WADD TECHNICAL REPORT 61-21
VOLUME II

# FUNDAMENTAL STUDY OF JET NOISE GENERATION AND SUPPRESSION

## VOL. II — BIBLIOGRAPHY

*PREPARED BY*
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*CHICAGO, ILLINOIS*

CONTRACT No. AF 33(616)-6976

*DECEMBER 1960*

PROPULSION LABORATORY
WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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PROPULSION LABORATORY

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UNITED STATES AIR FORCE
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## FOREWORD

This report was prepared by the Armour Research Foundation of Illinois Institute of Technology, Chicago, Illinois, on Air Force Contract AF 33(616)-6976, under Task Nr 30212 of Project Nr 3066, "Fundamental Study of Jet Noise Generation and Suppression". The work was administered under the direction of the Propulsion Laboratory, Wright Air Development Division. Mr. Buchanan was task engineer for the laboratory.

The work was begun in February 1960 and ended in December 1960.

The following scientists and engineers cooperated on this program: W. C. Sperry, Research Physicist and Project Engineer, E. G. Grimsal, Associate Physicist, Physics Research, C. C. Miesse, Senior Scientist, J. Ash, Senior Research Engineer and O. Curth, Research Engineer, Fluid Dynamics and Systems Research. Technical Information Research personnel who made significant contributions to the program were Ann Wennerberg, Elizabeth Isakson, and Roberta Winans.

## ABSTRACT

A comprehensive survey of the American and foreign literature of jet noise generation and suppression resulted in a two-volume report. Volume II of this final report consists of a two-part bibliography of references selected from 1150 documents. Part I of the bibliography contains a chronological list of 537 documents; an annotated, further selection of 73 documents comprises Part II.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

ERNEST C. SIMPSON
Chief, Turbine Engine Branch
Propulsion Laboratory
Aeromechanics Division

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## INTRODUCTION

The objective of this program was to extend the theories of jet noise generation and suppression. Toward this end, a comprehensive study of the technical literature published in the United States and foreign countries was made by The Technical Information Research staff.

The literature search was begun in February 1960 and ended in September 1960. Selections were based on subject categories suggested by the scientists and engineers who supervised the study and wrote the theoretical discussion to be found in Volume I of this final report. The major subject categories were:

1. Nonlinear acoustics
2. Nonlinear differential equations
3. Nonlinear mechanics
4. Fluid characteristics affecting noise
5. Jet parameters related to noise
6. Jet suppression devices

The survey was based on secondary sources and supplemented by information from primary sources when necessary. The secondary sources covered were the following:

| Title | Coverage (Inclusive Dates) |
|---|---|
| Aeronautical Engineering Review | 1950-1960 |
| Applied Mechanics Review | 1953 |
| Applied Science and Technology Index | 1959 |
| Engineering Index | 1950-1959 |
| Index Aeronauticus | 1950-1960 |
| Mathematics Review | 1945-1960 |
| Official Gazette | 1960 |
| Science Abstracts; Section A (Phys. Abs.) | 1953 |
| Technical Abstract Bulletin | 1959-1960 |

The bibliography is divided into two parts. The first part consists of unannotated references chosen from the 1150 documents which were evaluated during the program. They are considered to be significant contributions to the basic subject categories mentioned above. These references are arranged chronologically by year and within each year alphabetically according to author.

The second part consists of annotated references which were essential to the theoretical discussions to be found in Volume I. They are arranged alphabetically according to author. The name or names of the scientific personnel who selected each reference follows each annotation.

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# PART II

# ANNOTATED BIBLIOGRAPHY

PART II

1. Adams, M. C. On shock waves in inhomogeneous flow. J. Aeronaut. Sci. 16, 685-90, Nov. 1949. In connection with certain problems involving mixed subsonic-supersonic flow fields, and especially problems of normal shock waves in channels, it may become important to determine the configuration of a nominally "normal" shock wave in a slightly inhomogeneous steady field of flow. In this note it will be shown that the position assumed by the shockwave, its strength, and the details of the flow behind it can be calculated by a small perturbation theory, assuming that the velocity disturbances in the supersonic region are small compared to a parallel stream velocity. This calculation will be carried out in detail for the two-dimensional case-i. e., the case of plane disturbances of a parallel stream. The extension to axisymmetric cases would seem to offer no essential difficulties.
It will be necessary to account for first-order vorticity in the subsonic region; this can be done by means of the differential equation derived by Sears. Detailed results will be presented for two different typical disturbances profiles. (Ash)

2. Blokhintsev, D.I. Acoustics of a nonhomogeneous moving medium. NACA TN-1399, Feb. 1956. (Trans.) The theoretical basis of the acoustics of a moving nonhomogeneous medium is considered in this report. Experiments that illustrate or confirm some of the theoretical explanations and derivations of these acoustics are also included. (Ash)

3. Burgers, J. M. A mathematical model illustrating the theory of turbulence. Advances in Appl. Mech. 1, 171, 1948. The application of methods of statistical analysis and statistical mechanics to the problem of turbulent fluid motion has attracted much attention in recent years. From the theoretical side we are faced with the necessity of investigation of a complicated system of nonlinear equations, in order to find out enough about the properties of the solutions of these equations that insight can be obtained into the various patterns exhibited by the field and that data can be derived concerning the relative frequencies of these patterns, in hope that in this way a basis may be found for the calculation of important values. The difficulties encountered are of a twofold nature: in part they are connected with the complicated geometrical character of the hydrodynamical equations (vertical character of the velocity, condition imposed by the equation of continuity, properties of vortex motion); in part they are dependent upon the presence of nonlinear terms, containing derivatives of the first order of the velocity components, along with derivatives of the second order multiplied by the very small coefficient of viscosity. The latter feature in particular is responsible for a number of important characteristics of turbulence, among which are prominent those connected with the balance of energy and with the appearance of dissipation layers. These layers (boundary layers along the walls and similar phenomena in the interior of the field) play an important part in the energy exchange, as they represent the main regions where energy is dissipated. (Ash)

4. Callaghan, E. E. Investigations of acoustic, thrust, and drag characteristics of several jet noise suppressors. Soc. Automotive Engrs. Preprint 57-R, 1959. Although a very intensive program has been underway throughout the country, it has only been recently that we have obtained sufficient insight into the basic mechanism of jet noise production so that we can approach suppressor design on a rational basis. This does not mean that we have not been successful in achieving noise reduction in the past, but I think everyone in the field will admit that a lot of our effort in research and development was of the "ad hoc" variety. In the past year or so the muddy waters have cleared somewhat and we are able to rationalize our previous results to a great extent. It is not necessary to discuss the extensive work of Greatrex of Rolls-Royce or the efforts of Boeing, Douglas, and Pratt and Whitney; each has made substantial contributions both as to actual hardware and research. It is the accumulation of all their work and our own which has permitted us to reason a posteriori and begin to place suppressor design on a truly design basis. (Sperry)

5. Callaghan, E. E. and Coles, W. D. Far noise field of air jets and jet engines. NACA Rept. 1329, 1957. An experimental investigation was conducted to study and compare the acoustic radiation of air jets and jet engines. A number of different nozzle-exit shapes were studied with air jets to determine the effect of exit shape on noise generation. Circular, square, rectangular, elliptical-convergent nozzles, convergent-divergent, and plug nozzles were investigated.

At low jet pressure ratios (less than 2.2), the nozzle-exit shape has a negligible effect on the sound field; at higher pressure ratios the convergent and plug nozzles exhibited discrete frequencies associated with shockwaves in the jet. The convergent-divergent nozzle showed a substantial reduction in sound power at its design pressure ratio. This reduction resulted from the elimination of discrete frequencies caused by shock formations.

The acoustic power radiated by jets issuing from conical-convergent nozzles was correlated by the Lighthill parameter for both air jets and non-afterburning jet engines. The ratio of sound power to Lighthill parameter was $2.7 \times 10^{-5}$ for both air jets and jet engines. This result shows that the principal contribution to jet engine noise is the turbulent mixing of the jet with the surrounding medium. The sound power radiated by an afterburning jet engine was lower than indicated by the Lighthill relation.

Correction of sound-pressure-level directional data by the nozzle area ratio and the eighth power of the velocity ratio gave good agreement between engine and air-jet data.

