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Princeton University

Department of
Aerospace and
Mechanical Sciences

FINAL REPORT TO THE
OFFICE OF NAVAL RESEARCH
ON

RESEARCH ON NOISE GENERATED BY DUCTED AIR-FUEL COMBUSTION SYSTEMS

by

E. G. Plett and M. Summerfield

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March 1977

Guggenheim Laboratories for the Aerospace Propulsion Sciences
Department of Aerospace and Mechanical Sciences
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Princeton, New Jersey

SUMMARY

Throughout the research program, emphasis has been placed on obtaining a better understanding of the importance of combustion as a source of noise in jet engines. This has been pursued in terms of theoretical modeling and experimental investigations.

A theoretical model was developed to allow computation of the role of internal sources as well as external sources. Calculations based on reasonable approximations indicated that for subsonic jet velocities, internal sources could be much more important than the jet noise sources. Experiments in a cold flow with cylindrical struts immersed in the flow to generate unsteadiness demonstrated this effect. More to the point, experiments with a ducted combustor also verified that the combustion, though occurring inside the duct, causes unsteadiness in the exhaust flow which is directly responsible for noise generation. The noise thus attributable to the combustion was found to be dominant over jet noise for subsonic jets to Mach numbers of approximately 0.6.

A unified theory of combustion noise generation was developed. Direct verification of the importance of the various source terms was begun. Initial results suggest that at least several of the terms are important. Further work is needed in this aspect of this research. The theory applied to ducted combustors predicted strong resonant type oscillations in the combustor, which were observed in corresponding experiments.

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Throughout the research program, emphasis has been placed on obtaining a better understanding of the importance of combustion as a source of noise in jet engines. This has been pursued in terms of theoretical modeling and experimental investigations. A theoretical model was developed to allow computation of the role internal sources as well as external sources. Calculations based on reasonable approximations indicated that for subsonic jet →

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1.0 Introduction: Objective and General Description of the Research Program

The overall objective of this research program was to study the interaction of combustion with a flow system in the regime of interest for aircraft engine combustors and afterburners, to determine its importance as a source of noise. It has been known for some time that combustion can behave as a noise source by creating pressure waves due to non-steady heat addition or by amplifying unsteadiness existing in the flow. The aim of this study was to identify the dominant mechanisms by which combustion contributes to the noise emanating from the exhaust flow of a ducted air-fuel combustion system and to investigate ways of minimizing such noise.

Although combustion was known to produce noise, the information that was available previously did not provide a clear delineation of its importance in high speed flow conditions. To study its relative importance over a range of flow conditions, ducted flow systems were developed with the capabilities to include combustion inside the duct and/or a flow disturbance which created unsteadiness without combustion inside the duct. Measurements were taken of the unsteadiness levels inside the ducted system as well as of the total noise outside. Attention was focused on developing means of evaluating the relative contributions from the various sources inside the duct as well as from the external sources.

A theoretical basis was developed for understanding the mechanism by which internal unsteadiness became evident as noise outside the engine. An analysis of the unsteady flow field associated with turbulent combustion led to a unified theory of combustion noise which contains six source terms. Since it was not immediately evident that all the sources described by these terms were important for the combustion flow systems of interest, an experimental investigation was undertaken to compare the strengths of the various sources.

In the following pages, a brief outline of the results of each aspect of the research program is given along with references to more complete discussions of the respective contributions.

2.0 Achievements of this Research Program

2.1 Facilities Developed in this Program

2.1.1 Cold Flow Facility

Figure 1 schematically shows the arrangement of the components of the cold flow facility as first developed[1,2]. Air from a 400,000 s.c.f. supply at 3000 psia is regulated down in two stages to the pressure required to give the desired flow rate in the range of 250 ft/sec to 1000 ft/sec in the 1 inch diameter duct. Considerable attention was directed toward quieting the upstream noise sources and reducing upstream turbulence so that the jet emanating from the experimental duct end would exhibit true jet noise. Only after that was achieved could we deduce the effect of further disturbances created intentionally in the upstream section and compare the noise with and without upstream disturbances in a meaningful way.

The flow exhausted into an anechoic chamber constructed for this research program. Figure 2 shows the external dimensions of this chamber. Polyurethane foam was used as the sound absorbent material, with overall construction details given by Pike[1]. Tests showed that the chamber simulated free field conditions to frequencies as low as 125 Hz.

Further improvements were incorporated into this flow system during the continuing use of the facility. An upstream heat exchanger was added to aid in controlling the air inlet temperature and further sound absorbers were added to the plenum chamber to reduce the upstream noise effects even further[3]. This facility was used to simulate upstream sources of noise in ambient temperature situations. Results of these studies are summarized in a later section of this report.

2.1.2 Combustion Noise Facility

A second flow system was used to investigate some of the basic phenomena associated with combustion generated noise[4,5]. An anechoic room with 10 cm thick fire resistant glass fibre padding material and with dimensions of 2.75 m wide, 2.5 m high and 3.7 m long was used for this study. A premixed propane-air flame stabilized on a 1/4"(0.632 cm) dia. burner by a hydrogen flame was the source of combustion noise under study. Figure 3 schematically illustrates the flame-flow arrangement and the instrumentation used to examine the relative importance of the candidate noise sources. The details of this work are given in several publications[5,6].

