NAVY DEPARTMENT

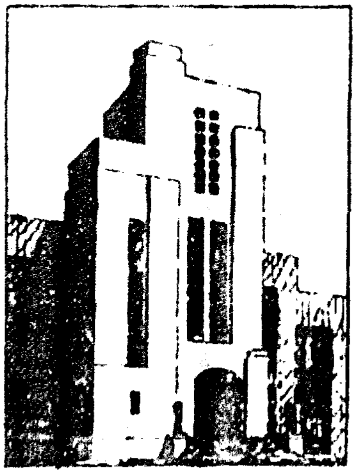
THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

MEASUREMENTS OF NOISE RADIATED BY SUBSONIC AIR JETS

by

H.M. Fitzpatrick and Robert Lee



November 1952

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Report 835
NS 715-102
NR 062-094

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ABSTRACT

The spectrum of the acoustic power radiated by turbulent air jets issuing from two nozzles of different diameters was determined over a range of subsonic flow speeds. Results, presented in dimensionless form, show substantial agreement with Lighthill's theory of turbulence noise which predicts that the ratio of radiated acoustic energy to expended mechanical energy is proportional to the fifth power of the Mach number with only minor dependence upon the Reynolds number. The factor of proportionality was determined to be of the order of 2×10^{-4}. This means that for any given jet the total radiated acoustic power is approximately proportional to the eighth power of the jet flow velocity. The spectrum exhibits a broad peak, whose frequency appears to be determined by the thickness of the shear layer and the sonic velocity (rather than the flow velocity) but the evidence is not conclusive.

INTRODUCTION

Modern advances in theory and technique in the study of turbulence have been accompanied by relatively slight attention to the question of noise production by turbulent flows. Fluid flow, whether turbulent or not, can produce sound in various ways. The phenomenon under discussion here, however, is the production and radiation of acoustic disturbances from within the region of turbulent flow. It is of interest, of course, to relate the characteristics of turbulence noise to the physical parameters describing the flow.

Previous experimental investigations of turbulence noise, from turbo-jets,[1-3] in air ducts[4] and in wind tunnels,[5-7] give general agreement that the intensity of noise produced is proportional to some high power of the flow velocity but no specific conclusion concerning the mechanism of noise production by turbulence seems to have been reached with any accord. One difficulty hampering investigations is the fact that turbulence noise is often accompanied by noise from other sources such as flow-induced vibration of solid boundaries.

Aside from its obvious scientific interest, the subject of turbulence as a source of noise is a matter of practical concern. A program entitled "Research in the Development and

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[1] References are listed on page 24.

Propagation of Hydrodynamic Noise " at the David Taylor Model Basin has included turbulence as one of the possible sources of hydrodynamic noise.[8] An immediate goal of this phase of the research program has been to determine whether or not turbulence in liquids generates appreciable noise; and if it does, what relation exists between the noise and the parameters describing the turbulence. To this end facilities and techniques for the study and characterization of turbulent flows were developed.[9-11]

Attempts were made to produce noise through stimulation of turbulence in water by means of grids, rods, rotating cylinders and submerged jets. In all cases, noise associated with vibration of the mechanical devices, cavitation, or surface disturbances prevented the certain identification of noise attributable to turbulence as such.

An approach to the problem of measuring turbulence-noise without the difficulties presented by cavitation and surface disturbances was suggested in a paper published by M. J. Lighthill on the production of aerodynamic noise.[12] The theory of noise production by turbulence presented in that paper is sufficiently general to apply to liquids as well as to air. Accordingly, some measurements of the noise radiated by turbulent air jets have been made and the results compared with the theory.

The presentation of these results and the interpretation of the experiments can be facilitated by the application of dimensional analysis. In a fluid flow system containing rigid boundaries of a given shape and a given pattern of imposed velocities, the relevant physical quantities governing the behavior of the flow may be listed:

ρ fluid density,

U fluid velocity,

L linear dimension, and

ν kinematic viscosity of the fluid.

Where compressibility effects or propagation of acoustic disturbances are involved there is also to be included:

c sonic velocity.

The sound radiated by the turbulent flow may be described by the frequency spectrum. This requires inclusion of the following quantities:

f sound frequency, and

P' radiated acoustic power.*

* The acoustic power P' whose dependence upon the frequency determines the spectrum of the radiated sound may be taken to be the product of the spectral density by a frequency band of width proportional to the frequency, for example, the acoustic power in an octave or half-octave band.

Dimensional considerations alone indicate the relation among the quantities listed to be expressible in the form

$$\phi_1\left(\frac{P'}{\rho U^3 L^2}, \frac{fL}{U}, \frac{UL}{\nu}, \frac{U}{c}\right) = 0 \qquad [1]$$

The first of the dimensionless ratios may be considered a measure of the ratio of acoustic power to the expended mechanical power, or, if one wishes, the *efficiency of conversion* of mechanical to acoustic power, except for a constant numerical factor.* The second is sometimes called a *reduced frequency*. The remaining ratios are the Reynolds and Mach numbers, respectively.

The relation indicated by [1] is given more explicitly in Reference 12. According to the theory developed therein, the efficiency of conversion is proportional to the fifth power of the Mach number so that the relation to be expected is of the form

$$\frac{P'}{\rho U^3 L^2} = \left[\frac{U}{c}\right]^5 \phi_2\left(\frac{fL}{U}, \frac{UL}{\nu}, \frac{U}{c}\right) \qquad [2]$$

where the dependence of the function ϕ_2 upon the Reynolds number and Mach number is expected to be slight.

If the total acoustic power P_t is considered, i.e., the total power radiated in all frequency bands, the corresponding relation predicted by the theory of Lighthill is

$$\frac{P_t}{\rho U^3 L^2} = \left[\frac{U}{c}\right]^5 K\left(\frac{UL}{\nu}, \frac{U}{c}\right) \qquad [3]$$

where again the function K, Lighthill's *sound power coefficient*, is expected to be only slightly dependent upon the Mach number and Reynolds number. Its value, determined experimentally for a flow system having boundaries of given shape and given pattern of imposed flow velocities, may be used to predict the acoustic power radiated by other similar systems. It will be noted that, for given flow boundaries and given fluid, the theory predicts that the sound power will be proportional approximately to the eighth power of flow velocity.

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*The mechanical power expended by the jet is very nearly $\frac{\pi}{8}\rho U^3 D^2$. Accordingly, the ratio used in Equation [1] is $\frac{8}{\pi}$ times the efficiency of conversion.

APPARATUS AND PROCEDURE

AIR FLOW SYSTEM

The experiments were carried out in the Flow Facility of the David Taylor Model Basin. The essential components of the system are shown schematically in Figure 1. Two large cylindrical tanks acted as primary and secondary air reservoirs. The jet nozzle was mounted rigidly at the end of a long gradually reduced section which leads from the bottom of the secondary reservoir. The jet was projected into a large tank open at the top, 13 by 10 feet in plan section and 13 feet in height.

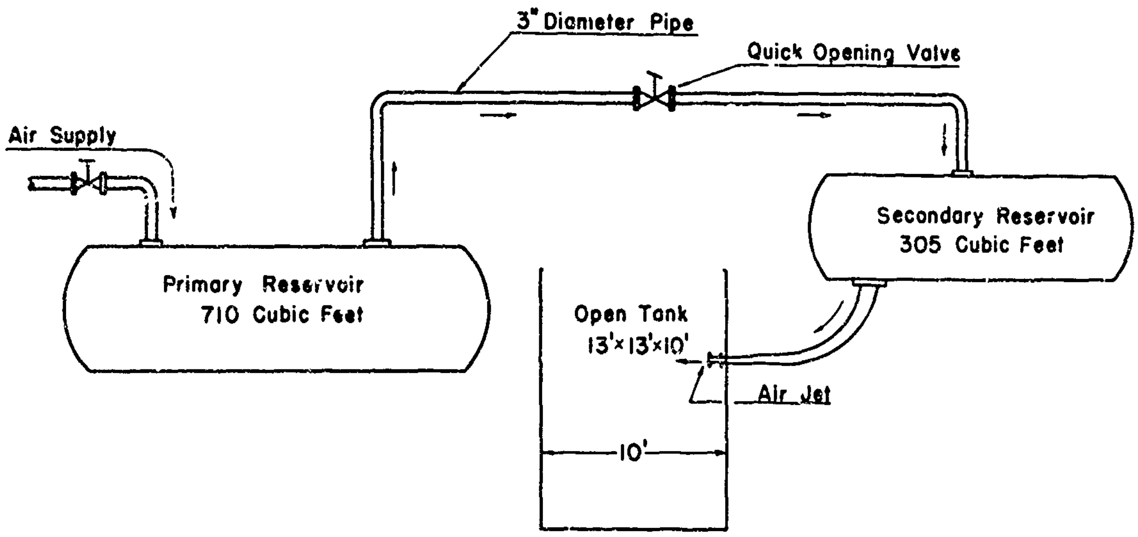

Figure 1 - Schematic Diagram of Air Flow System

The flow of air was initiated by first introducing air into the primary reservoir while the valve connecting the two reservoirs (Figure 1) was closed and the secondary reservoir was open to the atmosphere through the nozzle. When the desired pressure in the primary reservoir was reached, the high-pressure air supply to the primary reservoir was cut off. Quick opening of the pneumatically controlled valve allowed air to enter the secondary reservoir and subsequently to discharge to the atmosphere through the nozzle. After a rapid rise in velocity the discharge resulted in a continuous air jet flow of gradually diminishing velocity. Each run continued until the original air supply in the primary air reservoir was exhausted.

Figure 2 is a sketch of the two nozzles used for producing the air jets. The diameter of the larger is 1.53 in.; that of the smaller is 0.765 in. The material is polystyrene, the nozzles having been manufactured originally for a purpose not related to the present experiments. The possible effects of the lack of exact geometric similarity in the upstream portions of the two nozzles will be discussed in a later section.