The spectral distributions of the sound power for the engine and the air jet were in good agreement for the case where the engine data were not greatly affected by reflection or jet interference effects. Such power spectra for a subsonic or slightly choked engine or air jet show that the peaks of the spectra occur at the Strouhal number of 0.3. (Ash, Curth)

6. Chang, C. T. Interaction of plane shock and oblique plane disturbances with special reference to entropy waves. J. Aeronaut. Sci. 24, 675-82, Sept. 1957. Theoretical investigation indicates that three kinds of disturbances exist in the perturbed field downstream of shock, namely: the entropy mode, the vorticity mode, and the sound mode. It is shown that the nature of the sound wave generated depends on the orientation of the upstream disturbances. Some governing equations and illustrative examples are given for the interaction between the plane normal shock and the sinusoidal entropy wave. (Ash)

7. Chang, C. T. On the interaction of weak disturbances and a plane shock of arbitrary strength in a perfect gas. Johns Hopkins Univ., Doctoral Dissertation, 137pp., 1955. The present work deals specifically with the unsteady (including steady case as a special case) interaction of an upstream entropy disturbance with a plane shock wave in a uniform stream of a nonviscous, perfect gas.

   In Part I of the work, a general description of the governing equations and the boundary conditions for a first-order perturbed flow downstream of the shock are presented.

   In Part II, the influence on the downstream flow-field due to the interaction of a weak upstream entropy disturbance with a plane shock wave of infinite extent is investigated. Subsequently, the reflection of sound waves, (and hence the simultaneous generation of other modes: vorticity and entropy) at the shock due to a sound wave coming downstream is studied.

   In Part III, a more practical example is considered where the shock is assumed to be produced by an infinite wedge placed in a supersonic stream. The analysis starts with a steady interaction; the upstream disturbance is then taken as a function varying periodically both with respect to time and to space. Finally, the upstream disturbance is assumed to be a step-function with a constant drifting speed projected along the shock. (Ash)

8. Chu, B. T. and Kovasznay, L. S. G. Non-linear interactions in a viscous heat-conduction compressible gas. J. Fluid Mech. 3, 494-514, 1957-1958. The linearized equations of motion show that in a viscous heat-conducting compressible medium three modes of fluctuations exist, each one of which is a familiar type of disturbance. The vorticity mode occurs in an incompressible turbulent flow, the entropy mode is familiar as temperature fluctuations in low speed turbulent heat transfer problems, and the sound mode is the subject of conventional acoustics. A consistent higher order perturbation theory is presented with the only restrictions being that the Prandtl number is 3/4 and the viscosity and heat conductivity are monotonic functions of the temperature alone. The theory is based on expansion of the disturbance fields in powers of an amplitude parameter $\alpha$. The non-linearity of the full Navier-Stokes equations can be interpreted as interaction between the three basic modes; in order to help physical insight the interactions are classed as 'mass-like', 'force-like', and 'heat-like' effects.

Besides the amplitude parameter $a$ there is another subsidiary non-dimensional parameter $\epsilon$ which indicates that the relative importance of viscosity and heat conduction effects as compared to the inertial effects, $\epsilon$ is proportional to the ratio of the molecular mean free path and the characteristics length of the flow pattern (Knudson number). The main contribution of the paper is the outline of a consistent successive approximation of or an arbitrary order in $a$ and the presentation of explicit formulae for the second order (bilateral) interactions. (Grimsal)

9. Ciepluch, C. C., North, W. J., Coles, W. D. and Antl, R. J. Acoustic, thrust, and drag characteristics of several full-scale noise suppressors for turbojet engines. NACA TN-4261, Apr. 1958. An experimental investigation was conducted with an engine in the 10,000-pound-thrust class. The acoustic study was made with an outdoor thrust stand. Acoustic data are presented in terms of sound directionality, spectrum, and sound power. Aerodynamic properties of the suppressors were evaluated over a range of Mach numbers up to 0.5 in an altitude wind tunnel. The most efficient configurations from both acoustic and propulsive thrust considerations were a two-position mixing nozzle with ejector and a 12-lobe nozzle. At a Mach number of 0.5 the respective propulsive thrust losses were about 1 and 3 percent. Calculations indicate that these two configurations would reduce the noise heard during takeoff by 5 or 6 decibels. (Sperry)

10. Clark, W. E. and the staff of Bolt, Beranek and Newman, Inc. Noise produced by aircraft during ground run-up operations. AD 130763. Measurements of the noise field around six turbojet aircraft (T33-A, F84-G, F89-D, B-57, F84-F, and F86-D) and one propeller aircraft (C-124) during ground run-up operations are reported. Sound pressure levels in octave bands of frequency have been obtained for different operating conditions of the aircraft engines, at distances ranging from 100 to 1600 feet. These data are analyzed and the results reported in terms of the acoustic power level, directivity, and noise spectra. An empirical procedure is described for making engineering estimates of the characteristics of the noise field produced during ground run-up operations of jet aircraft. (Ash, Curth)

11. Cole, J. D. On a quasi-linear parabolic equation occurring in aerodynamics. Quart. of Appl. Math. 9, 225-36, Oct. 1951. The equation under discussion in this paper is the following:

$$(1)\quad \frac{\partial \mu}{\partial t} + \mu \frac{\partial \mu}{\partial x} = \nu \frac{\partial^2 \mu}{\partial x^2}$$

where $\mu = \mu(x, t)$ in some domain and $\nu$ is a parameter. The occurrence of the first derivative in t and the second in x clearly indicates the equation is parabolic, similar to the heat equation, while the interesting additional feature is the occurrence of the non-linear term $\nu\,\partial\mu/\partial x$. The equation thus shows a structure roughly similar to that of the Navier-

Stokes equations and has actually appeared in two separate problems in aerodynamics. The aim of this paper is to study the general properties of (1) and relate the various applications. (Ash)

12. Cole, J. N., Von Gierke, H. E., et al. Noise radiation from fourteen types of rockets in the 1000 to 130, 000 pounds thrust range. AD 130794. Detailed noise characteristics were measured in fourteen types of rockets, with both solid and liquid propellants, in the thrust range from 1000 to 130, 000 pounds. Near field and far field levels on static fired and vertical launched rockets were measured under essentially free field conditions. Measurements and data reduction methods are described. Final results are given as near field sound pressure spectra, far field directivities, acoustic power spectra and pressure-time histories. This noise environment is studied as a function of several nozzle configurations and as a function of flame front action in jet stream. Generalization and correlation of the data results in a formula for the overall acoustic power level output of rockets, OA PWL = 78 · 13.5 $\log_{10} W_m$ db re $10^{-13}$ watts, where $W_m$ is the rocket jet stream mechanical power in watts. Also given is an approximate generalized power spectrum dependent upon nozzle diameter and jet flow characteristics. These correlations result in procedures for predicting far field noise environments produced by static fired or launched rockets. (Ash)

13. Coles, W. D. Jet engine exhaust from slot nozzles. NASA TN-D-60, Sept. 1959. Acoustic characteristics of nozzles 14:1 and 100:1 nozzle height-to-width ratios, including a jet-augmented-flap configuration with the 100:1 nozzle, were investigated using a full-scale turbojet engine installed in an airframe. Directional distribution of sound-pressure level, frequency distribution, overall sound power, and power-spectrum level are compared with circular-nozzle noise characteristics. An analysis of the potential noise generation of slot jets and circular jets, based on fundamental mixing-zone structure, is included. (Sperry)

14. Coles, W. D. and Callaghan, E. E. Full-scale investigation of several jet-engine noise-reduction nozzles. NACA TN-3974, Apr. 1957. A number of noise-suppression nozzles were tested on full-scale engines. In general, these nozzles achieved noise reduction by mixing interference of adjacent jets; that is, by using multiple-slot nozzles. Several of the nozzles achieved reductions in sound power of approximately 5 decibels (nearly 70 percent) with small thrust losses (approx. 1 percent).
The maximum sound-pressure level was reduced by as much as 18 decibels in particular frequency bands. Some of the nozzles showed considerable spatial asymmetry; that is, the sound field was not rotationally symmetrical.
A method of calculating the limiting frequency effected by such nozzles is presented. Furthermore, data are shown that appear to indicate that further reductions in sound power will not be easily achieved from nozzles

using mixing interference as a means of noise suppression. (Sperry)