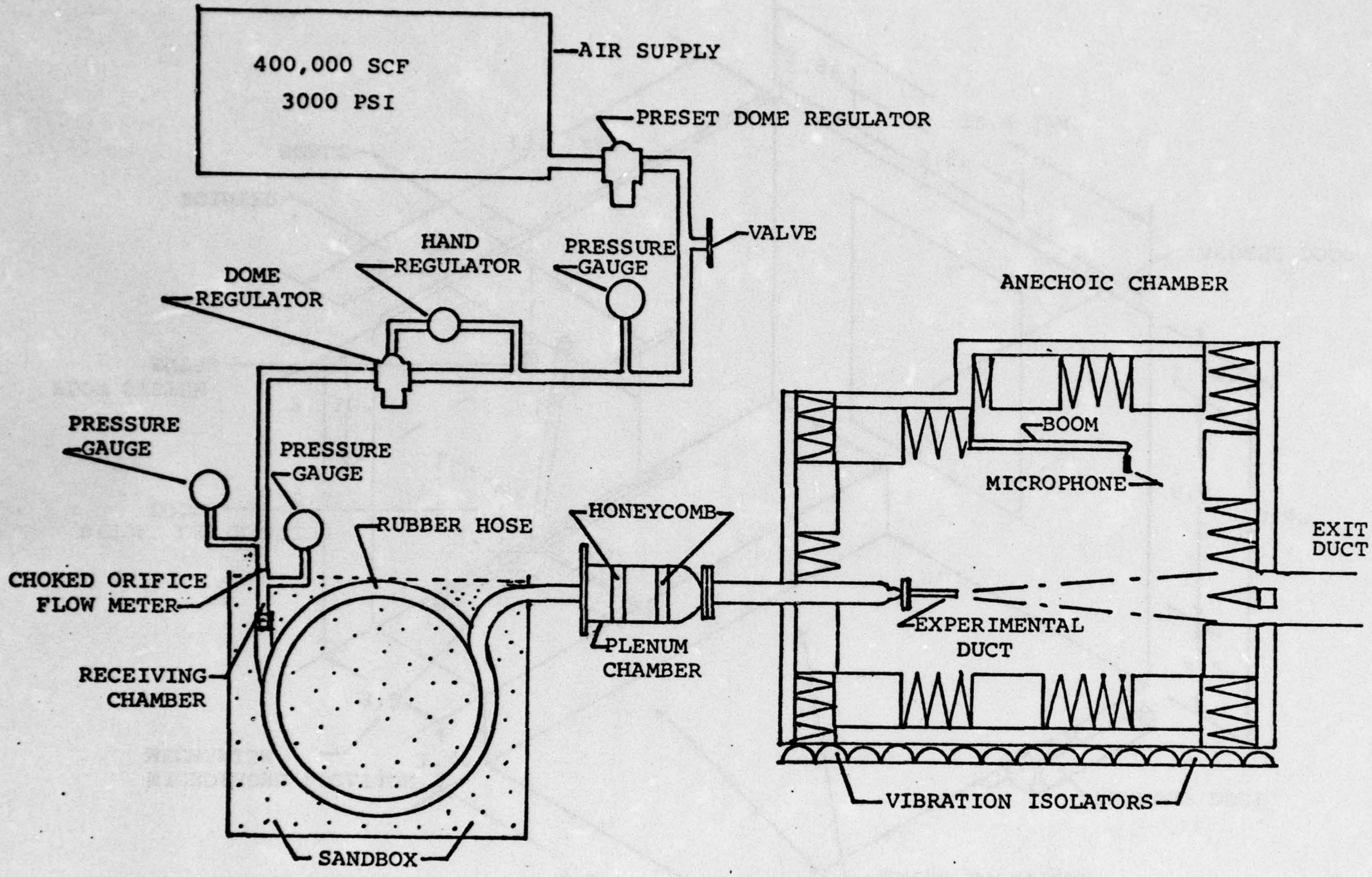

FIGURE 1 COLD FLOW NOISE RESEARCH FACILITY

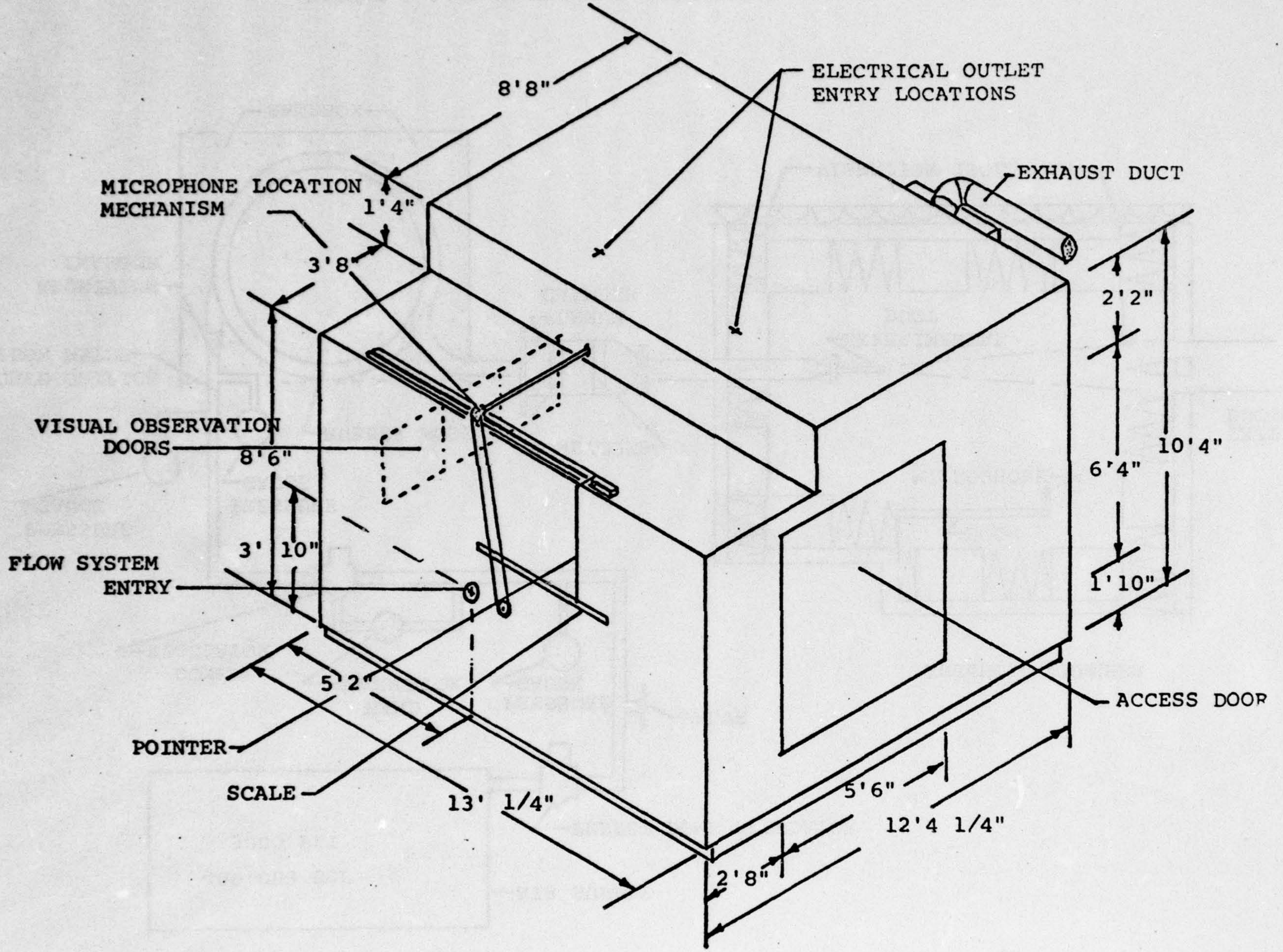

FIGURE 2 DETAILS OF EXTERNAL ANECHOIC CHAMBER DIMENSIONS

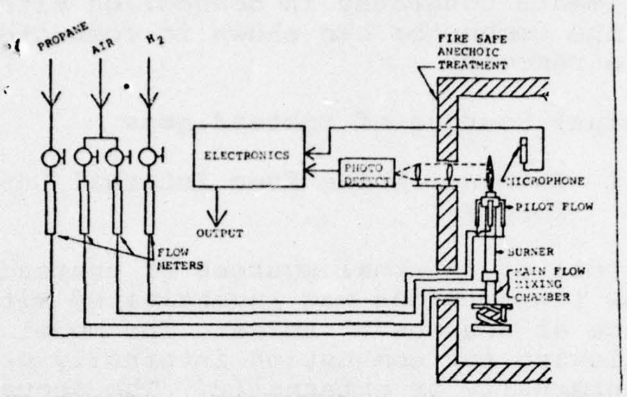

Fig. 3 Schematic diagram of combustion noise facility used to evaluate relative importance of noise source terms.

2.1.3 Ducted Combustor

A ducted combustor was used to demonstrate the noise effects of combustion in a duct upstream of a nozzle exhausting to the atmosphere as a jet. The details of the first experiments conducted with this facility also detailed the important features of the system[7-10]. A 3 inch I.D. combustor was fitted with a 2 inch I.D. nozzle and connected by flexible tubing to metered air and fuel supplies. The combustor assembly was mounted on a pylon 12 feet above the ground level to minimize ground reflections. Figure 4 shows the details of the combustor as used for one set of experiments.

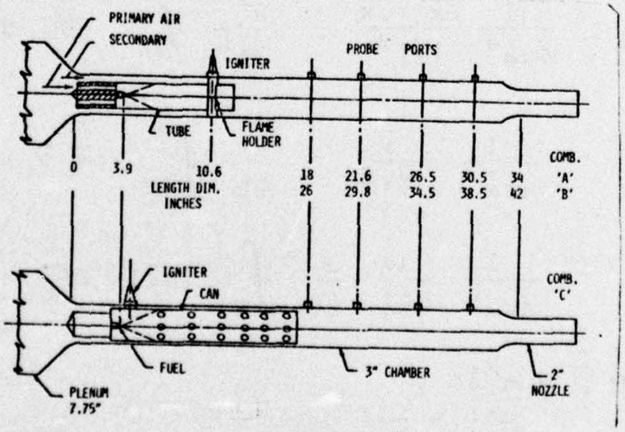

Fig. 4 Schematic of ducted combustors, showing important dimensions. Combustors "A" and "B" are identical except that "B" is 8 in. longer than "A"; combustor "C" has no primary air, but secondary air enters combustor can through side wall perforations.

The experiments conducted in connection with references 9 and 10 used the combustor can shown in combustor C of Fig. 4., with the nozzle removed.

2.2 Internal Sources of Unsteadiness

2.2.1 External Noise from Internal Unsteadiness - Theory