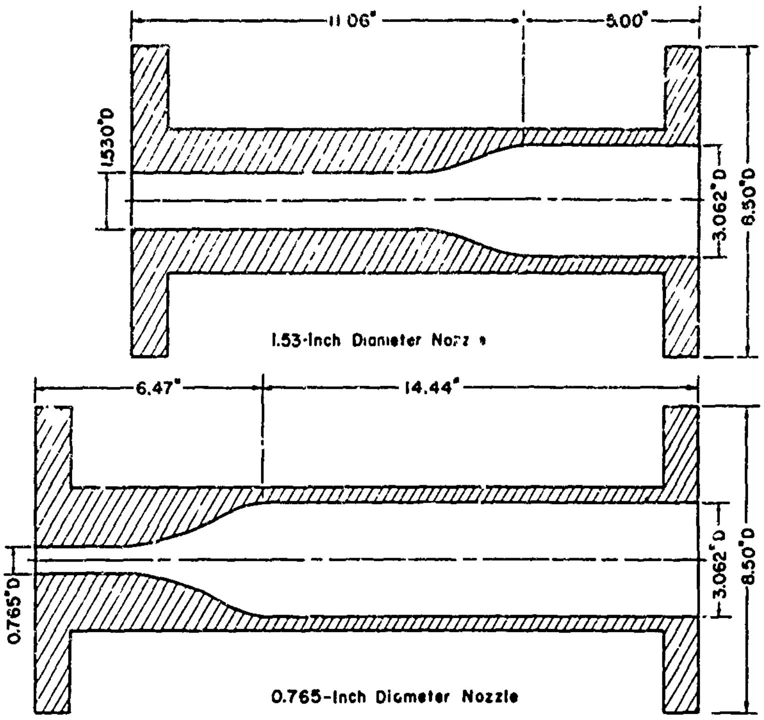

Figure 2 - Outlines of Polystereno Nozzles Used to Produce Subsonic Air Jets

PRESSURE AND TEMPERATURE MEASUREMENTS

Since the velocity of the jet was not measured directly, it was necessary to calculate it from the pressure and temperature in the secondary reservoir. Accordingly, records of these quantities were made during each test run, the duration of which was between one and two minutes.

The pressure in the secondary reservoir was read from precision laboratory gage at selected intervals and recorded as a function of the time elapsed from the initiation of the test run. The temperature in the secondary reservoir was monitored by an automatic recording system employing a resistance thermometer consisting of a very small thermistor bead (Western Electric Type D-176980). The pressure and temperature records thus obtained were typical of all those determined for runs with the same nozzle and were used to relate the jet velocity to the sound level, also plotted s a function of time by the automatic sound level recorder. The jet velocity calculations assumed compressible isentropic flow between the secondary reservoir and the nozzle exit.

ACOUSTIC MEASUREMENTS

The noise radiated by the jet was measured by conventional instrumentation. The microphone used was a Brush Development Company Model BM-101. A set of band pass filters (Gertsch Products Company BP-1 Filter Set) was used for measurement in half-octave bands. An amplifier of TMB design drove the filters and the automatic recorder. The recorder employed was a Sound Apparatus Company FR Recorder with its rectifier modified to respond to the mean square of the signal voltage. Calibration of the electrical system was made in the usual manner; a calibration signal of voltage amplitude corresponding to a known sound level was injected into the crystal circuit of the microphone before each run, the frequency of the calibration signal being the center frequency of the half-octave filter used for that run. The crystal sensitivity had been obtained separately by laboratory calibration of the microphone in air.

During the runs, the signal being recorded was monitored visually by means of a cathode-ray oscilloscope.

If a steady sound source is known to be a simple one, radiating equally in all directions, the determination of the total power radiated is relatively simple; the mean squared pressure $\overline{p^2}$ is determined at a distance r from the source in a free field. The total power P is then given by

$$P = \frac{4\pi \overline{p^2} r^2}{\rho c} \qquad [4]$$

If, however, the source is not known to be a simple one, the determination of the total radiated power requires the integration of the intensity of radiation over all directions. If this is done by pressure measurements, these must be made at distances not small compared to a wavelength.

The circular air jet is not a simple source [1,12]* so that measurement of the acoustic pressure at a single point would ordinarily not serve to determine the total radiated power. However, during the experiments, both the sound source (jet) and the microphone were located inside the large metal tank (Figure 1), open only at the top. The microphone was suspended level with the nozzle, about four feet distant, and 60 degrees off the centerline of the jet.

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*According to the theory of Reference 12 the sound source consists of a distribution of acoustic quadruple source strength of a kind and orientation such that the radiation pattern should exhibit broad maxima at angles of about 45 deg from the jet axis.

Under these conditions, the sound pressure at the microphone is due almost entirely to reverberations rather than direct radiation from the sources in the turbulent jet. This fact was verified by moving the microphone; the indicated sound level proved to be almost completely independent of position so long as the microphone was kept three feet or more from the jet. A calibration factor is needed, however, relating the total radiated noise power to the pressure measured by the microphone. This calibration factor was obtained by placing a noise source of known power in the tank at the approximate location of the jet and recording the pressure indicated by the microphone suspended in the test position. The noise source used for the calibration was a small nozzle connected by a garden hose to a tank of air at a selected fixed pressure. The noise power radiated by the small nozzle was determined by making a survey of its sound field when it was suspended several feet above ground in the open air. This indirect method was necessary because it was not practicable to perform the entire experiment in the open air but it had the very great advantage that the directional survey had to be made only once (for each frequency band); a directional survey about the jets in the experiment proper would have multiplied many times the work of recording and computing.

The calibration factor is conveniently expressed in terms of an "equivalent radius" r_e of an omnidirectional source, which when substituted in Equation [4] gives the correct relation between measured pressure at the microphone inside the reverberant tank and the radiated acoustic power.[13] The values obtained for three frequency bands are given below:

Frequency Band in kc	Equivalent Radius r_e in ft
6.8 - 13.6	1.35
3.4 - 6.8	1.24
1.7 - 3.4	1.50

It was not possible to estimate the equivalent radius at the lower frequencies because of insufficient strength of the calibrating jet at the lower frequencies.

One source of uncertainty introduced by the calibration employed is the possibility of frequency dependence of the reverberation characteristics of the tank. Such effects might result from excitation of resonant modes in the acoustic cavity or in the metal plates forming the tank walls. Errors arising from such effects should be sufficiently reduced, however, by the making of all measurements in sufficiently broad frequency bands. In addition, the open top of the tank limits the reverberation in the tank by allowing a considerable rate of escape of acoustic energy. Accordingly, the sound level at the microphone should not be too greatly dependent upon the reflective characteristics of the walls of the tank. A second source of uncertainty lies in the possibility that the directional characteristics of the sound source will result in erroneous interpretation of the sound level existing at the microphone. For an axially symetric jet, however, the directivity is known not to be sufficiently pronounced to result in any very large discrepancies from this cause. It is believed that the range of uncertainty inherent in the calibrations was not much greater than the scatter in the values of r_e shown in the table. A value of 1.5 feet was used in all calculations;* its uncertainty is probably the most serious single source of uncertainty in the measurements.

TEST RUN PROCEDURE

In making a test run, the large primary reservoir was first filled to approximately the required pressure from the air supply. An interval of time, determined by trial, was allowed for the air in the primary reservoir to reach thermal equilibrium with the room temperature. During this interval, the filter was set at the frequency band in which the sound measurements were to be made for that run and the calibration signal was injected and allowed to be recorded. Final adjustment of the pressure in the primary reservoir to a value determined by trial (25 psi, gage) was then made. With the sound level recorder running and recording the background level, the pneumatically controlled valve connecting the two reservoirs was opened and recording of the sound continued during the discharge of air from the nozzle. This procedure was repeated until a record was obtained for each half-octave band in the frequency range for which measurements were possible. These records, each being actually a recording of rms sound pressure at the microphone as a function of time for a single half-octave band, allow the sound pressure to be determined as a function of velocity by means of the records of pressure and temperature obtained in the manner described in the previous section.

In runs with the larger jet, the valve connecting the two reservoirs was left open during the entire run. With the smaller jet, this would have resulted in an unnecessarily long run; the valve was therefore closed after ten seconds, thus conserving the remaining air in the primary reservoir and shortening the run.

The sound level records are reproduced in Figures 8 and 9 in the Appendix. The flow velocities indicated are those calculated from the records of pressure and temperature in the secondary reservoir, compressible isentropic flow from the secondary reservoir to the jet being assumed. A discontinuity appearing in the record of the sound intensity indicates that the amplifier gain was changed by 20 db at that point. The sound intensity scale refers in all cases to the latter part of the run. The background noise level corresponding to each gain setting is apparent, either at the beginning or at the end of the run. These background noise intensities are subtracted from the total indicated intensities before presentation of the results in the following section.

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* For purposes of computation, the pressure levels in db relative to 0.0002 dyne/cm^2 measured in the tank may be converted to acoustic power in db relative to 1 milliwatt by subtraction of 86 db from the pressure levels.

RESULTS AND DISCUSSION

Figures 3 and 4 show the distribution in frequency of the sound power radiated by the two jets for various flow speeds. The spectrum exhibits a fairly broad peak, half of the total power being contained in a band ranging from about one and one-half octave for the larger jet at the low flow velocities to about one octave for the smaller jet at the highest velocity. All the spectra are of the same general form, however, and can be fairly well characterized in terms of the total power and the frequency of the peak. Figure 5 shows the total power* radiated in all frequency bands by the two jets as a function of flow velocity. The agreement with the eighth power relation derived by Lighthill is apparent on comparison with the broken line.

Figure 6 shows the sound power coefficient

$$\frac{P_t}{\rho U^8 D^2 c^{-5}}$$

as a function of the Reynolds number $\frac{UD}{\nu}$. Here the characteristic length is taken as the diameter D of the jet. In computing the values shown, the temperature in the secondary reservoir was taken into consideration in deriving the flow velocity, but the values of the density, viscosity, and sonic velocity correspond to the temperature of the air in the room. Computed values of the temperature in the jet are given in Table 1 which summarizes the results of all measurements.