15. Coles, W. D., Mihaloew, J. A. and Callaghan, E. E. Turbojet engine noise reduction with mixing nozzle-ejector combinations. NACA TN-4317, Aug. 1958. Maximum sound pressure level reductions of 12 decibels and sound power level reductions of 8 decibels were obtained with lobe nozzle and ejector combinations on two full-scale engines. The ejectors provided 3 to 5 decibels of the sound power level reduction. Several combinations of ejectors and nozzles were used and acoustic and engine performance data are presented. A study of jet profiles and boundaries at the ejector exit shows the effectiveness of the lobe nozzle and ejector combinations in diffusing the jet to a larger, lower velocity stream. Calculated noise reductions based on ejector exit flow conditions are not realized experimentally, probably because the noise generated inside the ejector is appreciable. (Sperry)

16. Corcos, G. M. Some effects of sound-reduction devices on a turbulent jet. J. Aero/Space Sci. 26, 717-22, Nov. 1959. The way in which ejectors, corrugated nozzles and multiple nozzles modify turbulent mixing and so reduce noise is explained. Noise reduction is primarily due to a decrease in turbulence in the mixing region effected by accelerating ambient air through a longitudinal pressure gradient before mixing it with the jet. The sheath of air reduces the lateral jump in mean axial velocity. An experiment at low speed with a corrugated nozzle is described. (Sperry)

17. Doelling, N., Dyer, I. and Mercer, D. M. A. The influence of engine design parameters and atmospheric conditions on the acoustic power output of turbojet engines. AD 91775. The study reported herein is restricted to engines operating at or near maximum revolution rate of the compressors. Further, the study is intended to cover turbojet engines of usual contemporary design, operating without thrust augmentation. Finally, only static engine operating conditions are considered, corresponding to ground or low speed take-off and landing operations. (Sperry)

18. Dyer, I., Franken, P. and Westervelt, P. J. Jet noise reduction by induced flow. J. Acous. Soc. Am. 30, 402-8, Aug. 1958. The effect on the generation of jet noise by the secondary air induction of a modified jet nozzle is analyzed. It is shown that the combination of the secondary air with the primary air of the jet creates a new jet stream of larger area, lower velocity, and lower noise generation. The decrease in noise radiation is found in terms of the area of the combined jet stream. Detailed check of the theory is not possible at present because measurements of the areas of the combined jet stream have not been generally made along with measurements of the noise. However, it is possible to estimate the upper limit on noise reduction obtained from the theory consistent with existing measurements. Qualitative conclusions from the theory with respect to the spectrum and directivity of the noise radiated by jets with modified nozzles are in accord with measurements. (Sperry)

19. Fowell, L. R. and Korbacher, G. K. A review of aerodynamic noise. AD 91311. A detailed review is presented of the theoretical and experimental advances that have been made in the study of aerodynamic noise and in devising means for its suppression. Since many workers in the fields of aerodynamics and aerophysics may be unfamiliar with acoustic principles, the necessary background of laws and ideas from the field of acoustics is included. The theories for noise caused by subsonic disturbances, which may include turbulence fields in overchoked jets, (Lighthill, Proudman) and for those noise sources peculiar to overchoked jets, (Lighthill, Powell, Ribner) are considered. Experimental results are quoted complete with numerous graphs, notes on correlation of data for model and engine jets, and a comparison with theory. The results of attempts at noise suppression are discussed, noting both untried and extensively tested suggestions. A list of references is included.
Those phases of aerodynamic noise research concerning which there is disagreement or in which there is confusion because of insufficient theoretical and experimental work, or which appear to have been neglected, are thus brought to attention.
It is hoped that this review will prove useful to the initiation of research programs in the field of aerodynamic noise and its control. (Ash)

20. Gordon, B. J. General Electric Company CJ805-23 noise level. (Informal Report). 26pp., Apr. 21, 1960. When the CJ805-23 aft-fan engine was first offered to the airline industry, General Electric stated that it would meet the noise criteria in existence at the time of its first service, and it would be as acceptable as the suppressed CJ805-3 turbojet engine. There is sufficient measured data to state that, unsuppressed, it does meet the the criteria established and is more acceptable than the suppressed CJ805-3 engine. In fact, CJ805-23 powered four-engined aircraft will be the quietest of the four-engined jet transports built in the country, and CJ805-23 powered twin-engined aircraft will be much quieter. Of more importance than the take-off noise level on approach conditions, CJ805-23 powered aircraft will be as quiet as those powered by the CJ805-3 and quieter than other jet transports currently in operation. (Sperry)

21. Greatrex, F. B. Jet noise. The Engr., pp. 23-5, 45-7, 92, 93, July 1-8, 15, 1955. Experimental measurements of the noise field around jet engines during ground-running, in flight while passing overhead of a community in take-offs and landings, and within the aircraft, with tests on a successful "corrugated" nozzle design to reduce sound levels. (Sperry)

22. Hollingsworth, M. A. and Richards, E. J. A Schlieren study of the interaction between a vortex and a shock wave in a shock tube. AD 140845. A method utilizing the reflected compression shock in a shock tube has been successfully developed to obtain Schlieren photographs of the sound wave pattern resulting from the interaction between a vortex and a shock wave. The interaction results in the propagation into the air behind the shock wave

of a sound wave of directionally varying intensity and sign. The amplitude of this sound wave appears to depend very directly upon the vortex strength: its dependence upon the shock strength is still under investigation. (Ash)

23. Hollingsworth, M. A. and Richards, E. J. On the sound generated by the interaction of a vortex and a shock wave. AD 140844. Recent work by Ribner has been utilized to estimate the distribution of intensity in the sound wave resulting from the interaction between a vortex and a shock wave, to obtain the order of magnitude of the sound pressures obtained and the dependence of their magnitude upon shock strength and vortex strength. The distribution is compared with a Schlieren photograph of the interaction. Based on the analysis, the sound pressures are found to increase steadily with both Mach number and vortex strength. Particular estimates of sound levels depend critically upon the flow conditions, but curves are attached for a typical wind-tunnel case indicating very intense sound levels for small percentage velocity fluctuations. (Ash)

24. Howes, W. L. Similarity of far noise fields of jets. Appendix A, B: Similarity relations. Appendix C: Experimental differences and errors. NASA TR-R-52, 1959. Similarity parameters for far-field noise from subsonic and supersonic jets issuing from circular nozzles are derived and tested using experimental data. Relations for the total acoustic power, acoustic-power spectrum, acoustic directivity, local mean-square-pressure spectrum, and acoustic-pressure probability-density are considered. Subsonic data correlated well in all respects. With the exception of total-power similarity, supersonic data also correlated well. Subsonic and supersonic correlations generally differed only slightly. (Curth, Sperry)

25. Howes, W. L., et al. Near noise field of a jet-engine exhaust. NACA Rept. 1338, 1957. Aircraft structures located in the near noise field of a jet engine are subjected to extremely high fluctuating pressures that may cause structural fatigue. Studies of such structures have been limited by lack of knowledge of the loadings involved.
The acoustic near field produced by the exhaust of a stationary turbojet engine having a high pressure ratio was measured for a single operating condition without afterburning. The maximum over-all sound operating condition without afterburning was found to be about 42 pounds per square foot along the jet boundary in the region immediately downstream of the jet-nozzle exit. With afterburning the maximum sound pressure was increased by 50 percent. The largest sound pressures without afterburning were obtained on a constant percentage band width basis in the frequency range from 350 to 700 cps.
Additional tests were made at a few points to find the effect of jet velocity on near-field sound pressures and to determine the difference in value between sound-pressure levels at rigid surfaces and corresponding free-field values. Near the jet nozzle, over-all sound pressures were found to vary as a low power (approximate unity) of the jet velocity. Over-all sound-

pressure levels considerably greater than the corresponding free-field levels were recorded at the surface of a rigid plate placed along the jet boundary.
The downstream locations of the maximum sound pressure at any given frequency along the jet-engine-exhaust boundary and the longitudinal turbulent-velocity maximum of the same frequency along a small cold-air jet at 1 nozzle-exit radius from the jet axis were found to be nearly the same when compared on a dimensionless basis. Also, the Strouhal number of the corresponding spectra maximums was found to be nearly equal at similar distances downstream.
In addition to the magnitude and frequency distribution of the acoustic pressures, it is necessary to know the cross correlation of the pressure over the surface area. Cross-correlation measurements with microphones were made for a range of jet velocities at locations along the jet and at a distance from the jet. Free-field correlations of the over-all sound pressure and of the sound pressure in frequency bands from 100 to 1000 cps were obtained both longitudinally and laterally. In addition, correlations were obtained with microphones mounted at the surface of a rigid plate that was large compared with the distance over which a positive correlation existed.
The region of positive correlation was generally found to increase with distance downstream of the engine to 6.5 nozzle-exit diameters, but remained nearly constant thereafter. In general, little change in the correlation curves was found as a function of jet velocity or frequency-band width. The distance from unity correlation to the first zero correlation was greater for lateral than for longitudinal correlations for the same conditions and locations. The correlation curves obtained in free space and on the surface of the plate were generally smaller. The results are interpreted in terms of pressure loads on surfaces. (Curth)

