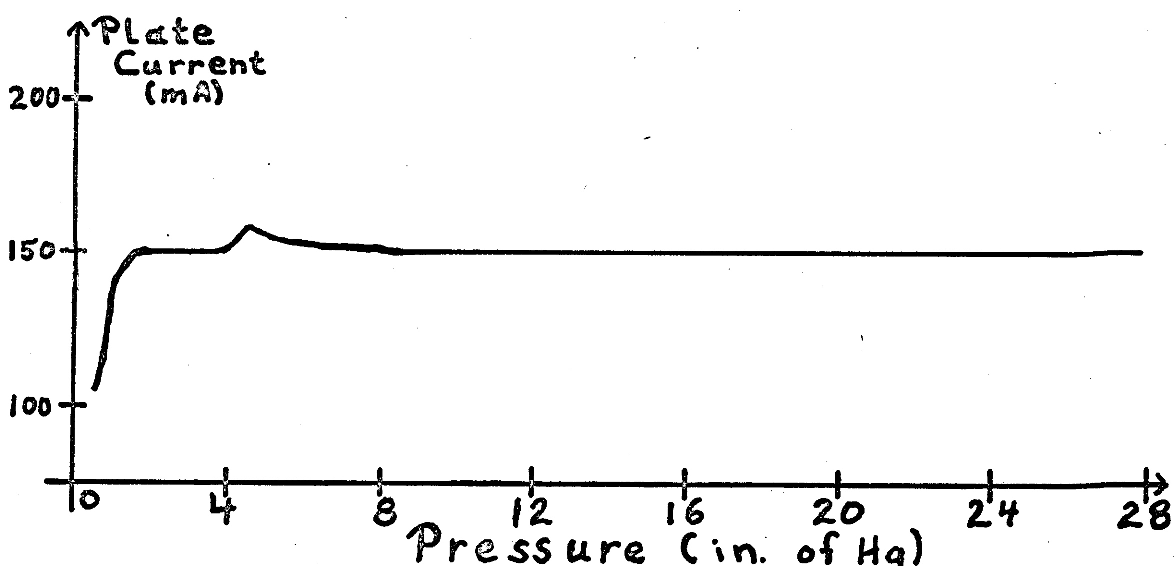
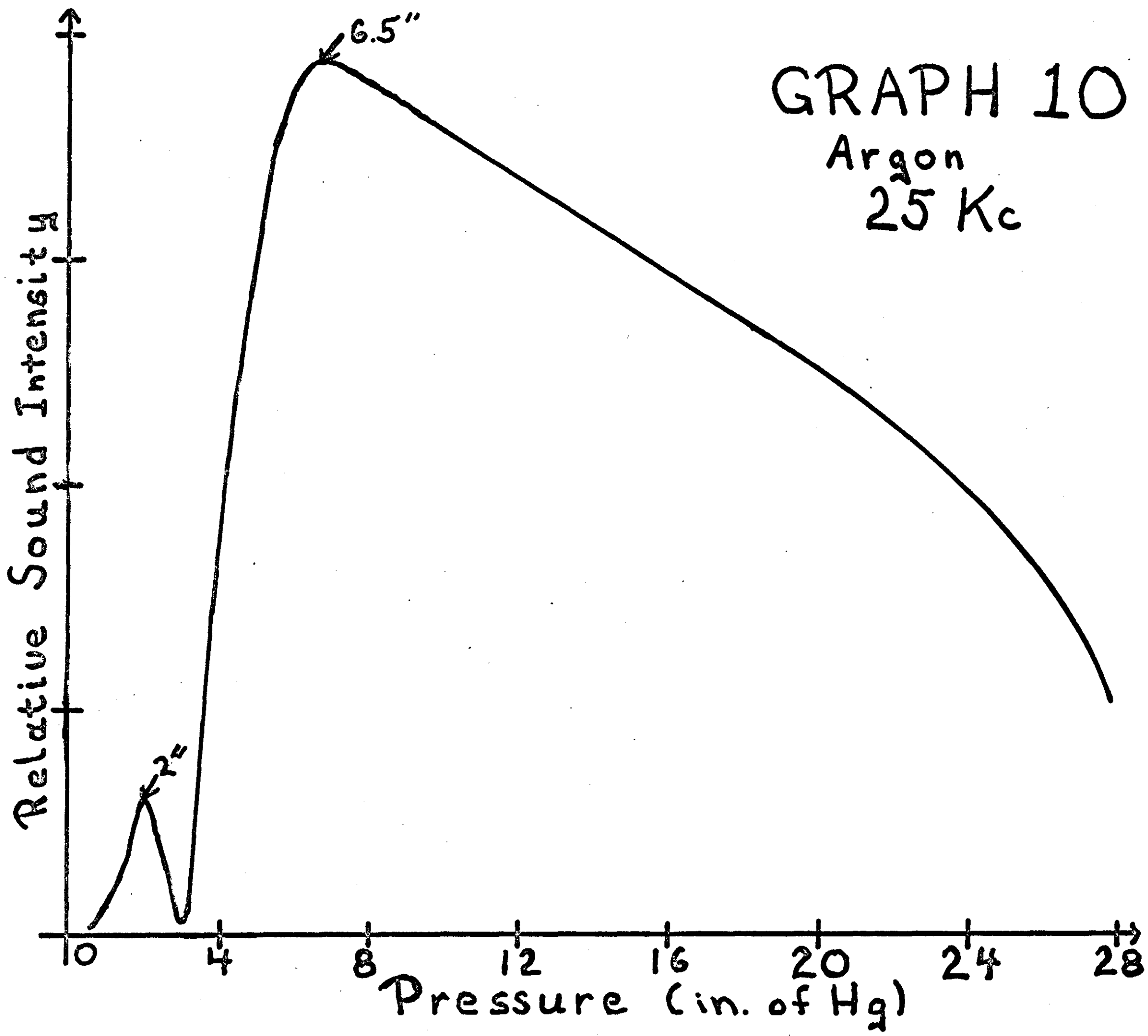