The role of internal sources of unsteadiness causing exit plane flow fluctuations was investigated with respect to their importance as sources of noise. The model developed was a general one allowing for combustion internally or other sources of unsteadiness internally or externally. The acoustic equation was derived based on the conservation of mass and momentum in the absence of sources of mass or external forces. The equations used in this formulation may be written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = 0 \qquad (1)$$

$$\frac{\partial (\rho \bar{v})}{\partial t} + \nabla \cdot (\rho \bar{v} \bar{v}) = - \nabla \cdot \bar{\bar{p}} \qquad (2)$$

where $\bar{\bar{p}}$ is the compressive stress tensor.

The steps in formulating the final acoustic equation are outlined in ref 1. The density perturbation at a far field position due to a compact source region is expressed in terms of the various source terms as given by equation 3.

$$\begin{aligned} \rho(\bar{x},t) - \rho_i = {} & \frac{1}{4\pi a^4} \frac{\bar{x} \cdot \bar{x}}{|\bar{x}|^3} \cdot \frac{\partial^2}{\partial t^2} \int_{V_o} [\bar{\bar{T}}] \, dV_o \\ & - \frac{1}{4\pi a^3} \frac{\bar{x}}{|\bar{x}|^2} \cdot \frac{\partial}{\partial t} \oint_{S_o} [\rho \bar{v} \; \bar{v} + \bar{\bar{p}}] \cdot d\bar{S}_o \\ & + \frac{1}{4\pi a^2} \frac{1}{|\bar{x}|} \frac{\partial}{\partial t} \oint_{S_o} [\rho \bar{v}] \cdot d\bar{S}_o \qquad (3) \end{aligned}$$

where $\bar{\bar{T}} = \rho \bar{v} \; \bar{v} + \bar{\bar{p}} - a^2 \bar{\bar{\delta}} \rho$,

V_O is the volumetric source region outside the ducted flow system(engine),

S_O is the exit plane surface through which the unsteady flow exhausts.