26. Kovasznay, L. S. G. Turbulence in supersonic flow. J. Aeronaut. Sci. 20, 657-74, Oct. 1953. First-order perturbation theory indicates that Navier-Stokes equations for a compressible, viscous, and heat-conductive gas can have three distinctly different types of disturbance fields, obeying three independent differential equations. These three "modes" of disturbance fields are: vorticity mode, entropy mode, and sound-wave mode. The modes are independent when the intensities of the fluctuations are small, but they interact at larger intensities when linearization is not permissible. (Ash)

27. Lassiter, L. W. and Hubbard, H. H. The near noise field of static jets and some model studies of devices for noise reduction. NACA TN-3187, July 1954. Experimental studies of the pressure fluctuations near jets were made during unchoked operation of both a full-scale turbojet engine and a 1-inch-diameter high-temperature model jet and during choked operation of model jets of 0.275-inch and 2.00-inch diameter with unheated air. Frequency spectra and spatial distributions of pressure magnitude are given for the full-scale configuration and model data are used to illustrate probable trends at different operating conditions for the unchoked jets. Model tests for choked operation indicate the presence of a discrete-

frequency component, and shadowgraph records illustrate that an unusual type of flow formation is associated with this condition. The frequency of this component is shown to be somewhat related to the shock-separation distances and to nozzle diameter. Laboratory methods of reducing the magnitude of pressure fluctuations from choked and unchoked jets are discussed and sample illustrations are given. (Curth)

28. Laurence, J. C. Intensity, scale, and spectra of turbulence in mixing region of free subsonic jet. NACA Rept. 1292, 1956. The intensity of turbulence, the longitudinal and lateral correlation coefficients, and the spectra of turbulence in a 3.5-inch-diameter free jet were measured with hot-wire anemometers at exit Mach numbers from 192,000 to 725,000. The results of these measurements show the following: (1) Near the nozzle (distances less than 4 or 5 jet diameters downstream of the nozzle) the intensity of turbulence, expressed as percent of core velocity, is a maximum at a distance of approximately 1 jet radius from the center line and decreases slightly with increasing Mach and/or Reynolds number. At distances greater than 8 jet diameters downstream of the nozzle, however, the maximum intensity moves out and decreases in magnitude until the turbulence-intensity profiles are quite flat and approaching similarity. (2) The lateral and longitudinal scales of turbulence are nearly independent of Mach and/or Reynolds number and in the mixing zone near the jet vary proportionally with distance from the jet nozzle. (3) Farther downstream of the jet the longitudinal scale reaches a maximum and then decreases approximately linearly with distance. (4) Near the nozzle the lateral scale is much smaller than the longitudinal and does not vary with distance from the center line, while the longitudinal scale is a maximum at a distance from the center line of about 0.7 to 0.8 of the jet radius. (5) Farther downstream this maximum moves out from the center line. (6) A statistical analysis of the correlograms and spectra yields a "scale" which, although different in magnitude from the conventional, varies similarly to the ordinary scale and is easier to evaluate. (Grimsal)

29. Lee, R. Free field measurements of sound radiated by subsonic air jets. David Taylor Model Basin, Rept. No. 868, 1953. Measurements are reported of the sound radiated by small air jets at subsonic velocities. The measurements were made in a free acoustic field to obtain the directional pattern of the radiation in half-octave frequency bands covering the range 38 to 13,600 cps.
The directional patterns show an angle of maximum intensity at higher frequencies. As the frequency decreases, this angle moves toward the jet axis, finally ceasing to exist for the lower frequencies and for the wideband measurements.
The directional patterns and the total sound power radiated in all directions are compared with other available data. Certain differences are attributed to the effect of the length diameter ratio of the nozzle. (Curth)

30. Lee, R. and Smith, E., et al. First biannual progress report program of research on noise suppression. Appl. Res. Operation, Flight Propulsion Lab., Dept., General Elec. Co., Evendale, Ohio, 61pp., Jan. 1960. The prediction of noise produced by a jet, as well as the explanation on the mechanism of noise generation and the prediction may be greatly facilitated if the various acoustical characteristics of a jet can be uniquely related to its aerodynamic characteristics. The dimensionally derived equation by Lighthill relating total acoustic power to the velocity and the area of a jet is not sufficiently detailed to provide full information on the jet noise spectra. Consideration of this basic theory, however, has led to development of a more exact formulation which mathematically links the sound power spectrum to the spatial distribution of the local velocities at the various mixing regions of a round jet. This was the essence of the so-called "velocity profile theory".
The basic idea is that each typical region (jet slice whose plane is perpendicular to the jet axis) in the free subsonic jet field is responsible for the noise of some particular band of frequency, and that the acoustic power output at the frequency may be approximated by the basic relation:

$$P_f = K' \rho_o \, C_o^{-5} \frac{x}{L} \int_{o(at\ x)}^{A} U^8 \, dA$$

where frequency f (in octave band) is related to position x downstream of the jet by an empirically-developed equation, namely,

$$\frac{fD}{U} = (1.25 \frac{x}{D}) - 1.22$$

Prediction of the sound power spectrum of a round jet through the use of a more developed form of equation 1 was found to be accurate when compared to generalized experimental data.
Purpose of the present series of aero-acoustical experiments involving two parallel jets is to determine whether the basic formulation, according to equation 1, may also be applied to mixed jets (parallel jets) whose downstream mixing and noise characteristics are different from those of a single jet. If the basic method is shown to be applicable, one can then assign more credence on its generality by inductive reasoning. It can then be further applied to later studies on the description of jet noise suppression phenomena as found in various types of suppressor devices. (Sperry)

31. Lee, R. and Smith, E., et al. Second biannual progress report program of research on noise suppression. Appl. Res. Operation, Flight Propulsion Lab., Dept., General Elec. Co., Evendale, Ohio, 20pp., June 30, 1960. Comprehensive investigation on the subject of shock-induced noise in choked jets has been completed, thus, fulfilling Task II requirements of the program. Compilation of all the findings into a final report form is still in progress. Therefore, only a summary of all essential results are presented here. The most important finding is this investigation has been the experi-

mental confirmation of the flow model responsible for the mechanism of shock noise generation. It is recalled that results by previous investigations on this subject had been confined mainly to intuitive and qualitative reasonings. Experimental evidence is also obtained to provide an explanation on the absence of screech noise in jet engines. (Sperry)

32. Lighthill, M. J. On sound generated aerodynamically. Part I: General theory. Proc. Roy. Soc. 211A, 564-87, 1107, Mar. 20, 1952. A theory is initiated, based on the equations of motion in a gas, for the purpose of estimating the sound radiated from a fluid flow, with rigid boundaries, which as a result of instability contains regular fluctuations or turbulence. The sound field is that which would be produced by a static distribution of acoustic quadrupoles whose instantaneous strength per unit volume is $pv_i v_j + p_{ij} - a_0^2 p \delta_{ij}$, where p is the density, $v_i$ is the velocity vector, $p_{ij}$ the compressive stress tensor, and $a_0$ the velocity of sound outside the flow. This quadrupole strength density may be approximated in many cases as $p_0 v_i v_j$. The radiation field is deduced by means of retarded potential solutions. In it, the intensity depends crucially on the frequency as well as on the strength of the quadrupoles, and as a result increases in proportion to a high power, near the eighth, of a typical velocity U in the flow. Physically the mechanism of conversion of energy from kinetic to acoustic is based on fluctuations in the flow of momentum across fixed surfaces, and it is explained in section 2 how this accounts both for the relative inefficiency of the process and for the increase of efficiency with U. It is shown in section 7 how the efficiency is also increased, particularly for the sound emitted forwards, in the case of fluctuations convected at a not negligible Mach number. (Ash, Grimsal)

33. Lighthill, M. J. On sound generated aerodynamically. Part II: Turbulence as a source of sound. Proc. Roy. Soc. 222A, 1-32, 1954. The theory of sound generated aerodynamically is extended by taking into account the statistical properties of turbulent airflows, from which the sound radiated (without the help of solid boundaries) is called aerodynamic noise. The theory is developed with special reference to the noise of jets, for which a detailed comparison with experiment is made. (Ash, Grimsal)