The data presented in Figure 6 appear to be a striking confirmation of Lighthill's theory in that the sound power coefficient formed from the ratio of conversion efficiency to the fifth power of the Mach number appears to be completely independent of the latter. The spot indicating the value of the coefficient for the larger jet at the lowest flow velocity is justifiably given less weight in drawing the curve shown because the measured sound levels were close to the background noise for this condition. The nearly exact agreement indicated by the remaining spots in the range of Reynolds number where the data for the two jets overlap is probably not significant, however. Nevertheless, definite corroboration of the theory of Reference 12 is indicated along with a value of 10^{-4} as the order of magnitude of the sound power coefficient. The principal sources of uncertainty in the final value of the coefficient are four: 1) acoustic and electrical measurement (including calibration of microphone); 2) calibration of acoustic properties of the test tank; 3) measurements and assumptions in obtaining the flow velocity; and 4) neglect of temperature differences in the choice of values of air density and sonic velocity used in the calculations. The probable error in the acoustic

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* The values of total power were computed by integration of the spectral values indicated by the curves drawn in Figures 3 and 4, the assumption being made that no substantial contribution to the total power is made by unsuspected components of radiated noise outside the frequency range covered.

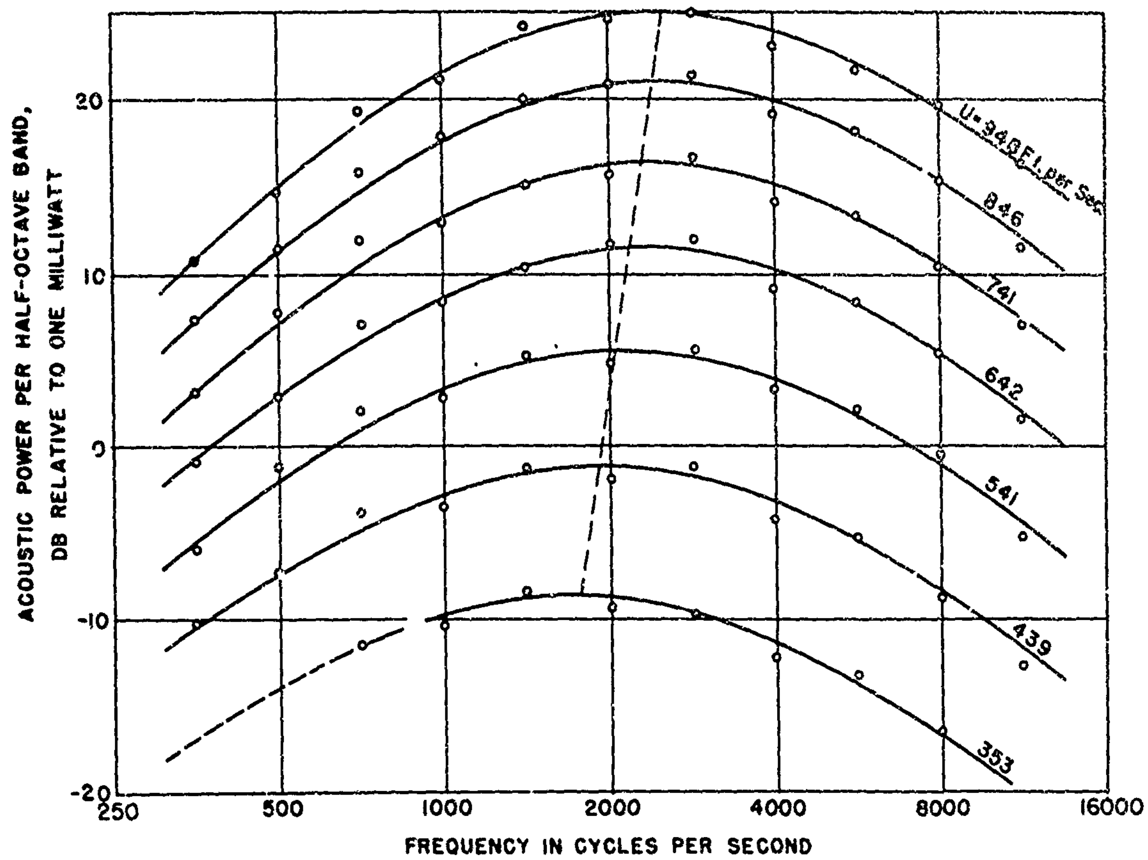

Figure 3 - Acoustic Power Radiated by the 1.53 Inch Diameter Air Jet as a Function of Frequency and Jet Velocity

power coefficient associated with each of these is about 1 db; except for the test tank calibration, for which an uncertainty of about 3 db exists. The consequent over-all probable error is about 4 db. The estimate assumes that the temperature gradients do not in themselves constitute an additional significant mechanism of sound production.

The broken lines in Figures 3 and 4 indicate approximately the positions of the peaks in the sound spectra. Since considerable ambiguity is associated with the determination of the frequency of the peak, a more detailed description of its variation with flow velocity is hardly warranted and some reservation should accompany acceptance even of the apparent trends indicated. The conclusion seems justified, however, that the frequency is nearly independent of the flow velocity rather than proportional to the latter as might have been expected. Figure 7 shows the dimensionless ratio $\frac{f_p D}{c}$ as a function of the Reynolds number, the frequency f_p here being the peak frequency as indicated in Figures 3 and 4. The apparent correlation obtained in presenting the frequency data in this manner suggests that the sonic velocity, not the flow velocity, is relevant in determining the frequency scale. This

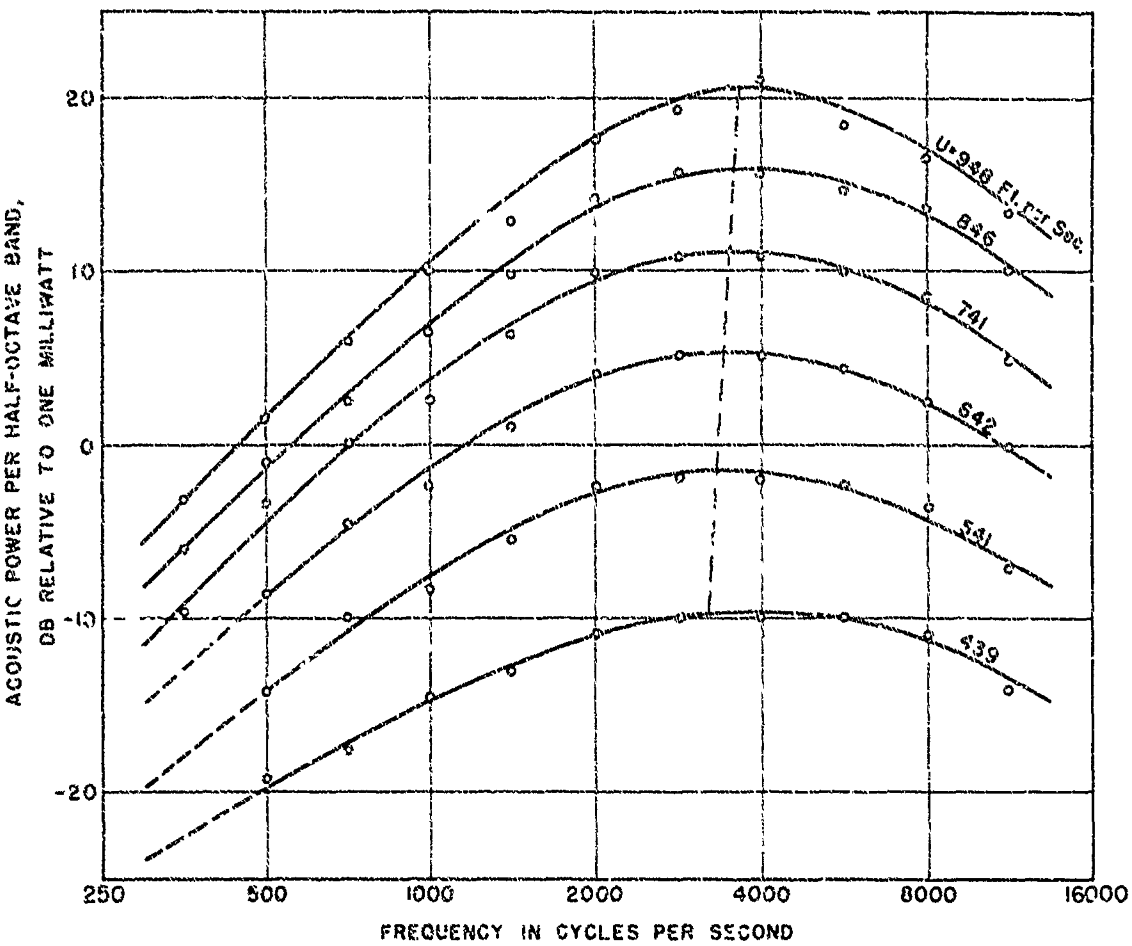

Figure 4 - Acoustic Power Radiated by the 0.765 Inch Diameter Air Jet as a Function of Frequency and Jet Velocity

conclusion, while quite admissible so far as dimensional considerations are concerned, is, nevertheless, somewhat surprising and should be further investigated since it would appear to have an important bearing on the theory of Reference 12.