Using equation 3 as the basis for computations, estimates were made of the relative importance of the various source terms for a range of conditions representative of a jet engine exhaust, for some assumed levels of unsteadiness. The assumed levels of unsteadiness were based on measured unsteadiness levels obtained in experiments in the laboratory. A free parameter in the estimates, which was based on the size of source coherent regions, was obtained by a curve fit to the laboratory data, as described in ref. 11. The predictions are summarized in Fig. 5.

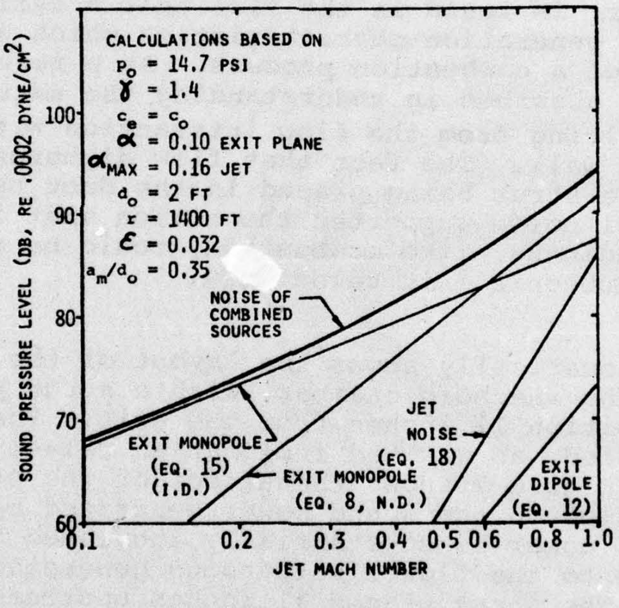

Fig. 5 Predicted individual and combined contribution of internal and jet noise sources in a jet engine. (See Ref. 11 for explanation of the terminology)

Based on the assumptions used and the results which followed, it may be said that mass-flow fluctuations generated at the exit plane by combustion-driven acoustic-resonant-type fluctuations inside the engine are expected to be dominant up to jet Mach numbers around 0.55, after which mass-flow fluctuations at nozzle-dominated frequencies become most dominant. The jet contribution, or exit plane momentum fluctuations, are not found to be significant below Mach 1, for the conditions considered.

2.2.2 External Noise from Internal Unsteadiness-Experiment

a) Noise Generated by Cylindrical Spoilers in an Air Flow

Rather than go directly to a ducted combustion system and try to determine the importance of the unsteady combustion as a source of noise, experiments were performed with a cylindrical spoiler immersed in the air stream to generate internal unsteadiness. The attractiveness of this approach is found in the relative ease with which measurements can be made in an ambient flow compared with a high temperature flow. The disadvantage, however, is found in the fact that a cylindrical spoiler has noise generation characteristics which are quite different from that of a combustion process. As a result, part of the attention was absorbed in understanding the nature of the noise source resulting from the flow interaction with the strut and the confining wall. The fact that flow disturbances following from the strut being placed in the duct resulted in increased external noise supported the notion that internal sources of unsteadiness, like combustion, could be an important noise source at subsonic exit velocities.

Figure 6 schematically shows the layout of the flow system exhausting into the anechoic chamber, with a strut placed across the duct at a position 11 inches from the exit. The location of the strut was varied, as was the inclination relative to the plane of measurement. Figure 7 shows the effect of the strut interacting with the flow on the sound power generated by the flow. Clearly the sound power is substantially increased by the presence of the strut, due to the flow fluctuations generated by the flow over the strut. The strut placed 11 inches upstream of the exit has a greater effect on the noise level because the regular fluctuations are reinforced by reflections from the duct wall. Many of the interesting ramifications of this observation were not pursued because they did not fall within the scope of the present study.

b) Noise Generated by Combustion in a Ducted System

In a related study conducted under NASA sponsorship, noise measurements were made to determine the possible contribution to the overall noise of a jet system that could be due to unsteady