34. Lilley, G. M. On the noise from air jets. Aeronaut. Res. Council 20376, 42pp., Sept. 1958. From Lighthill's theory of jet noise and a prescribed flow structure for a low-speed jet, an attempt is made to calculate the strength and distribution of the equivalent acoustic quadrupoles, which make up the jet, and so determine the sound intensities emitted from the mixing, transition and fully developed turbulent flow regions of the jet. The calculation is divided into the contribution from 'self-noise' in the turbulence and the interaction between the turbulence and mean shear. For the first part of the calculation Proudman's results are used while for the second, an approximation is developed for the $\partial p/\partial t$ covariance in incompressible

shear flow turbulence. These estimates for the sound intensity from a low-speed jet are then modified to include the effect of eddy convection velocity so that they can be applied to the case of the high-speed jet.
It is found that the central region of the mixing region is mainly responsible for the bulk of the noise emitted, since the distribution of acoustic quadrupole strength across the mixing region is roughly Gaussian, with a half-width less than a quarter of the mixing region breadth. From approximate estimates of the sound spectrum from the turbulence it is found that the high frequency contribution comes from first 2 to 3 diameters of the mixing region, though the low frequency contribution is not negligible. The bulk of the low frequency noise comes from 4 to 6 diameters from the jet exit. The remainder of the low frequency noise, from regions further downstream, is of low intensity for the quadrupole strength falls off rapidly with distance being proportional to $1/y_1^7$.
The change in polar distribution of the sound intensity with increase in Mach number is found to be in fair agreement with Lighthill's theory with the eddy convection effect included. The magnitude of the noise intensity is however grossly over-estimated unless a large reduction in quadrupole strength with increase in Mach number is admitted. The suggestion made by Lighthill that this is the result of radiation damping whereby the intensity of the turbulence will be diminished in a region of intense sound, does have strong support from the available measurements, but at very high speeds it would appear to only partly explain the required reduction in quadrupole strength.
It is shown that by including the Doppler effect on frequency, associated with the moving eddies relative to an observer in the forefield of the jet, the measured spectra on model and full-scale jets and that estimated, from the Fourier transform of the $\partial p/\partial t$ covariance, are in fair agreement.
It is found that the size of eddies emitting noise of greatest intensity are slightly smaller than the scale of the main energy containing eddies, a fact which agrees with earlier statements made by Lighthill and by Proudman, for the rather different case of zero mean flow. The importance of the non-dimensional sound wave-number d, ($2\pi$ x diameter)/sound wave length, to define the noise spectrum, is discussed. Apart from the Doppler effect mentioned previously, it is equal to the corresponding wave number in the turbulence. The Strouhal number is not satisfactory for describing jet noise spectra because its speed dependence cannot easily be determined.
A similar analysis for the supersonic jet fully expanded to ambient pressure is not possible, owing to the lack of information on its turbulent structure. It is shown again, however, that enormous reductions in the strength of the quadrupoles must take place with increase in Mach number for theoretical results to line up with the few available experimental data. The latter data does show, however, that a reduction in acoustic efficiency, compared with that of a hot jet just below choking, is obtained at high Mach numbers.
A short section is included on applying qualitatively these results to methods of noise reduction. (Grimsal)

35. Love, E. S., Grigsby, C. E., Lee, L. P. and Woodling, M. J. Experimental and theoretical studies of axisymmetric free jets. NASA TR-R-6, 1959. Results are presented of some experimental and theoretical studies made of axisymmetric jets exhausting from sonic and supersonic nozzles into still air and into supersonic streams with a view toward problems associated with propulsive jets and the investigation of these problems. (Ash)

36. Maglieri, D. J. and Hubbard, H. H. Preliminary measurements of the noise characteristics of some jet-augmented-flap configurations. NASA Memo 12-4158L, Jan. 1959. Far-field noise characteristics of some proposed jet-flap configurations are presented in the form of noise radiation patterns and frequency spectra. The tests were conducted using cold-air jets of circular and rectangular exits having equal areas. The pressure ratio was such that the exit velocity was slightly below choking. The effect of changing nozzle geometry, flap length, flap deflection, and the effect of changes in the jet-mixing patterns on the noise radiation and frequency spectra are presented. A discussion of some possible implications of the data is also presented. (Sperry)

37. Mawardi, O. On the spectrum of noise from turbulence. J. Acous. Soc. Am. 27, 442-5, May 1955. An approximate method is developed for the estimation of the acoustic power frequency spectrum of the sound generated from isotropic turbulence. The method is based on a hypothetical model for the sound sources, originally produced by Lighthill, consisting of an assembly of quadrupoles extending over the region of turbulence. (Grimsal)

38. Meecham, W. C. and Ford, G. W. Acoustic radiation from isotropic turbulence. J. Acous. Soc. Am. 30, 318-22, Apr. 1958. The high frequency end of the power spectrum of the acoustic energy emitted by isotropic turbulence of large Reynolds' number is found to be a universal function independent of the nature of the driving forces. (Grimsal)

39. Miesse, C. C. A theory of spray combustion. Ind. Eng. Chem. 50, 1303-4, Sept. 1958. A method is presented of determining the optimum design of a combustor with given performance requirements. Existing information on the effect of atomization of performance of liquid propellant combustors has been limited to the beneficial effects of finer atomization and detrimental effects of liquid viscosity. The roles of the intermediate processes of evaporation and chemical conversion were also investigated. The applicability of these experimental data to this problem was given previously, in which the present theory was outlined. The dimensionless groups which include the above effects and should facilitate correlation of experimental data were established by Damkohler, and were subsequently applied to the problem of scaling combustors by Penner. (Miesse)

40. Miesse, C. C. The effect of a variable evaporation rate or the ballistics of droplets. J. Franklin Inst. 264, 391-401, July-Dec. 1957. In order to allow for the effect of the variation of evaporation rate of a liquid droplet with its Reynolds number on its velocity and diameter variations, the present analysis considers the ballistics and evaporation (Frossling's) equations simultaneously. The resultant nonlinear equation yields analytical solutions for discrete values of the viscosity to still air evaporation rate parameter, which permits ready determination of the variation of drop size and relative velocity with time and/or distance. The results indicate that the constant evaporation rate analysis is valid for large values of the parameter mentioned above, but should be modified for smaller values. Numerous illustrative curves are presented, and the analysis is applied to available experimental data. (Miesse)

41. Mollö-Christensen, E. and Narasimha, R. Sound emission from jets at high subsonic velocities. J. Fluid Mech. 8, 49-60, May 1960. From a consideration of the similarity relations obtained from experiments, it has been possible to outline a theory of noise emission from subsonic and low supersonic jets.
The sound is generated in the high shear region of the jet, the shear layer of which is considered a dipole sheet with the dipoles oriented along the jet axis. This radiation is emitted both outward and inward. The inwardly emitted radiation is subject to multiple scattering before emergence from the jet. One effect of scattering is the occurrence of a low-frequency peak in the spectrum of emitted sound at an oblique angle to the jet axis; another effect is the increase of energy radiated to $\theta = \cos^{-1}[1/(1+M)]$. With this description of the mechanism for jet noise, some methods of silencing of jets suggests themselves. It would be beyond the scope of the present paper to discuss them. The apparently intimate connection between jet stability and noise generation appears worthy of further investigation, as does the effect of sound scattering upon the mean flow in the jet. (Grimsal)

42. Moore, F. K. Unsteady oblique interaction of a shock wave with a plane disturbance. NACA Rept. 1165, 1954. Analysis is made of the flow field produced by oblique impingement of weak plane disturbances of arbitrary profile on a plane normal shock. Three types of disturbance are considered: (a) Sound wave propagating in the gas at rest into which the shock moves. The sound wave refracts either as a simple isentropic sound wave or an attenuating isentropic pressure wave, depending on the angle between the shock and the incident sound wave. A stationary vorticity wave of constant pressure appears behind the shock. (b) Sound wave overtaking the shock from behind. The sound wave reflects as a sound wave, and a stationary vorticity wave is produced. (c) An incompressible vorticity wave stationary in the gas ahead of the shock. The incident wave refracts as a stationary vorticity wave, and either a sound wave or attenuating pressure wave is also produced. Computations are presented for the first two types of incident wave, over the range of incidence angles, for shock Mach numbers of 1, 1.5 and $\infty$. (Ash)