The consideration that the frequency parameter $\frac{f_p D}{c}$ is the ratio of the jet diameter to the wavelength corresponding to the peak in the noise spectrum suggests, of course, the possibility that some resonance phenomenon associated with the linear dimensions of the nozzles plays a role in determining the spectrum shape. On the other hand its manner of variation with the Reynolds number lends some support to the hypothesis that the wavelength of the most strongly radiated sound is related rather to the thickness of the turbulent shear layer. In attempting to evaluate the present evidence, two considerations must be noted: first, the determination of the frequency of the peak in the spectrum is, as noted, not precise; and second, the lack of exact geometric similarity in the upstream portions of the two nozzles

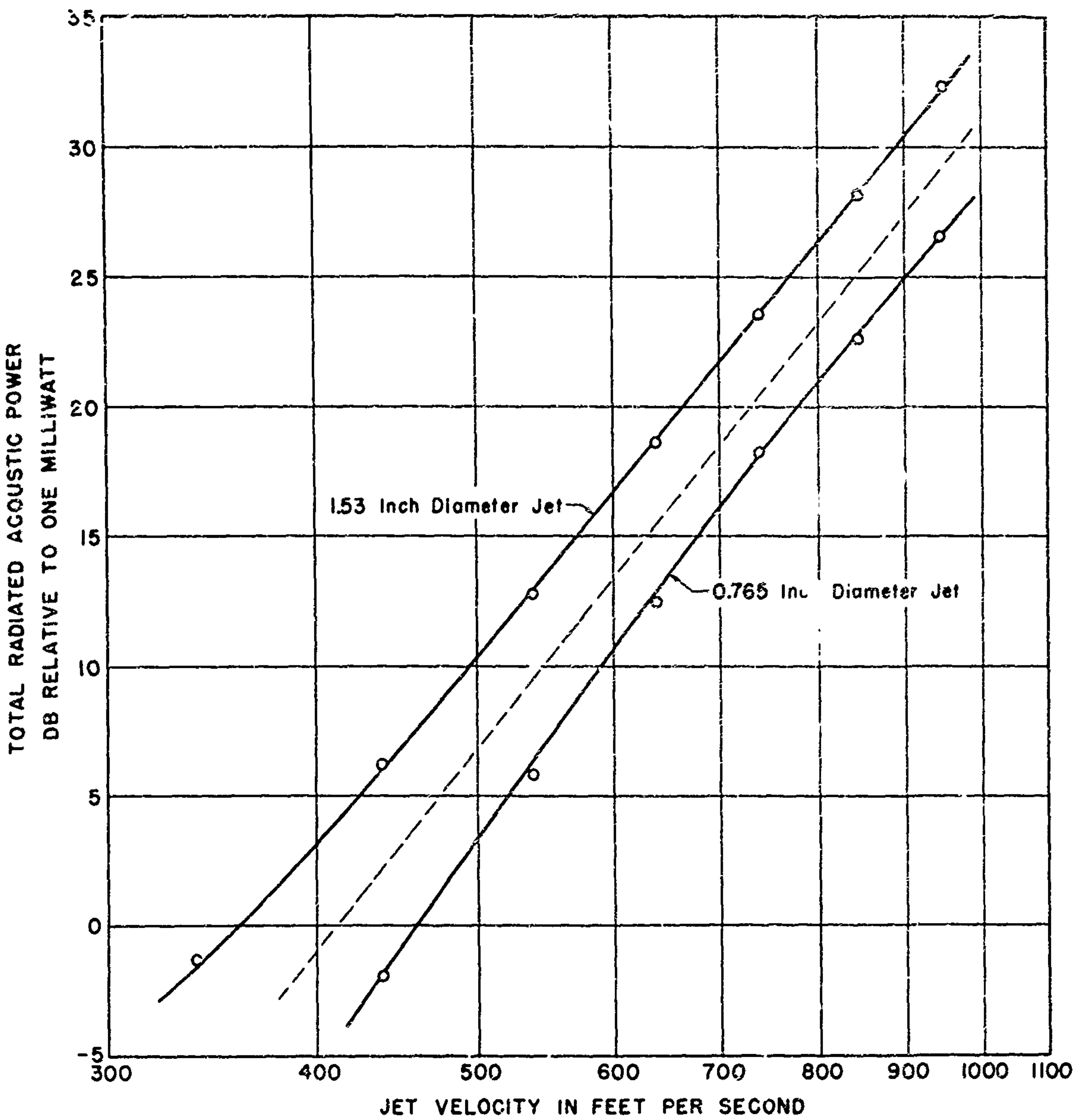

Figure 5 - Total Acoustic Power Radiated by Two Subsonic Air Jets as a Function of Jet Velocity

forestalls the conclusion that duplication of the Reynolds number provides exact duplication of the velocity profile. It is quite possible, and even likely, that, given exact geometric similarity, the frequency spectrum, however described, will depend upon both the Mach and Reynolds numbers. On the basis of the evidence presented, this would seem to be the case,

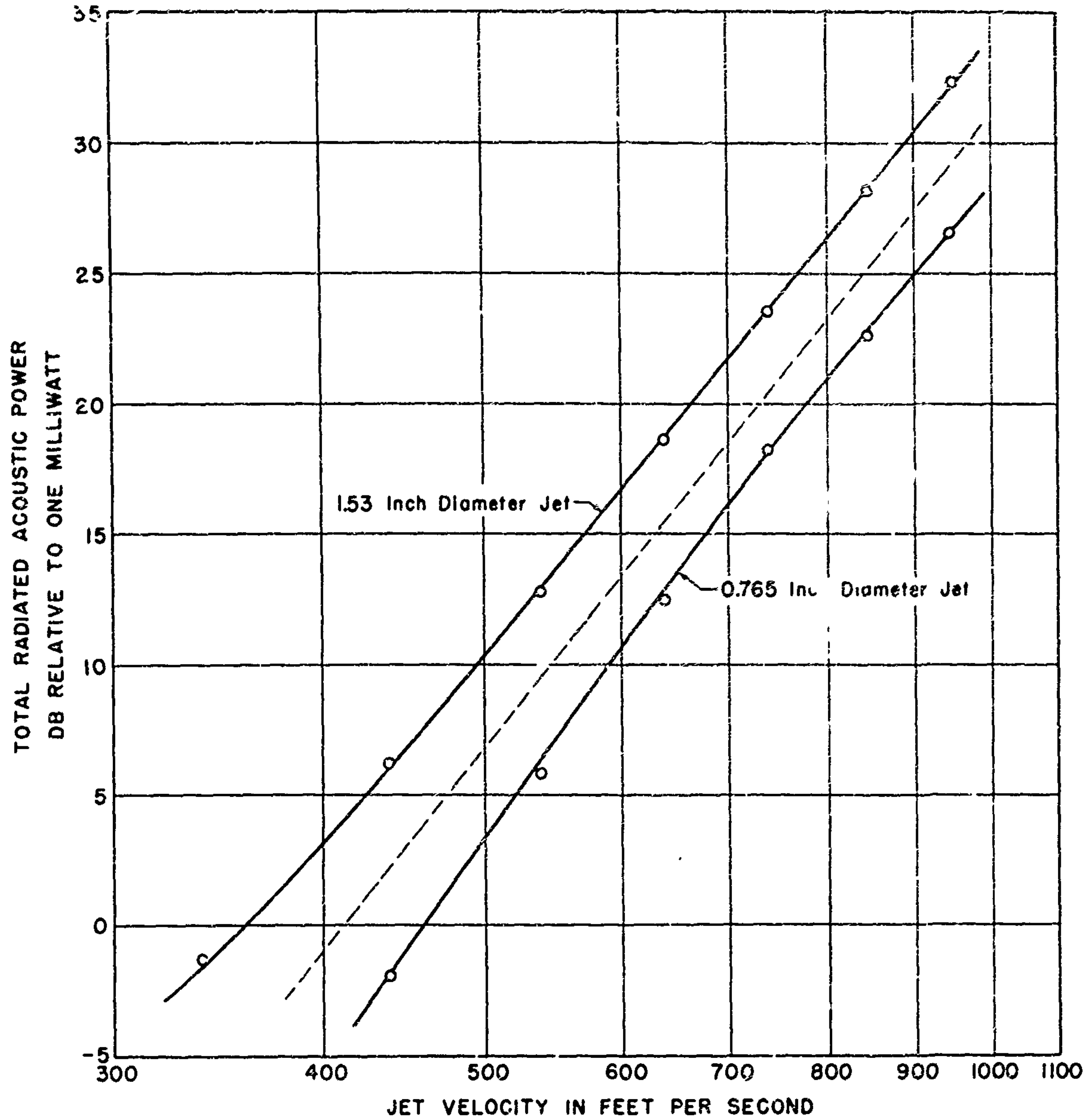

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TABLE 1

Summary of Data

Jet Velocity, U, ft/sec	Jet Temp. deg F	Reynolds Number $\frac{UD}{\nu} \times 10^{-5}$	Mach No. $\frac{U}{c}$	Total Acoustic Power, P_t milliwatts	Acoustic Power Coefficient $K = \frac{P_t}{c^{-5}U^8D^2}$
0.765 in. Dia. Jet - Room Temp. 70 deg F					
948	6	3.75	0.841	450	0.96
846	13	3.35	0.752	190	1.00
741	16	2.92	0.659	66	1.03
642	23	2.54	0.571	18	0.83
541	33	2.14	0.481	3.8	0.72
439	39	1.76	0.390	0.65	0.65
1.530 in. Dia. Jet - Room Temp. 65 deg F					
943	0	7.54	0.846	1650	0.85
846	4	6.75	0.755	660	0.85
741	14	5.90	0.661	230	0.86
642	26	5.11	0.573	75	0.84
541	36	4.31	0.484	19	0.86
439	44	3.49	0.392	4.2	1.0
353	50	2.81	0.315	0.8	1.2

SUMMARY AND CONCLUSIONS

The experiments described indicate that the ratio of acoustic power radiated to mechanical power expended by circular jets is proportional to the fifth power of the Mach number. The proportionality factor was determined to be of the order of 2×10^{-4} for jets produced by two nozzles tested, temperature differences between the issuing jet and the surrounding medium being slight.

The frequency scale of the noise spectrum appears to be related to the sonic velocity (rather than the flow velocity) and the linear dimensions of the flow system, perhaps to the thickness of the turbulent shear layer. The evidence is not conclusive, however.

Quantitative estimates of the noise level associated with types of flow systems other than those tested are difficult becasue of possible differences in the nature of the turbulent shear layers.