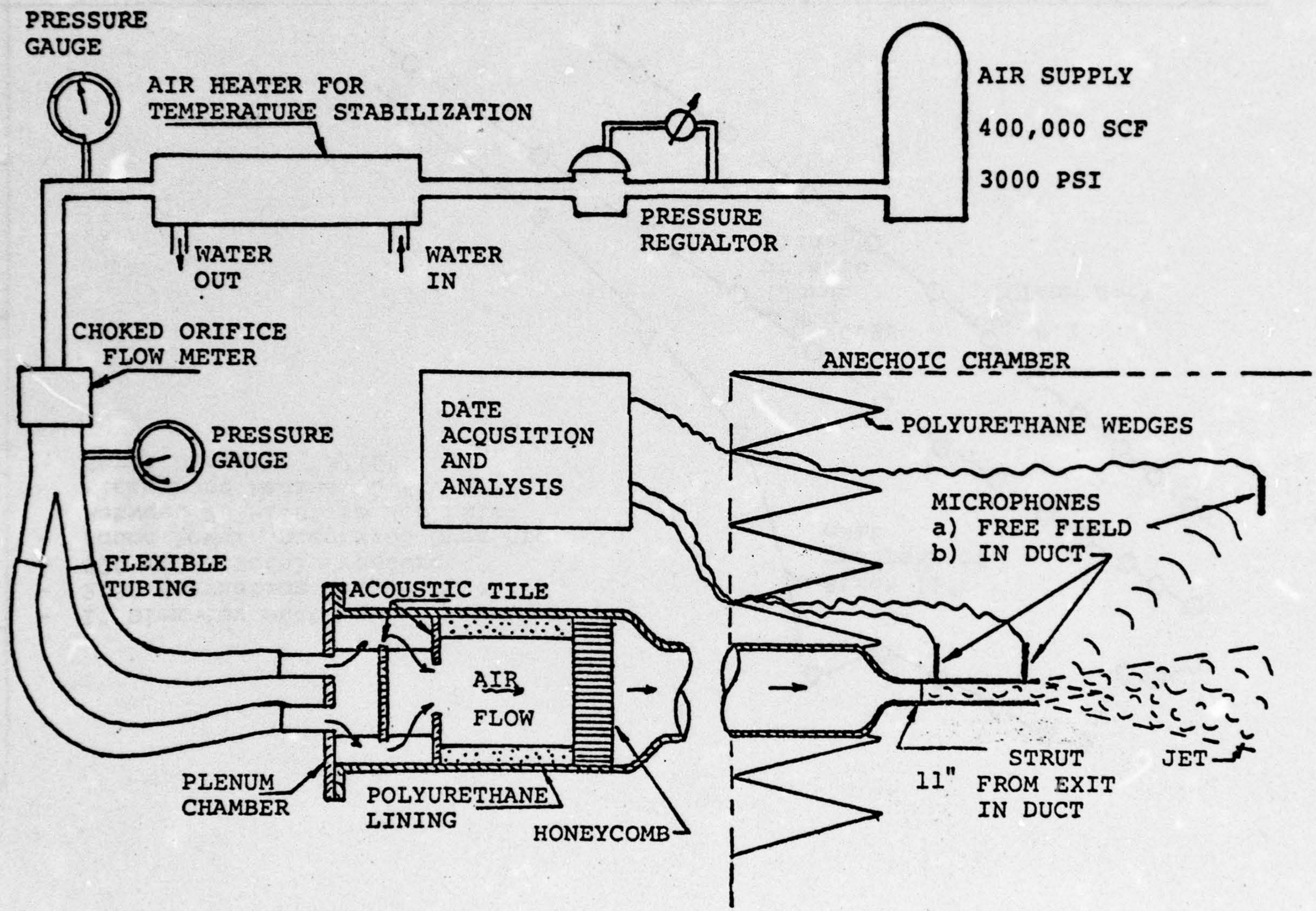

FIGURE 6 SCHEMATIC REPRESENTATION OF THE FLOW SYSTEM WITH THE STRUT IN THE DUCT

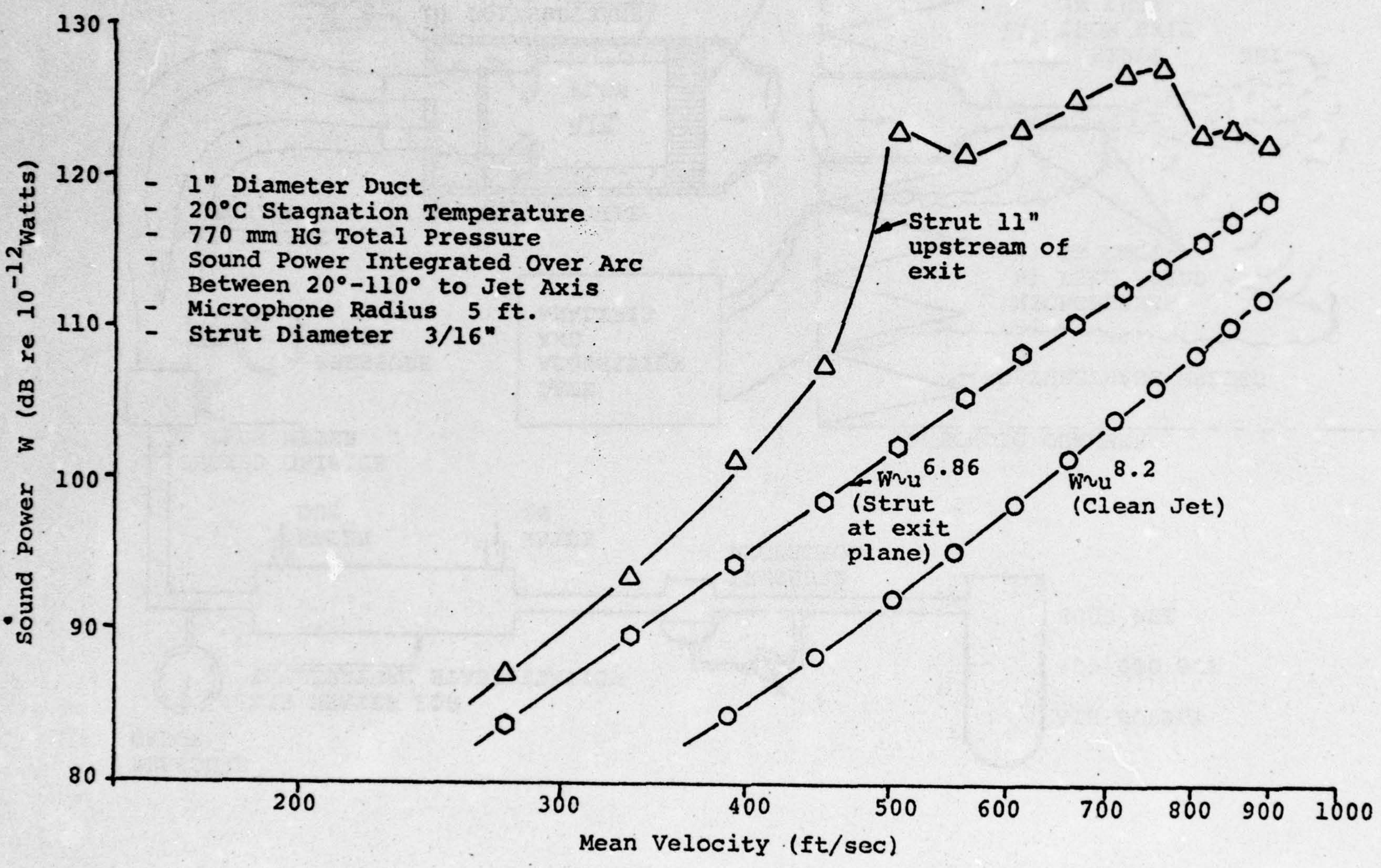

Figure 7 Effect of strut and strut location on noise generated by flow exhausting from a duct.