43. Moyal, J. E. The spectra of turbulence in a compressible fluid; eddy turbulence and random noise. Proc. Cambridge Phil. Soc. 48, 329-44, 1952. The state of a real fluid is completely specified by its velocity, density, pressure and temperature fields. When the fluid is in turbulent flow, all these quantities fluctuate in a disordered manner. The method of space Fourier spectra is used to show that these field variables separate into two physically distinct groups, one corresponding to fluctuating acoustical waves or random noise, and the other to fluctuating vorticity, or eddy turbulence. The corresponding decomposition of the spectral and correlation tensors in a homogeneous field of turbulence is given. The noise Fourier components are shown to be coupled to the eddy Fourier components only through the nonlinear inertia terms in the dynamical equations of the fluid; whereas the former propagate as acoustical waves, the wave character of the latter is due entirely to the mean motion of the fluid. The measurement of the noise component, its attenuation through absorption by walls and its effects on the eddy component are discussed. Finally, the dynamical equations for the eddy component of the velocity spectral tensor in a homogeneous field of turbulence are compared with the corresponding equations for an incompressible fluid. (Grimsal)

44. Mull, H. R. Effect of jet structure on noise generation by supersonic nozzles. J. Acous. Soc. Am. 31, 147-9, Feb. 1959. In this study the near noise field of a supersonic jet (Mach 2.87) exhausting into quiescent air, is analyzed with respect to the aerodynamic structure of the jet. The noise field is shown to be shifted away from the jet exit with the most intense sound near the end of the supersonic portion of the exhaust structure. Downstream of this point, the jet radiates noise in the same manner as a subsonic jet. (Ash)

45. Mull, H. R. and Erickson, J. C., Jr. Survey of the acoustic near field of three nozzles at a pressure ratio of 30. NACA TN-3978, Apr. 1957. The sound pressures radiating from the exhaust streams of two convergent-divergent and one convergent nozzle were measured. Exit diameters were 1.206 in. for the expanded nozzle and 0.625 in. for the convergent nozzle. The results are presented in a series of contour maps of overall and fine 1/3-octave-band sound pressures. The location of the source of the noise in each 1/3-octave-band in the frequency range of 30 to 16,000 cps and the total power radiated were determined and compared with those of subsonic jets. (Ash)

46. Powell, A. A survey of experiments on jet noise; a study of the mechanism of noise production of jet engines, with brief notes on its reduction. Aircraft Eng., p. 2, Jan. 1954. The bulk of jet engine noise developed at high powers arise from the turbulent mixing of jet efflux in the surrounding air, as judged from model experiments, and has a continuous spectrum with a single flat maximum. The high frequency sound arises fairly close

to the orifice, and reaches its maximum intensity at fairly large acute angles to the jet direction. Lower frequency noise arises lower downstream and its maxima make smaller acute angles with the jet axis. The possible origins are briefly discussed in view of Lighthill's theory and refraction effects. The most intense sound has a wavelength of the order of three or four exit diameters, and originates between five and ten diameters from the orifice. A semi-empirical rule of noise energy depending on the jet velocity to the eighth power and the jet diameter squared gives a rough estimate of noise level for both cold and heated jets. Further noise from heated and supersonic jets may occur through eddies travelling at supersonic speed and so produce small shockwaves. Model experiments have shown that interaction between shockwave configurations in choked jets and passing eddy trains generates sound and this initiates further eddies at the orifice. The directional properties of this sound are quite distinctive, the maximum being in the upstream direction. Methods of reducing jet noise are briefly discussed. (Ash)

47. Powell, A. On the mechanism of choked jet noise. Proc. Phys. Soc. London 66B, 1039-56, 1953. The character of jet noise undergoes a marked change above choking, the noise due to turbulent mixing being dominated by a powerful whistle or screech whose wavelength is related to the regular shock wave spacing. The mechanism in two-dimensional flow is further examined (by the aid of a dynamic Schlieren apparatus), verifying the suggested mechanism and showing the similarity to that in axially symmetric flow where discontinuities in frequency, partly analogous to edge tones, occur. The resultant sound emitted as the periodic eddy system traverses the regular shock wave pattern is highly directional producing a powerful beam at doubled frequency normal to the jet and an intense beam at eddy frequency in the upstream direction adjacent to the jet, resulting in fluctuations in jet velocity direction at the orifice which initiate new stream disturbances.
A gain criterion for the self-maintained cycle is given, enabling certain qualitative deductions concerning the intensity to be made, and use will be made of this in considering methods of reducing the noise level. (Ash)

48. Proudman, I. The generation of noise by isotropic turbulence. Proc. Roy. Soc. 214A, 119-32, Aug. 7, 1952. A finite region, with fixed boundaries of an infinite expanse of compressible fluid is in turbulent motion. This motion generates noise and radiates it into the surrounding fluid. The acoustic properties of the system are studied in the special case in which the turbulent region consists of decaying isotropic turbulence. It is assumed that the Reynolds number of the turbulence is large, and that the Mach number is small.
The noise appears to be generated mainly by those eddies of the turbulence whose contribution to the rate of dissipation of kinetic energy by viscosity is negligible.
It is shown that the intensity of sound at large distances from the turbulence is the same as that due to a volume distribution of simple acoustic sources

occupying the turbulent region. In this analogy, the whole fluid is to be regarded as a stationary and uniform acoustic medium. The local value of the acoustic power output P per mass of turbulent fluid is given approximately by the formula:

$$P = -\frac{3}{2}\,\alpha\,\frac{d\overline{u^2}}{dt}\left(\frac{\overline{u^2}}{c^2}\right)^{\frac{5}{2}}$$

where $\alpha$ is a numerical constant, u is the mean-square velocity fluctuation, t is the time, and c is the velocity of sound in the fluid. The constant $\alpha$ is expressed in terms of the well-known velocity correlation function f(r) by assuming the joint probability distribution of the turbulent velocities and their first two time-derivatives at two points in space to be Gaussian. The numerical value $\alpha \sim 38$ is then obtained by substituting the form of f(r) corresponding to Heisenberg's theoretical spectrum of isotropic turbulence.
It is found that the effects of decay make only a small contribution to the value of $\alpha$, and that the order of magnitude of $\alpha$ is not changed when widely differing forms of the function f(r) are used. (Grimsal)

49. Ribner, H. S. Convection of a pattern of vorticity through a shock wave. NACA Rept. 1164, 1954. An arbitrary weak spatial distribution of vorticity can be represented in terms of plane sinusoidal shear waves of all orientations and wave lengths (Fourier integral). The analysis treats the passage of a single representative weak shear wave through a plane shock and shows refraction and modification of the shear wave with simultaneous generation of an acoustically intense sound wave. Applications to turbulence and to noise in supersonic wind tunnels are indicated. (Ash)

50. Ribner, H. S. Convection of a pattern of vorticity through a shock wave. AD 1411. An arbitrary weak spatial distribution of vorticity can be represented in terms of plane sinusoidal shear waves of all orientations and wave lengths (Fourier integral). The analysis treats the passage of a single representative weak shear wave through a plane shock and shows refraction and modification of the shear wave with simultaneous generation of an acoustically intense sound wave. Applications to turbulence and to noise in supersonic wind tunnels are indicated. (Ash)

51. Ribner, H. S. Energy flux from an acoustic source contained in a moving fluid element and its relation to jet noise. J. Acous. Soc. Am. 32, 1159-60, Sept. 1960. It is found that a high-frequency source (or multipole) imbedded in a moving patch of fluid emits a constant acoustic power independent of the motion. (The directivity is, however, altered). This holds when the wavelength $\lambda \ll$ radius R' of the entire region of flow. At the other extreme $\lambda \ll 2\pi R'$ it appears that the acoustic power is enhanced by the motion, somewhat (but not exactly) as the emission of the source is enhanced by motion through fluid at rest. A typical wavelength of a radiating eddy in a jet lies between the two extremes and a limited convective enhancement of power is inferred. The amount should be less than that

predicted by Lighthill or the much more conservative values suggested by the work of Ribner; it could conceivably lie within experimental error, justifying the nonconvective law, power $\sim U^8$, found by measurement. (Grimsal)