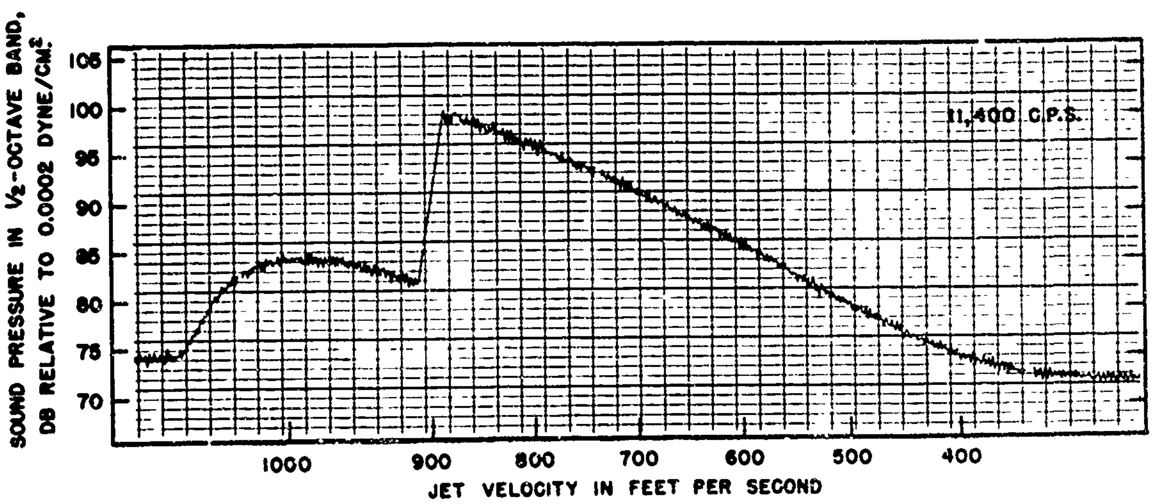
APPENDIX

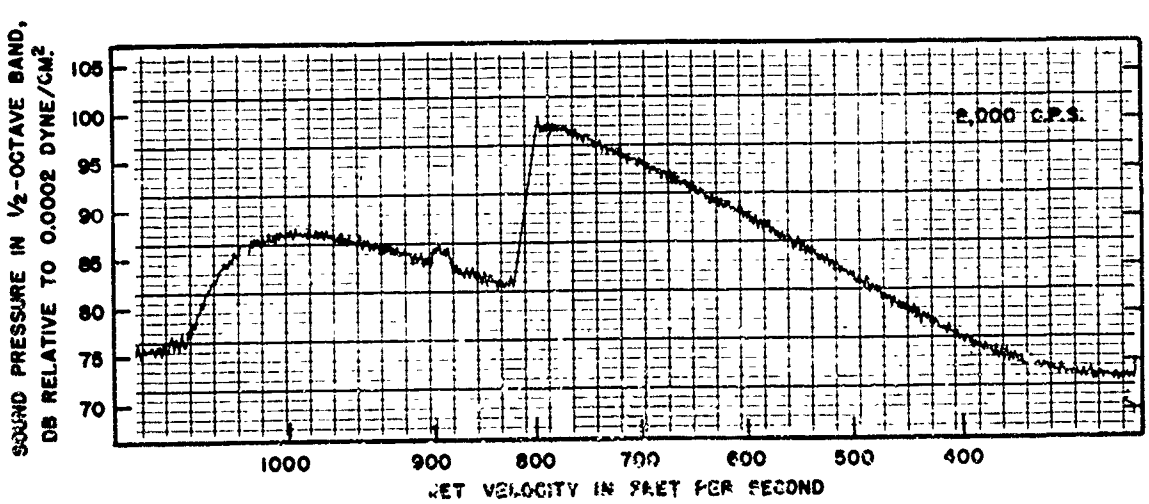
SOUND-LEVEL RECORDS FOR THE 1.53- AND 0.765-INCH AIR JETS

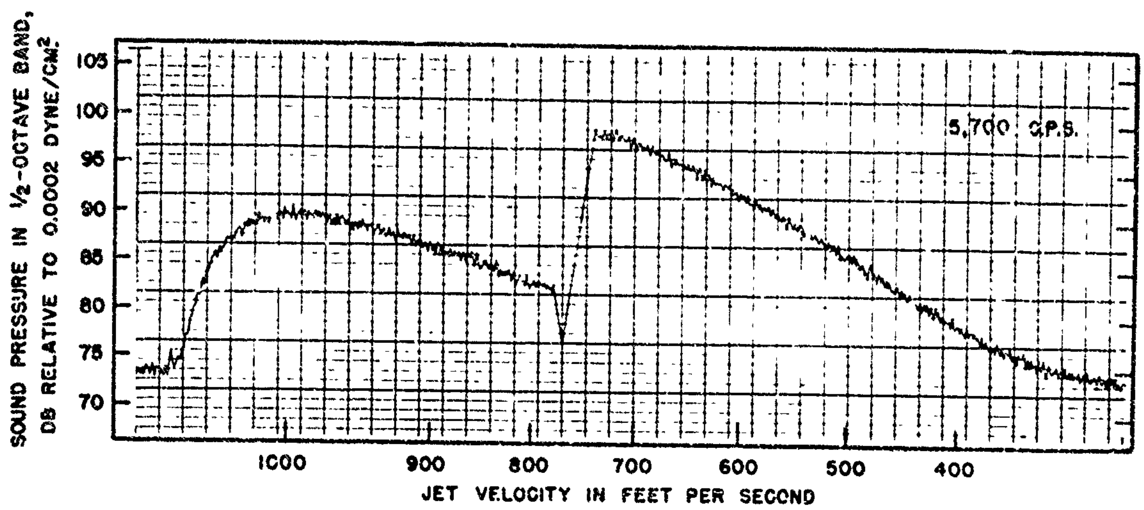
Figures 8 and 9 are reproductions of the sound-level records for the two air jets tested.

Figure 8 - Reproductions of Sound Level Records of Noise in Half-Octave Bands Centered at Indicated Frequencies for 1.53-Inch Air Jet

Discontinuities in the records correspond to a 20 db change in amplifier gain. The sound pressure scale refers to the right-hand portion of the record; for the portions at lower gain, the sound pressure level is 20 db higher than indicated by the scale. The effective distance at which these pressures were measured is 1.5 feet (see text).