combustion inside the duct leading to the jet nozzle. The results of that study are given in detail in references 7, 8, and 12. Figure 8 shows the comparison of overall sound power obtained

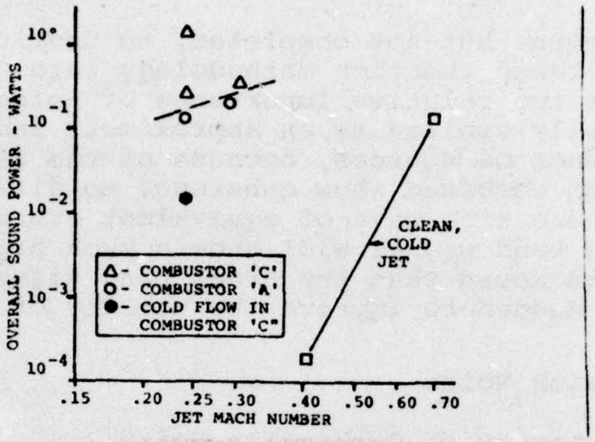

Fig. 8 Comparison of over-all sound power of combustor-jet with that of equivalent clean jet with 2-in.-diam. nozzle, using Mach number (equal thrust) as base of comparison.

with a clean jet having no upstream disturbances with that for a combustion augmented flow, using jet Mach number as the basis for comparison. The combustor can generates unsteadiness in the flow resulting in increased noise even without combustion (dark spot on Fig. 8), but the combustion gives rise to much higher sound power levels as shown by the open symbols in the jet Mach number range between 0.20 and 0.30. From this result it is clear that combustion inside a ducted flow system can substantially increase the noise levels experienced outside the duct.

2.2.3 Crosscorrelations

Crosscorrelations between internal unsteadiness and external noise with appropriate instrumentation were used to demonstrate the cause-effect relationship between them. This was first reported in connection with the internal strut-flow interaction noise[13] and later with reference to combustion noise[7,8,12]. In each of the cases for which the overall noise was observed to be substantially increased as a result of internal unsteadiness, a strong crosscorrelation between internal unsteadiness and external noise was obtained. In some cases, the normalized crosscorrelation between the time derivative of the internal pressure fluctuation and the external noise, for the case with unsteady combustion preceding flow through a nozzle, was observed to approach unity, which it should if the noise is predominantly caused by the unsteady combustion. This is further evidence of the importance as a noise source of unsteady combustion in a flow system.

Work was begun, but not completed, to develop the cross-correlation-coherence function methodology into a quantitative tool to evaluate the relative importance of noise sources. The method as generally applied is an approximate indication of relative importance of sources, because of the fact that different signal types when combined show coherence to different degrees. As a result, a pure sine wave of equivalent overall sound power level to a broad band signal will show a much higher coherence with the combined sound than the broad band signal will[14]. Further work is needed to improve the utility of this technique.

2.3 Combustion Noise

2.3.1 Theory of Combustion Noise

A unified theory of noise generation and amplification by turbulent combustion of premixed fuel and liquid fuel droplets was developed within the framework of the fluid mechanics of the reacting gas[15,16]. The overall sound generation processes were classified in terms of the sound due to an isolated turbulent flame and that due to the interaction of a flame with its environment in a typical combustor. The analysis focused on the mechanisms of sound generation, dispersion and transmission in the vicinity of the flame and on the resulting far field noise. The acoustic intensity generated by a turbulent premixed flame was found to be a function of various aerothermochemical parameters and the flame structural factor, and was expressed in terms of six double correlation functions characterizing the flame structure, equations 4 - 9. (See nomenclature at the end of this section.) The far field noise intensity due to a

$$S_{11} = \frac{\partial \dot{Q}'(\alpha)}{\partial \tau}\,\frac{\partial \dot{Q}'(\beta)}{\partial \tau} \tag{4}$$

$$S_{22} = u_i(\alpha)u_j(\beta)\frac{\partial \dot{Q}'(\alpha)}{\partial \xi_i}\,\frac{\partial \dot{Q}'(\beta)}{\partial \xi_j} \tag{5}$$

$$S_{33} = \left[u_i(\alpha) - \frac{\theta'(\alpha)}{\theta(\alpha)}u_i(\alpha)\right]\left[u_j(\beta) - \frac{\theta'(\beta)}{\theta(\beta)}u_j(\beta)\right]\frac{\partial \dot{\bar{Q}}(\alpha)}{\partial \xi_i}\,\frac{\partial \dot{\bar{Q}}(\beta)}{\partial \xi_j} \tag{6}$$

$$S_{12} = 2u_i(\alpha)\frac{\partial \dot{Q}'(\alpha)}{\partial \xi_i}\,\frac{\partial \dot{Q}'(\beta)}{\partial \tau} \tag{7}$$

$$S_{13} = 2\left[u_i'(\alpha) - \frac{\theta'(\alpha)}{\theta(\alpha)}\,u_i(\alpha)\right]\cdot \frac{\partial \dot{Q}'(\beta)}{\partial \tau}\,\frac{\partial \dot{\bar{Q}}(\beta)}{\partial \xi_i} \tag{8}$$

$$S_{23} = 2\left[u_i'(\alpha) - \frac{\theta'(\alpha)}{\theta(\alpha)}\,u_i(\alpha)\right]\cdot \frac{\partial \dot{Q}'(\beta)}{\partial \xi_j}\,u_j(\beta)\,\frac{\partial \dot{\bar{Q}}(\alpha)}{\partial \xi_i} \tag{9}$$

turbulent flame was expressed in terms of these parameters as follows (Equations 10 and 11)

$$I = \frac{(\gamma - 1)^2(\Delta H)^2(W_o)^2 \ell_f^{\,2} U_f^{\,2}(\Sigma R_{ij})}{16\pi\rho_\infty a_\infty^5\, r^2} \tag{10}$$

where

$$R_{ij} = \int\limits_{V(\alpha)}\int\limits_{V(\beta)} S_{ij}(\alpha,\beta)\,dV(\alpha)\,dV(\beta) \tag{11}$$

Explicit expressions for the sound intensities were obtained based on a wrinkled flame model and a distributed reaction model. Noise generated by liquid droplets was classified in terms of intrinsic and turbulent driven noise components.