52. Ribner, H. S. New theory of jet-noise generation, directionality, and spectra. J. Acous. Soc. Am. 31, 245-6, Feb. 1959. A theory of jet noise is dev. from the observation that in low-speed turbulence Lighthill's quadrupoles combine to behave like simple sources $\sim \partial_p^2 p^{(o)}/\partial t^2$, where $p^{(o)}$ is the incompressible local pressure in the turbulence. An integral for the far-field intensity involves the space-time pressure covariance $\mathcal{R}$ within the turbulence. Choice of $\mathcal{R}$ in a worked example shows pronounced directionality results from pattern "convection" (modified by fluctuation) in conjunction with the time retardation. Further directionality is accounted for in terms of the Green's function (discussed qualitatively but not worked out) for a point source at rest in the mean shear flow, describing the lateral refraction and diffraction. (Grimsal)

53. Ribner, H. S. On the strength distribution of noise sources along a jet. Inst. of Aerophys., Univ. of Toronto Rept. 51, Apr. 1958. The spatial distribution of noise sources along a jet is investigated theoretically. The analysis refers to the noise power emitted by a 'slice' of jet (the section between two adjacent planes normal to the axis) as a function of distance X of the slice from the nozzle. It is found that this power is essentially constant with X in the initial mixing region ($X^0$ law), then further downstream (say 8 to 10 diameters from the nozzle) falls off extremely fast ($X^{-7}$ law or faster) in the fully developed jet. Because of this striking attenuation of strength with distance, the 'fat' part of the jet must contribute much less to the total noise power than is commonly supposed. Further implications, especially for multiple-nozzle and corrugated mufflers, are discussed. (Ash)

54. Ribner, H. S. Shock-turbulence interaction and the generation of noise. NACA TN-3255, July 1954. The interaction of the convected field of turbulence with a shockwave is analyzed to yield modified turbulence, entropy spottiness, and noise generated downstream of the shock. The analysis is a generalization of a single-spectrum-wave treatment of TN 2864. Formulas for spectra and correlations are obtained. Numerical calculations yield curves of rms velocity components, temperature, pressure, and noise in decibels against Mach number for $M = 1$ to $\infty$; both isotropic and strongly axisymmetric (lateral/longitudinal = 36/1) initial turbulence are treated. In either case, turbulence of 0.1 percent longitudinal component generates 120 decibels of noise. (Ash)

55. Ribner, H. S. The sound generated by interaction in a single vortex with a shock wave. Inst. of Aerophys., Univ. of Toronto Rept. 61, 11pp., July 1959. The passage of a columnar vortex 'broadside' through a shock is investigated. The vortex is decomposed (by Fourier transform) into plane sinusoidal shear waves disposed with radial symmetry. The plane

sound waves produced by each shear wave-shock interaction, known from previous work, are recombined in the Fourier integral. The waves possess an envelope that is essentially a growing cylindrical sound wave, partly cut off by the shock. The sound wave is centered at the transmitted (and modified) vortex and the peak pressure attenuates inversely as the square root of the growing radius. The strength varies smoothly around the arc, from compression at one shock intersection to rarefaction at the other shock intersection. Comparison is made with results of a shock-tube investigation and heuristic theory by Hollingsworth and Richards in England. (Ash)

56. Richards, E. J. On the noise from supersonic jets. J. Roy. Aero. Soc. 61, 43-5, Jan. 1957. In parallel with the work undertaken at the Univ. of Southampton on the study of the noise from subsonic jets, a further investigation has been made into the noise from supersonic or choked jets. Whereas in the former case the noise is due to the turbulent velocity fluctuations and thus contains a wide spectrum of random frequencies, the latter case contains, in addition to this wide spectrum, noise caused by turbulence-shock wave interaction. (Sperry)

57. Richards, E. J. Research on aerodynamic noise from jets and associated problems. J. Roy. Aeronaut. Soc., p. 318, May 1953. After two years research work in the Universities of this country and elsewhere, there is need for a comprehensive review of the present position on the suppression of aerodynamic noise from jet engines. This report outlines the fundamental understanding of the problem that has been achieved, the basic experimental work done, and the noise suppression techniques which have been suggested. A study is made of measured noise levels on advanced types of engines and an analysis is made of reductions required and so far achieved with proposed noise suppression devices. While the basic principles underlying noise formation both in subsonic and supersonic jet streams are beginning to be understood, the noise reductions so far achieved are still insufficient and warrant an extended programme of research.
The report includes helicopter noise analyses with pressure and pulse jets, and touches on the problem of structural fatique in the vicinity of a jet stream. (Ash)

58. Richards, E. J. Some thoughts on noise suppression nozzle design. Biblo: 30. Combustion and propulsion: Third Advisory Group for Aeronaut. Res. and Development colloquium, Mar. 17-21, 1958. Advisory Group for Aeronaut. Res. and Development Publ., pp. 197-223, 1958. Following a brief review of jet nozzles tests carried out in England and the United States during the last seven years and aimed at noise suppression, some attempt is made to correlate the results and to indicate the main parameters. It is suggested that two mechanisms of noise suppression occur, the first of velocity reduction, the second of frequency raising. When frequency raising occurs, experiments indicate an overall attenuation to occur on most nozzles. Multi-tube nozzles, corrugated nozzles, slit nozzles and ejectors are

examined with a view to their classification into either of these classes or into combinations of both. The need to examine aspect ratio as well as area ratio is stressed. It is suggested, for example, that multi-tube nozzles can advantageously be assembled into a two-dimensional array rather than into the circular array at present favored. The advantages of such arrays in forward flight is also commented upon. The sources of performance loss are studied and the unlikelihood of obtaining nozzle configurations with zero losses emphasized. Among other suggestions, the need for reduced velocity jets and the possibility of retractable two-dimensional ejector systems are emphasized. (Sperry)

59. Richards, E. J. Technical possibilities of reducing noise of jet aircraft. Shell Aviation News, No. 227, p. 19, May 1957. In the broad sense, two methods of noise reduction, probably used concurrently, are available. The first is to arrange the testing station so that the direction of the nearest houses coincides with the direction of minimum annoyance. Much can be done in any new airport by the suitable location and orientation of test sites and by the intelligent use of maintenance hangers and walls for screening. Unfortunately, however, most airports have already been developed and the amount of reduction obtained by suitable siting cannot in general be enough in the majority of cases. The other method, which is becoming prevalent, is the addition of ground mufflers, of a portable or more permanent nature to the jet of the aeroplane during its period of running-up. Much work has gone into the development of such devices during the last ten years with varying success and certainly with varying complication. The vary from completely closed cells to the type in which normally aircraft engines would be tested in the development stage, to small portable mufflers clamped on to the engine for a particular run. Since it is impossible to cover all such items here, it is proposed to describe three new and promising approaches being used or developed in the United Kingdom. (Sperry)

60. Rollin, V. G. Effect of jet temperature on jet-noise generation. NACA TN-4217, Mar. 1958. Sound measurements were made on a 9/16-inch-model air jet over a range of pressure ratios from 1.3 to 1.9 and jet-air temperatures from 80° to 1000° F. Results indicated that sound power can be adequately predicted by the Lighthill parameter based on ambient temperature over the range of temperatures investigated. (Curth)

61. Sanders, N. D. and North, W. J. Jet engine noise reduction. Biblo: 32. Combustion and propulsion: Third Advisory Group for Aeronaut. Res. and Development colloquium, Mar. 17-21, 1958. Advisory Group for Aeronaut. Res. and Development Publ., pp. 185-96, 1958. Fundamental research on noise generation and recent developments in noise reduction techniques are described. The acoustic and aerodynamic characteristics of several noise-suppression exhaust nozzles are compared. The internal thrust losses and the external drag increases caused by noise suppressors may manifest serious penalties in aircraft cruise performance. (Sperry)

62. Schmeer, J. W., Salters, L. B., Jr. and Cassetti, M. D. Transonic performance characteristics of several jet noise suppressors. NASA TN D-388, 48pp., July 1960. An investigation was made of the transonic aerodynamic performance characteristics of six noise-suppressor nozzles using a hot jet exhaust provided by a hydrogen peroxide system. The 12-tube and 12-lobe nozzles had the lowest internal losses at static conditions and the 8-lobe nozzle with center-body shroud; secondary air had the least propulsive losses at transonic speeds. (Sperry)