SOUND PRESSURE IN ½-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
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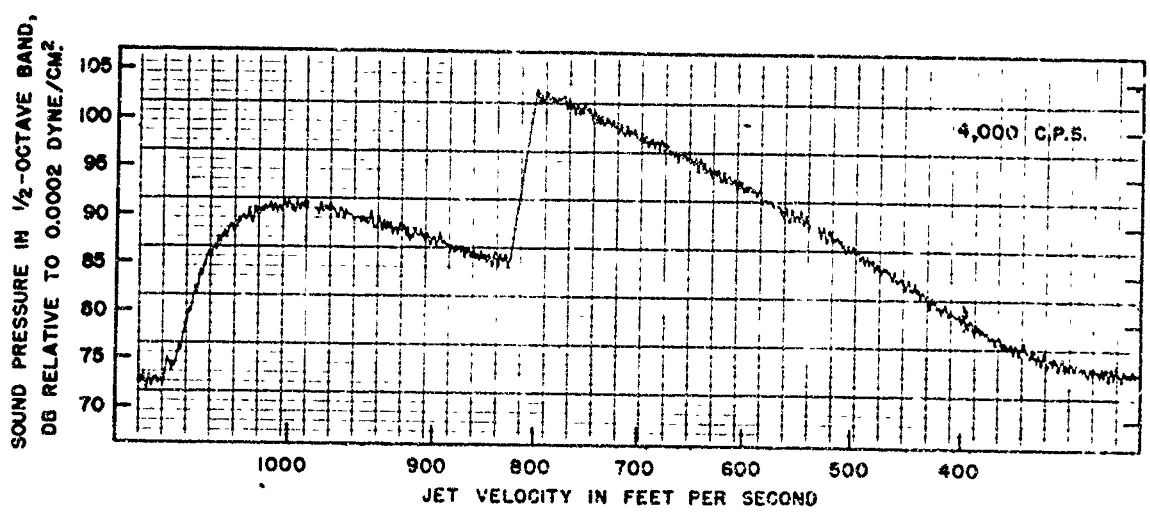
JET VELOCITY IN FEET PER SECOND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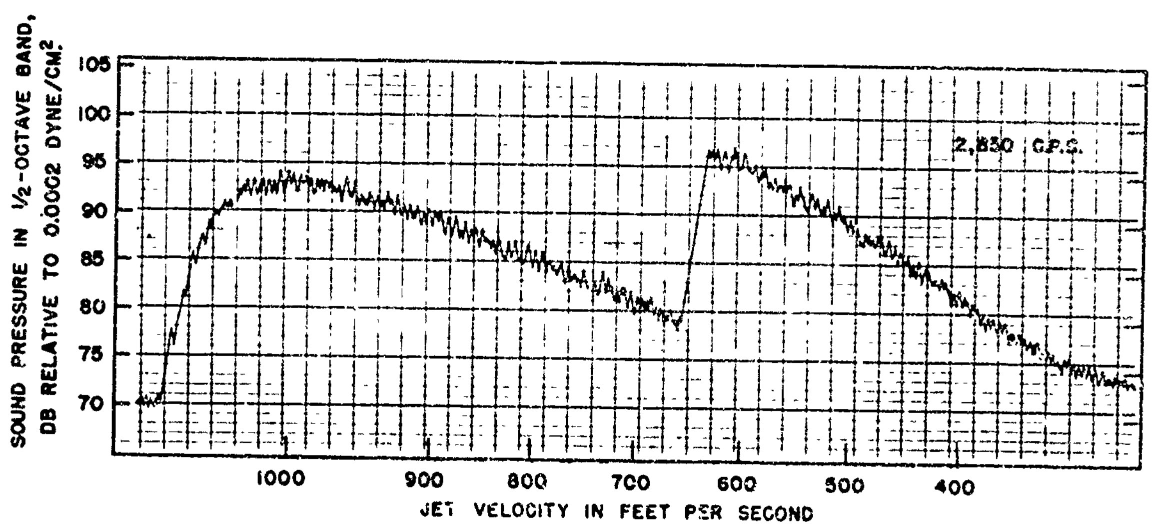
SOUND PRESSURE IN ½-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
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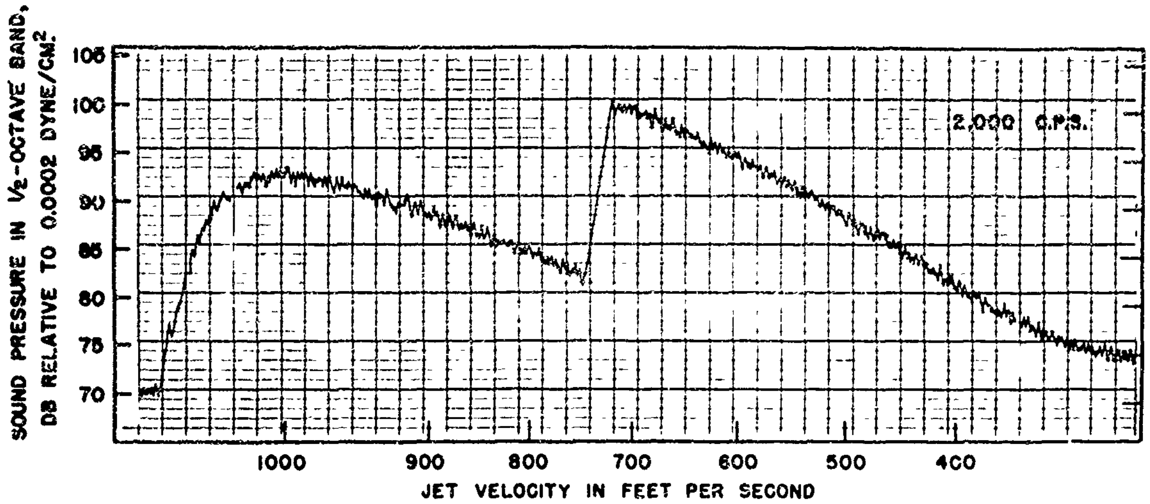
SOUND PRESSURE IN 1/2-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
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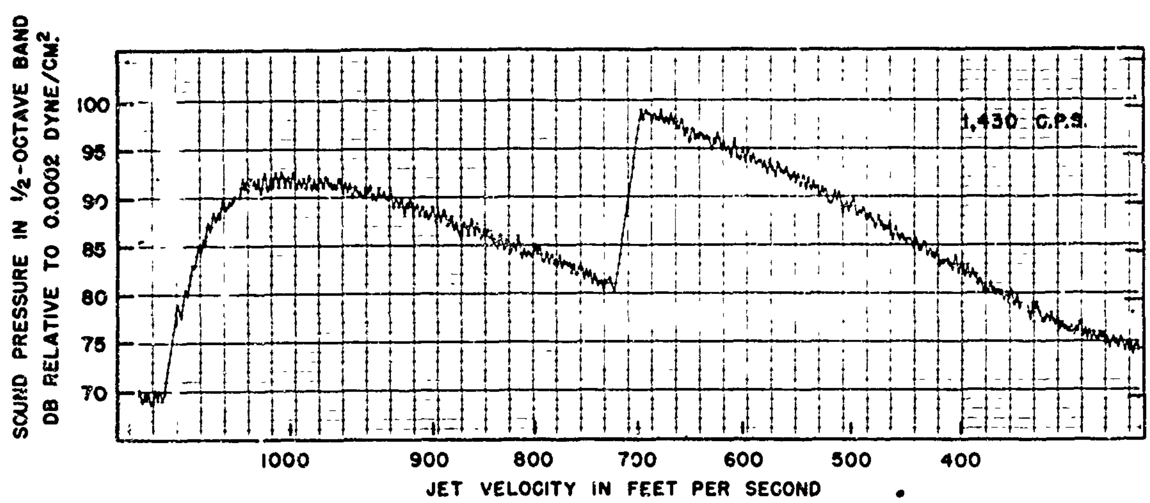
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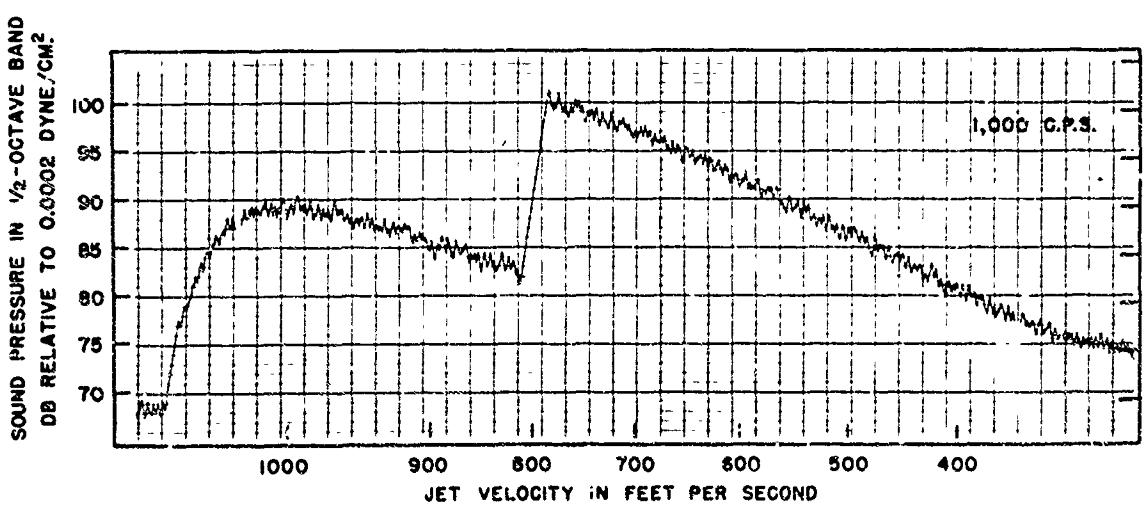
SOUND PRESSURE IN 1/2-OCTAVE BAND DB RELATIVE TO 0.0002 DYNE/CM²
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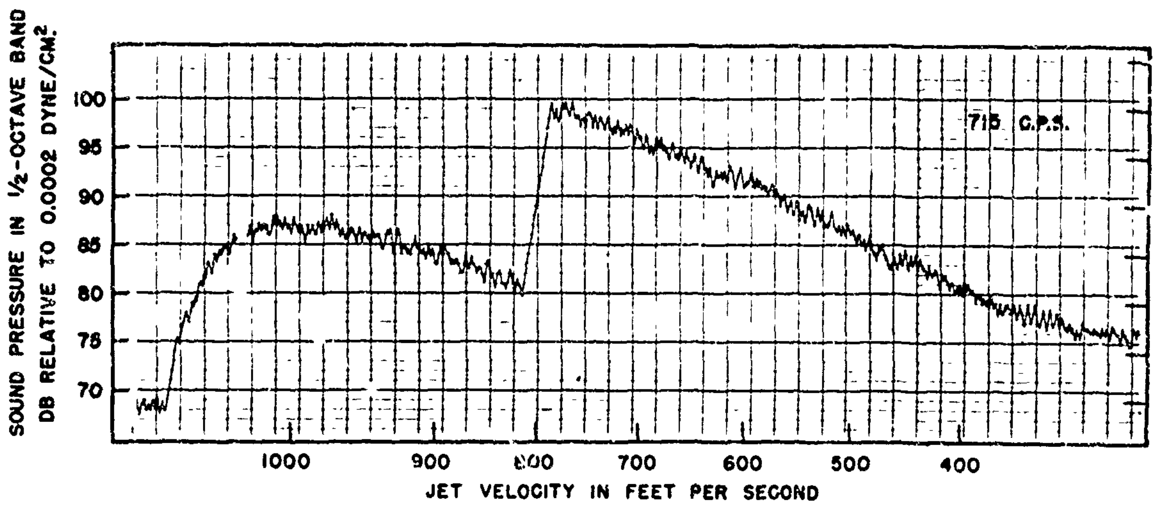
SOUND PRESSURE IN ½-OCTAVE BAND
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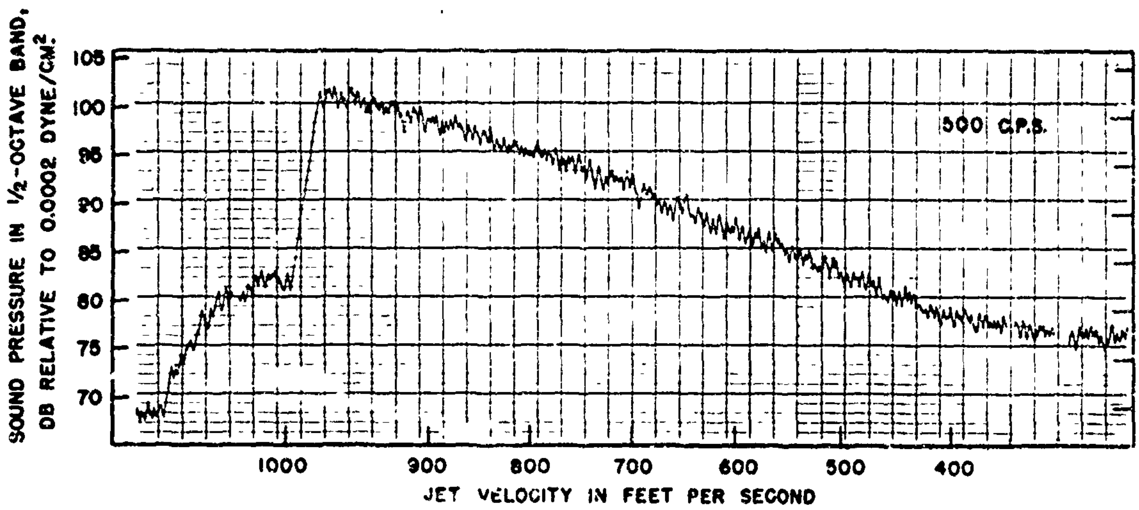
400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN ½-OCTAVE BAND,
DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
500 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND

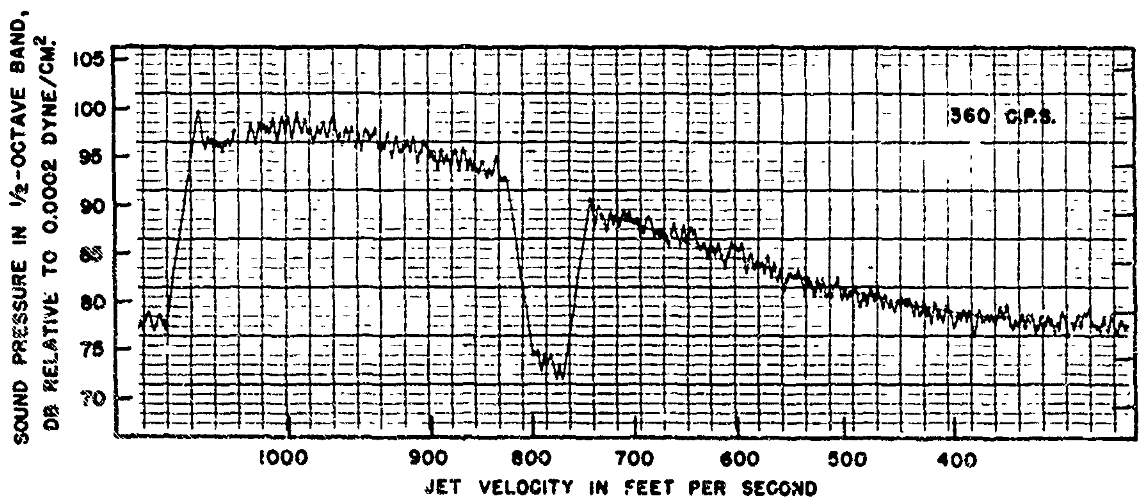
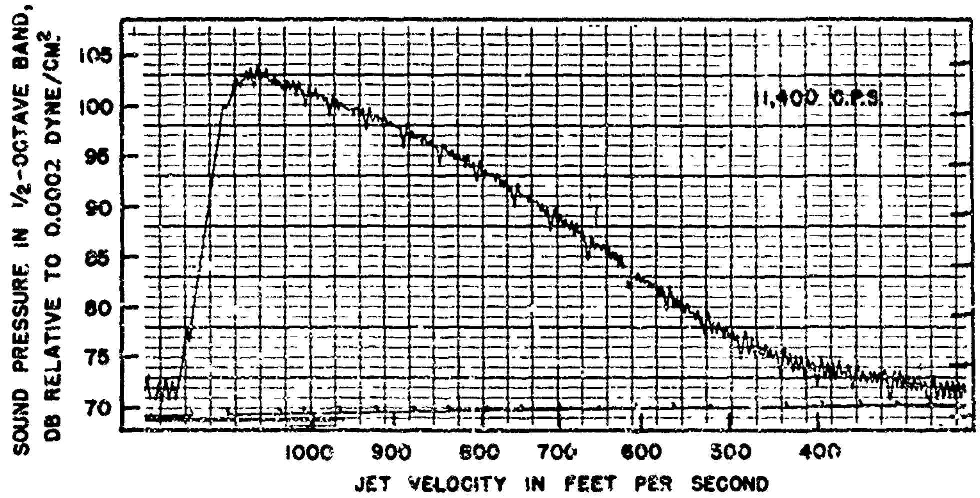
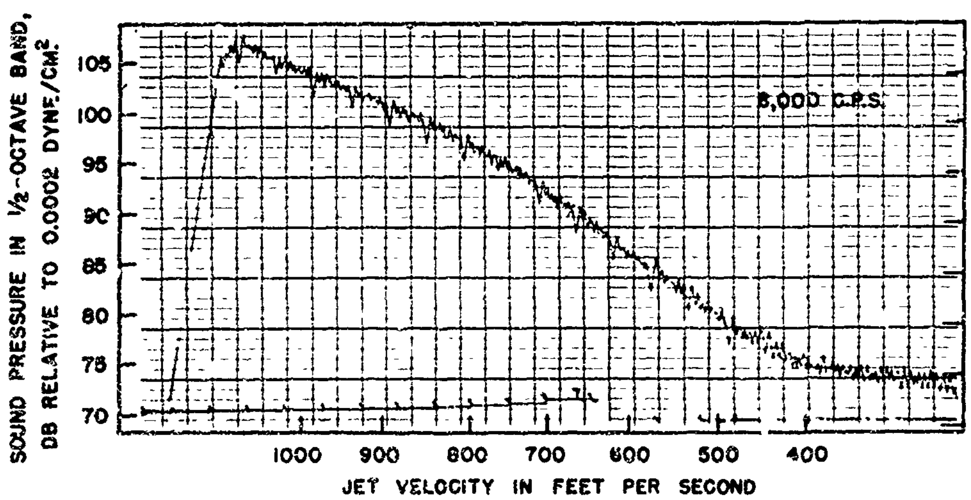
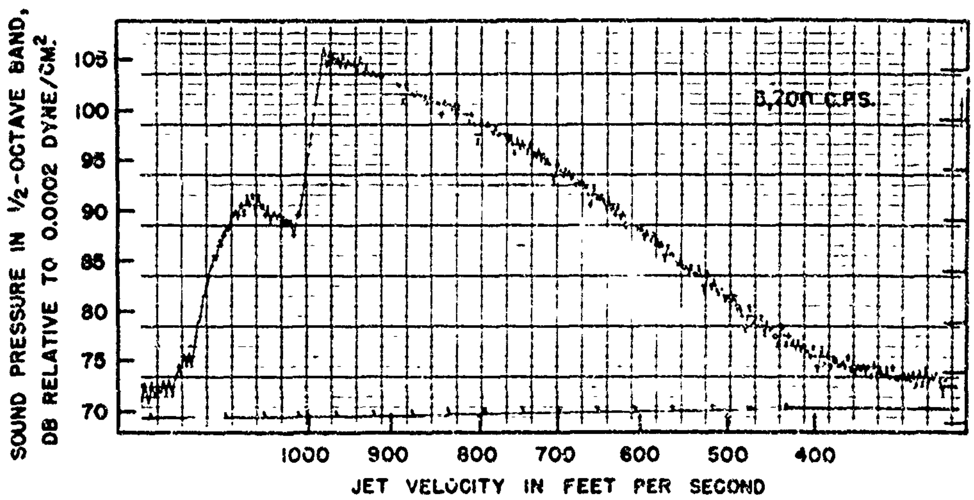

SOUND PRESSURE IN ½-OCTAVE BAND,
DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
360 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND

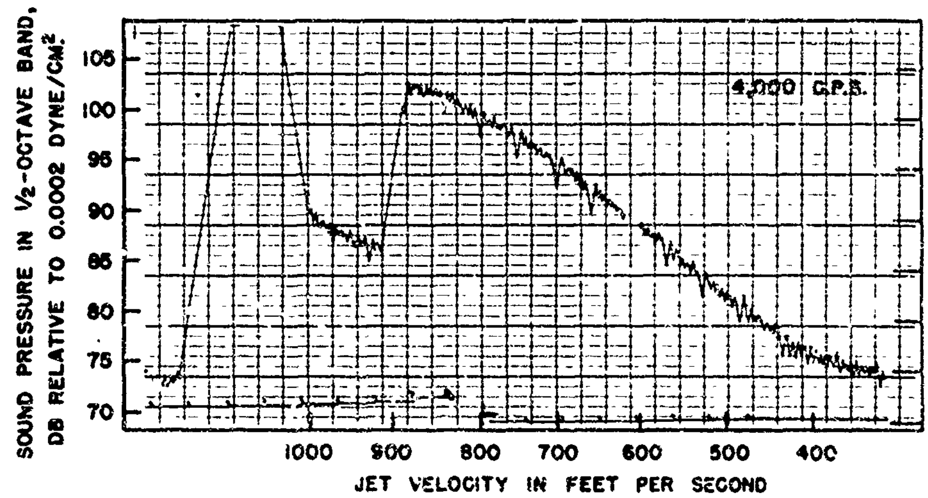
Figure 9 - Reproductions of Sound Level Records of Noise in Half-Octave Bands Centered at Indicated Frequencies for 0.75-Inch Air Jet

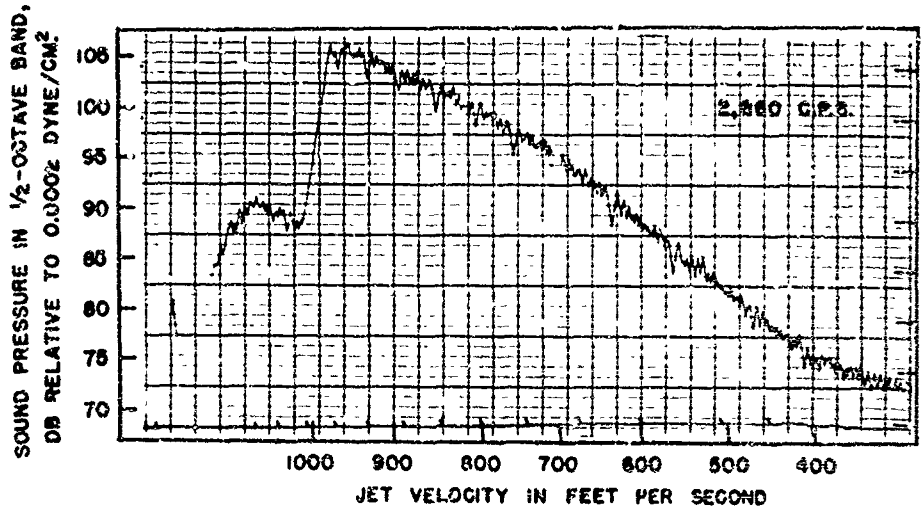
Discontinuities in the records correspond to a 20 db change in amplifier gain. The sound pressure scale refers to the right-hand portion of the record; for the portions at lower gain, the sound pressure level is 20 db higher than indicated by the scale. The effective distance at which these pressures were measured is 1.5 feet (see text).