Nomenclature: a = speed of sound
ΔH = heat of reaction
I = sound intensity
ℓ_f = flame thickness
$\dot{Q}$ = effective rate of heat release
$\dot{Q}'$ = time varying component of the rate of heat release
$\dot{\bar{Q}}$ = RMS value of the rate of heat release
R_{ij} = defined by Eq. (11)
r = radial distance
S_{ij} = defined by Eqs. (4) - (9)
U = velocity of gas at the edge of the reacting zone
$u_{i,j}$ = velocity components
V = volume of source region

Subscripts

f = denoting conditions at the edge of the reacting zone
i,j = directional vectors
∞ = relating to conditions far from the flame

Greek Symbols

α = position coordinate
β = position coordinate
γ = ratio of specific heats$=c_p/c_V$
ξ_ι = x_i/ℓ_f = dimensionless distance
ρ = gas density
θ = temperature, nondimensional$=T/T_f$
τ = nondimensional time$=tU_f/\ell_f$
ω_0 = rate of chemical reaction at the reference state

2.3.2 Evaluation of Combustion Noise Source Terms

The unified model described in section 2.3.1 has six candidate source terms whereas previous derivations by others working in combustion noise (e.g., ref. 17 - 19) have derived simpler expressions corresponding to only one of these terms. It seemed important, therefore, to evaluate the relative importance of these terms to determine which of the six were important enough to retain and which could be neglected.

The evaluation, as may be deduced from equations 4 through 9, would involve detailed simultaneous measurements of the time derivative of the heat release rate, the spatial variation of the heat release rate, fluid velocity components as well as local mean and fluctuating temperatures. In addition, as shown by equation 11, the coherent size of each of the terms was required in order that the relative sound intensity due to each could be compared.

An optical technique of monitoring the CH band radiation was chosen for measurement of the heat release rates[5,20]. Initially, two photomultiplier tubes were used to simultaneously monitor the CH band radiation, through focused optics, at two independent points in the flame. With that as input, and appropriate electronics to take differences and time derivatives, the information required to compare the S_{11} and S_{12} terms was obtained. Figures 9 and 10 show the measured values in partially reduced form, for one flame condition. Based on these measurements, at two flame conditions and two points in the flame for

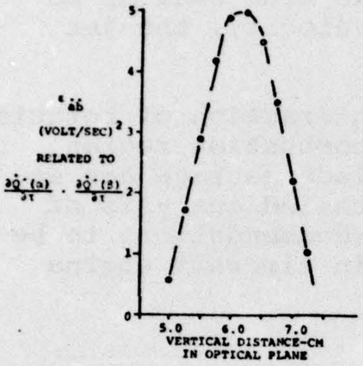

Fig. 9 Spatial crosscorrelation of the time derivative of the CH radiation at (0,4,0) in the flame for one flow condition.

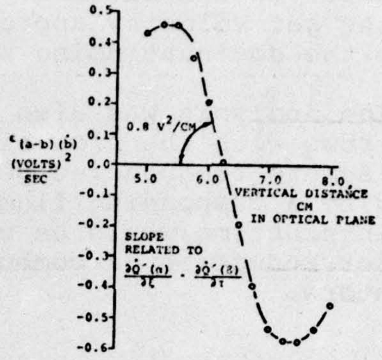

Fig. 10 Product of the difference of two point photomultiplier readings of CH radiation and the time derivative of one of them, also at (0,4,0) in the flame for the same condition as used for Fig. 9.

each condition, it was concluded that the $\overline{S}_{11}$ and $\overline{S}_{12}$ terms were of comparable strength. The overall intensity of sound contributed by each would be dependent on the coherent size of each source as well as the local strength. To obtain this information, a more elaborate set-up using four photomultipliers was set up. Results of that aspect of the study are now being summarized.[6]

2.3.3 Application of Theory to Ducted Combustors

The theoretical model for combustion generated noise, which was described in section 2.3.1, was applied to a ducted combustion system[9,10]. The analysis showed that the interaction between a zone of nonsteady combustion and its confining duct results in resonant type oscillations with resulting noise intensities far greater than from corresponding unconfined flame zones. Ducted combustor experiments verified the predicted resonant type noise, the amplitude and frequency of which were strongly influenced by the duct dimensions and end impedances. When a convergent nozzle was attached to the duct exhaust end, a stronger internal resonance was observed due to the stronger reflection from the partially closed end. The nozzle also had the effect of increasing the jet velocity so that the attendant jet noise became stronger. Therefore, although internal oscillations were increased in intensity, the jet was noisier, and the smaller nozzle opening allowed less direct transmission of sound from the inside to the outside. As the nozzle was made smaller so that the jet velocity approached the sound velocity, the jet became the dominant noise source.

The analysis was also applied to the interaction of rotating blade rows with the flow exhausting from a combustion region. The discrete frequencies generated by the blade passage are enhanced by a responding flame zone. More detailed analysis of this interaction would be useful to allow recommendations to be made for reduction of combustion roughness in aircraft engine combustors.