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)


GRAPH 10
Argon
25 Kc
6.5"
2"
Relative Sound Intensity
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

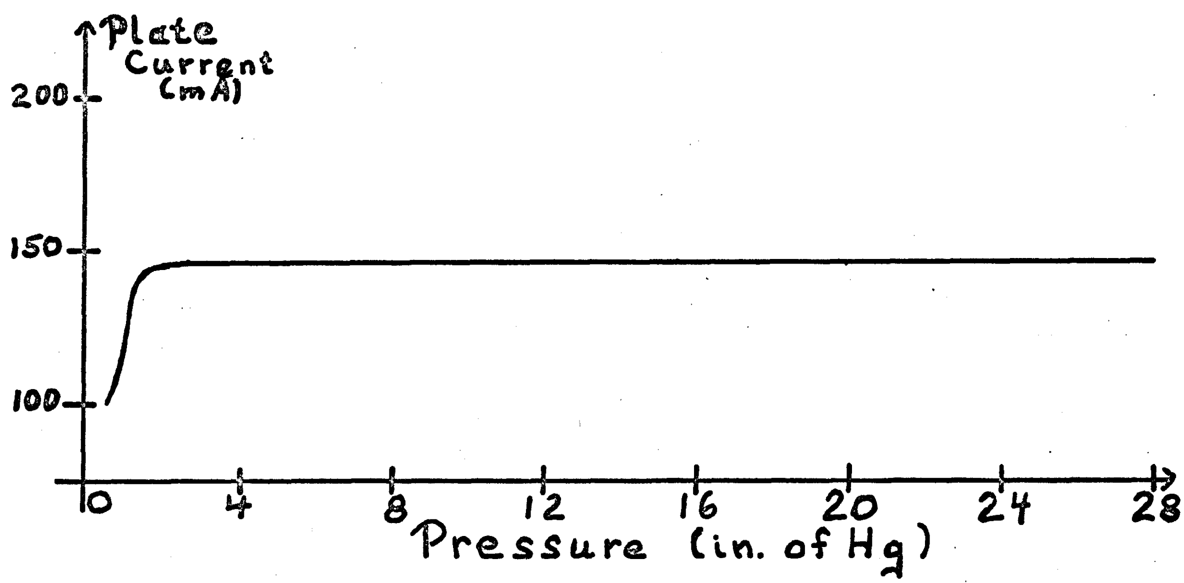


Plate Current (mA)
200
150
100
0
4
8
12
16
20
24
28
Pressure (in. of Hg)

Appendix C

Footnotes

[1]S. Klein, Acoustica, 4, 77, (1954).

[2]Ackerman, "Corona Type Loudspeakers for Animal Studies," Proc. Acoustical Society of America, 33, no. 12, pp. 1708, (1961).

[3]Oda, Fujio, "Corona Type Loudspeaker," WADC Technical Report 58-368, ASTIA Document No. 155782, 64 pages, July, 1958.