63. Sidor, E. N. Aircraft noise. Boeing Airplane Co., Renton, Washington, 41pp., 1956. This paper will cover very briefly three somewhat different items which we felt would be of interest to you. First, to establish quantitative requirements for jet exhaust suppressors, a method of relating subjective responses to quantitative noise factors and the results of applications of this method will be described. Second, current progress at Boeing in the development of suppressor devices will be discussed and results of static and in-flight tests will be shown. Third, a ground terminal handling demonstration made with the 707 prototype airplane will be described and noise factors in ground handling will be discussed. (Sperry)

64. Squire, H. B. The round laminar jet. Quart. J. of Mech. and Appl. Math. 4, 321-9, 1951. An exact solution of the equations of viscous fluid flow for axially-symmetric motion is derived. It is shown that this corresponds to the round laminar jet, or, alternatively, to the flow produced by the application of a force at a point in a viscous fluid. Some examples of the calculated streamlines are given. The effect of a source of heat at the point of application of the force is also considered. (Miesse)

65. Stringas, E. J. and Auer, H. In-flight turbojet noise suppression studies. AD 218638. The turbojet flight suppression problem was studied from both the inlet and exhaust point of view in order to produce design criteria for a turbojet noise suppression system. At maximum engine speeds the noise generated by a jet engine is predominantly that from the exhaust and is of such magnitude to be injurious to both personnel and structures. Reduced engine rpm operation such as taxiing and ground handling does not pose the high noise level problems associated with full throttle operation but becomes actually more objectionable to personnel due to the predominance of inlet source noise. Hence suppression of jet engine noise both inlet and exhaust, is required throughout the operating range. A complete suppression system which treats both the inlet and exhaust eliminates the need for unwieldy ground suppressors, and also reduced inflight noise and its associated problem areas. (Sperry)

66. Szebehely, V. G. and Pletta, D. H. The analogy between elastic solids and viscous liquids. Bull. Va. Polytech. Inst. 45, 24pp., Nov. 1951. Eng. Experiment Sta. Series No. 80. A striking analogy between the stress tensors of viscous fluids and elastic solids can be obtained if certain linear assumptions are made. For viscous fluids, Stokes proposed a linear

relation between the elements of the stress tensor and the elements of the rate of deformation tensor. For elastic solids, Hooke suggested a linear relation between the elements of the stress tensor and the elements of the strain tensor. The validity of the assumption made by Stokes is questionable, especially in the field of super-aerodynamics. Regarding Hooke's suggestion, reference is made to the fields of "nonlinear elasticity" and to the problem of thin plates and shells, where the validity of any linear assumption necessarily fails. (That two linear assumptions are actually made in the classical theory of elasticity will be shown later in the paper.) In several important and practical cases, however, the above described linear theories give experimentally justifiable results and it seems advantageous therefore to build up an analogy between linear elasticity and classical fluid mechanics.
The fact should be emphasized that the two phenomena are physically distinct. In elasticity the stress is connected with the deformation, whereas in the study of viscous fluids, the stress is caused by the rate of deformation. The mathematical methods and expressions, however, are basically identical.
The mathematical tool used in this paper is tensor calculus, since the quantities involved are tensors. The word tensor (without giving the rank) will be used for tensors of rank two; "vector" will mean a tensor of rank one; and "scaler", a tensor of rank zero. The notations and concepts of the popular vector-analysis will be omitted, except for a few references to divergence. The range of indices used is 1 to 3, and A. Einstein's summation convention is used throughout the paper. The cooperation of the members of the Hydro and Aerodynamics Graduate Seminar is acknowledged, whose devoted work, digest of the literature, and suggestions were of great assistance in writing this paper.
This project was financed partly by a grant-in-aid from the Sigma Xi-Resa Research Fund, and partly by the V.P.I. Engineering Experiment Station.
(Sperry)

67. Truesdell, C.A. Precise theory of the absorption and dispersion of forced plane infinitesial waves according to the Navier-Stokes equations. J. Rat. Mech. and Analysis 2, 643-741, Oct. 1953. Let a continuous medium be maintained in one-dimensional motion at a certain plane x = 0 according to the law

$$\frac{I}{I_0} = \mathfrak{R}\, e^{iwt},$$

where I stands for particle displacement, velocity, acceleration, pressure, density, or temperature, and $I_0$ is a corresponding constant amplitude. Whatever be the physical units selected, by considering only excitations in which the various amplitudes $I_0$ are sufficiently small we may render all non-linear terms in the differential equations of motion as small as we please in comparison to the linear ones, and while in the absence of a proper mathematical approximation theorem we cannot actually prove, yet may with some confidence expect, that the actual motion does not sensibly differ from that which satisfies the differential equations obtained by omitting all non-linear terms from the original system. (Ash, Sperry)

68. Westervelt, P.J. Aerodynamic noise: its generation and suppression. General Eng. Lab., General Electric, Rept. 57GL222, July 1957. This is a discussion of aerodynamic noise from the point of view of physical acoustics. It is helpful to understand the basic principles underlying the generation of aerodynamic- or flow-noise in order to be able to suggest ways for reducing this noise. The principles of this field can be understood in terms of three different kinds of sources. In order of increasing complexity, these sources are: 1. the monopole or simple source; 2. the force-source or dipole; 3. the doublet-force source, otherwise called the quadrupole. The radiation field of each of these three sources is obtained in terms of source strengths which are defined in such a fashion as to coincide with four different physical situations out of which these noises arise. Some specific cases are analyzed quantitatively in order to emphasize the fact that each of the four types of aerodynamic noise arises from the predominance of one or the other of the three basic sources. The last section is devoted to a discussion of some techniques and devices for suppressing aerodynamic noise. (Sperry)

69. Williams, J.E.F. Measuring turbulence with a view to estimating the noise field. AD 207235. An experimental procedure is suggested which is designed to measure, by hot wire techniques, the distribution of acoustic sources in an air jet. The noise producing parameters are discussed along with the capabilities of present experimental equipment and it is suggested that the proposed experimental programme is the only one which is at present within the scope of equipment available at Southampton. Throughout the paper a stationary reference frame is used and it is shown that although the theory based on this system is not as revealing as Lighthill's moving axes analysis, it is nevertheless the only one available for experimental purposes. (Grimsal)

70. Williams, J.E.F. On convected turbulence and its relation to near field pressure. Univ. of Southampton Rept. No. 109, 51pp., June 1960. The problem examined is that of analysing a convected field of turbulence with respect to axes which move with the local flow convection velocity. The general analysis is restricted to homogeneous turbulence, but some of the results are applicable to shear flows. Experimental techniques for measuring the velocity of convection are discussed together with some implications of Taylor's hypothesis. Some properties of the acoustic sources in convected turbulence are considered and particular reference is made to jet mixing regions. Lastly a crude estimation of the frequency spectrum of noise sources at a certain position in the jet is attempted from observations of the hydrodynamic field close to that point. (Grimsal)

71. Withington, H. W. Silencing the jet aircraft. Noise Control 2, 46, Sept. 1956. The Boeing 707 jet transport will incorporate a sound-silencing device which will substantially reduce the external jet noise. Technical progress has been achieved which will result in an airplane capable of operation from present airport facilities with no more noise for the surrounding areas than that produced by present-day propeller-driven transport aircraft. This noise reduction has been achieved with only a minor degradation of airplane performance. (Sperry)

72. Wolfe, M. O. W. Near field jet noise. Advisory Group for Aeronaut. Res. and Development Rept. 112, 41pp., Apr.-May 1957. This paper deals with the subject of jet engine noise in relation to its effects on aircraft structures. Near field noise measurements are described for a range of jet shear velocities on two representative turbojet engines, one of them operating with an afterburner. Contours of equal noise pressure in the horizontal plane containing the axis of the jet are presented for a range of shear velocity for overall noise pressure and for noise pressures in 1/3 octave frequency bands in the noise spectra. In the velocity range 790 to 1800 ft/sec, 400 cycles/sec is the dominant frequency. At most velocities the noise pressures at this frequency are about 10 decibels less than the corresponding overall noise pressures. The increase in noise level due to reheat is not as great as would have been predicted from a consideration of the noise level trends at much lower values of velocity without reheat. (Curth)

73. Wolfe, M. O. W. The structural aspects of jet noise. Roy. Aeronaut. Soc. 61, 103-6, Feb. 1957. The increase in jet engine thrust has been accompanied by an increase in the noise generated by the jet stream to such an extent that the associated noise pressures are not capable of exciting vibrations in an aircraft structure which are potentially dangerous from the fatigue aspect. Several examples of fatigue damage of this kind have appeared already on aircraft in this country and in the United States. (Ash)