3.0 Conclusions

An experimental and theoretical program of research has been carried out to investigate the interaction of combustion with a flow system in the regime of interest for aircraft engine combustors and afterburners, to determine its importance as a source of noise. It was established that for typical combustors exhausting through a convergent nozzle to the atmosphere, the noise due to unsteady combustion was dominant for jet exhaust Mach numbers below about 0.4 to 0.7, with the cross-over point being directly dependent on the roughness level in the combustion zone. It was found from experiments that the combustion roughness was dependent on the flame holder configuration and on the duct geometry. Theory and experiment were both found to show that dominant frequencies in the ducted combustor were directly related to the flame-combustor geometry and end impedances. Further work is needed to optimize ways of reducing the combustion roughness.

A theoretical model was developed to describe the mechanisms of combustion noise generation. Source terms were described in terms of six double correlation functions. Experiments were conducted to evaluate the relative importance of the six terms for an open flame since their importance is dependent on the relationship of various turbulent parameters which cannot be predicted from basic theory. Experiments conducted show comparable strengths of at least two of the source terms. The noise contribution from each remains to be deduced.

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APPENDIX A

TECHNICAL REPORTS, PAPERS AND PRESENTATIONS AT TECHNICAL SOCIETY MEETINGS RESULTING FROM OUR NOISE RESEARCH PROGRAM

SEPTEMBER 1971 - MARCH 1977

1. "Design and Construction of a Noise Research Facility." MSE Thesis, AMS Department, Princeton University, September 1971. Author: D. L. Pike.

2. "Noise From Aircraft Engines Arising From Rough Combustion." Invited paper, presented at the Environmental Engineering Panel of the ASME 1972 Aviation and Space Conference, Anaheim, California, Sept. 11-13, 1974. Authors: A. N. Abdelhamid, D. T. Harrje, E. G. Plett and M. Summerfield.

3. "Noise of Jets Discharging from a Duct Containing Bluff Bodies." Presented at the Inter-Noise 72 Conference, Washington, D. C. October 4-6, 1974. Authors: E. G. Plett, T. M. Tower, A. N. Abdelhamid and M. Summerfield.

4. "Estimates of the Contribution to Jet Engine Exhaust Noise Made by Internal Sources." Presented at the 84th Meeting of the Acoustical Society of America, 28 November - 1 December 1974, Authors: E. G. Plett and M. Summerfield.

5. "Noise of High Speed Jets with Rough Combustion." Presented at the 84th Meeting of the Acoustical Society of America, 28 November - 1 December, 1972. Authors: A. N. Abdelhamid, D. T. Harrje, E. G. Plett and M. Summerfield.

6. "Noise Characteristics of Combustion Augmented High Speed Jets." Presented at the AIAA 11th Aerospace Sciences Meeting, Washington, D.C., January 10-12, 1973. Authors: A. N. Abdelhamid, D. T. Harrje, E. G. Plett and M. Summerfield.

7. "Combustion Noise in Aircraft Engines." Presented at the Inter Agency Symposium on University Research on Transportation Noise, March 28-30, 1973, Stanford University. Authors: E. G. Plett, H. H. Chiu and M. Summerfield.

8. "Combustion Roughness as a Contribution to the Jet Noise Component of Aircraft Engines." Interagency Symposium on University Research in Transportation Noise Proceedings, March 1973, pp. 495-514. Authors: E. G. Plett, H. H. Chiu, and M. Summerfield.

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10. "Noise Generated by Ducted Air Fuel Combustion Systems." Interagency Symposium on University Research in Transportation Noise Proceedings, March 1973, pp. 515-535. Authors: E. G. Plett, H. H. Chiu and M. Summerfield.

10. "Theory of Combustion Noise." Presented at the 4th International Colloquium on Gasdynamics of Explosions and Reactive Systems, San Diego, Calif. July 1974. Authors: H. H. Chiu and M. Summerfield.

11. "Noise Generated by Ducted Combustion Systems." AIAA Paper 73-1024, presented at the AIAA Aero-Acoustics Conference, Seattle, Wash., October 1973. Authors: H. H. Chiu, E. G. Plett and M. Summerfield.

12. "Cylindrical Spoiler Effects on the Sound Power of Subsonic Jets." Presented at the 86th Meeting of the Acoustical Society of America, Los Angeles, Calif., Oct.-Nov. 1973. Authors: T. M. Tower, E. G. Plett and M. Summerfield.

13. "Crosscorrelation Evaluation of the Contribution to Engine Exhaust Noise made by Internal Sources." Presented at the 86th Meeting of the Acoustical Society of America, Los Angeles, Calif. Oct.-Nov. 1973. Authors: E. G. Plett and M. Summerfield.

14. "Blast-Noise Environment of Impulsive Rocket Firings." AIAA Paper 74-48, presented at the AIAA 12th Aerospace Sciences Meeting, Washington, D.C. Jan.-Feb. 1974. Authors: H. H. Chiu, E. G. Plett, M. Summerfield and C. W. Nelson.

15. "Noise Characteristics of Combustion Augmented Jets at Midsubsonic Speeds." AIAA Journal, Vol. 12, No. 3, pp. 336-342, March 1974. Authors: A. N. Abdelhamid, D. T. Harrje, E. G. Plett and M. Summerfield.

16. "Noise Due to Jet Motion Caused by Internal Unsteadiness." Presented at the 87th Meeting of the Acoustical Society of America, New York, April 1974. Authors: E. G. Plett and M. Summerfield.

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22. "Combustion Intensity and Distribution Relation to Noise Generation." AIAA Paper No. 75-524, Presented at the AIAA 2nd Aero-Acoustics Conference, Hampton, VA., March 1975. Authors: E. G. Plett, M. D. Leshner and M. Summerfield.

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28. "Blast-Noise Environment of Recoilless Rifle and Impulsive Rocket Firings Part II. Theoretical Prediction of Blast Pressures Caused By Expansion of Rocket Exhaust Plumes." U.S. Army Ballistic Research Laboratories Report No. CR 274, 1975. Authors: H.H. Chiu , H. H. Chiang, E. G. Plett and M. Summerfield.

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