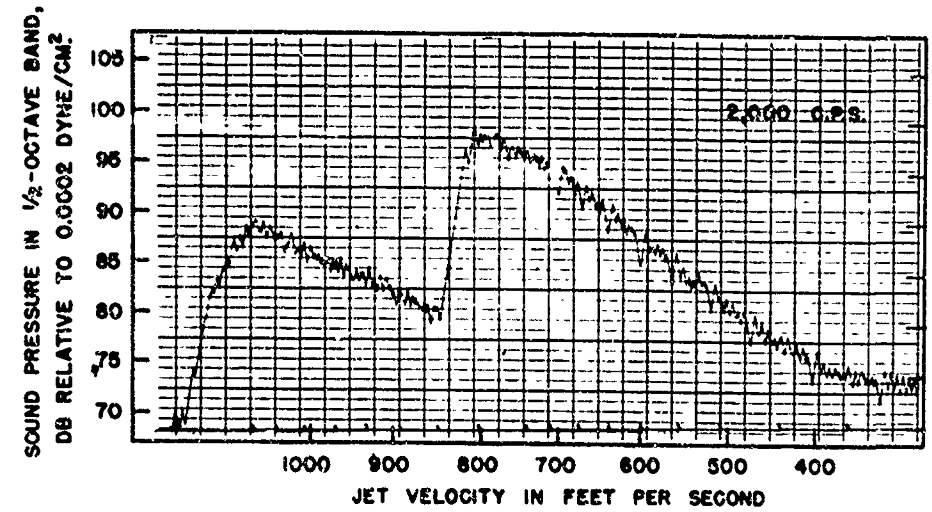


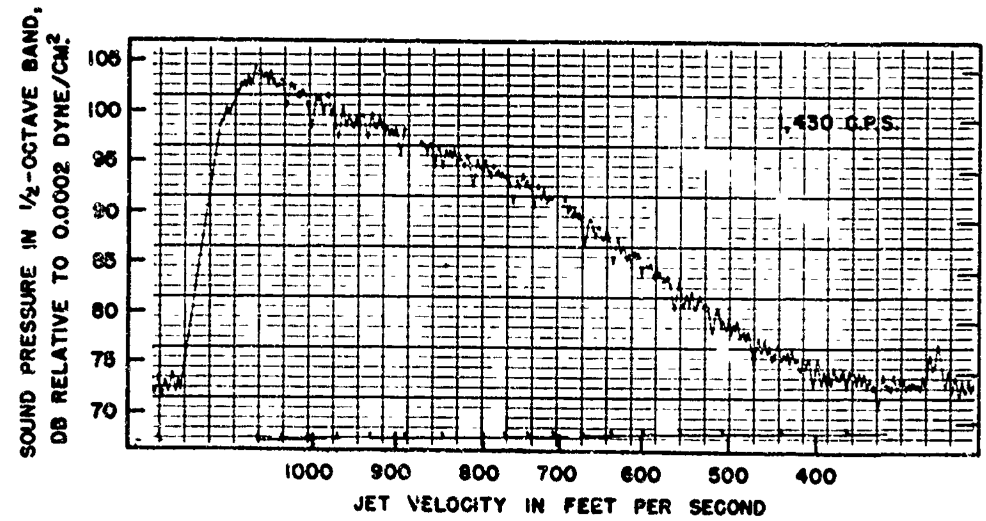


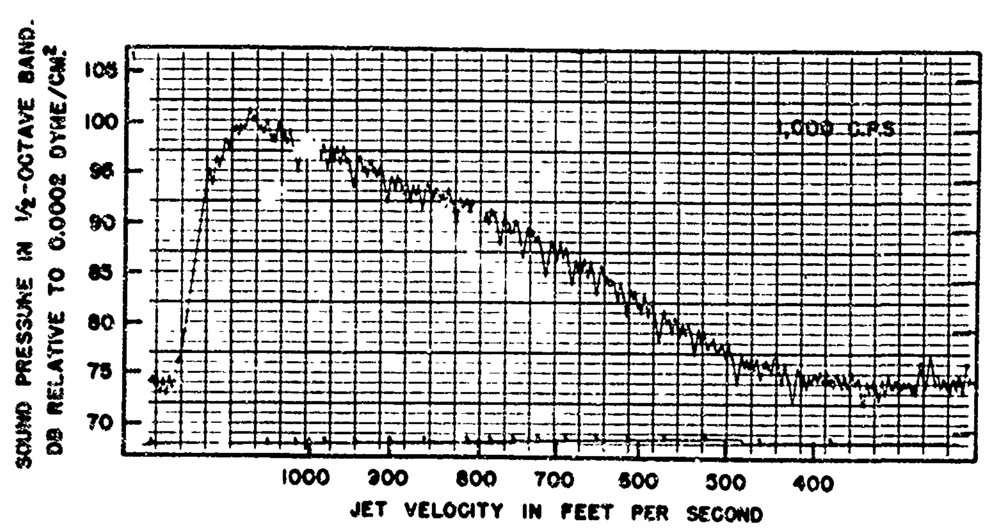

SOUND PRESSURE IN ½-OCTAVE BAND,
DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
3,200 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND

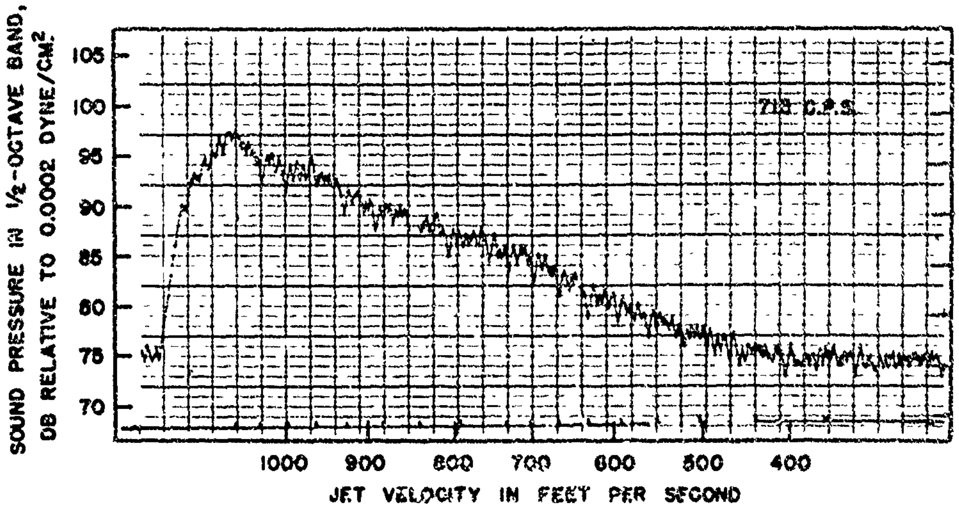

SOUND PRESSURE IN ½-OCTAVE BAND,
DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
4,000 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND

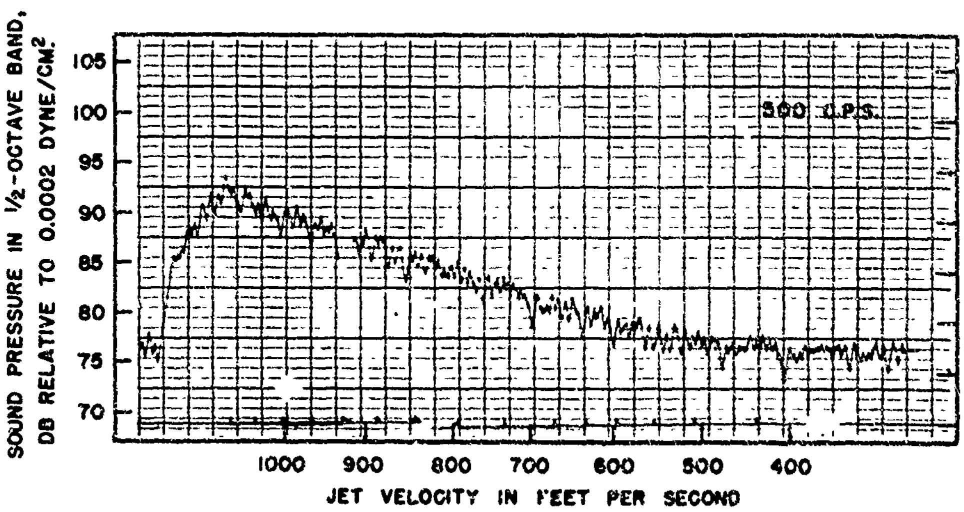

SOUND PRESSURE IN ½-OCTAVE BAND,
DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
2,560 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND

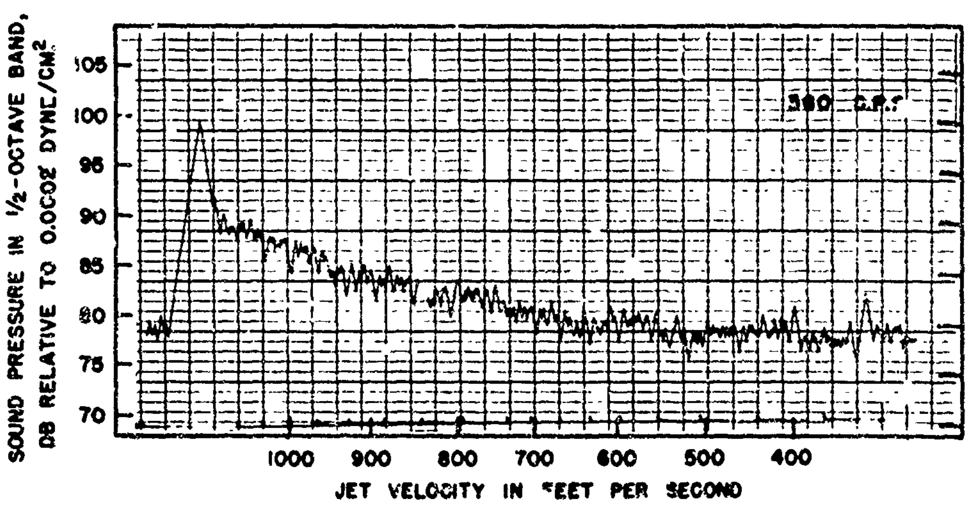

SOUND PRESSURE IN ½-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
2,000 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN ½-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
1,430 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN ½-OCTAVE BAND. DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
1,000 C.P.S.
1000
900
800
700
600
500
400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN 1/2-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
713 C.P.S.
1000 900 800 700 600 500 400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN 1/2-OCTAVE BAND, DB RELATIVE TO 0.0002 DYNE/CM²
105
100
95
90
85
80
75
70
500 C.P.S.
1000 900 800 700 600 500 400
JET VELOCITY IN FEET PER SECOND


SOUND PRESSURE IN 1/2-OCTAVE BAND, DB RELATIVE TO O.OCO2 DYNL/CM²
105
100
95
90
85
80
75
70
1000 900 800 700 600 500 400
JET VELOCITY IN FEET PER SECOND

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