N.C.

[redacted]

FACILITY FORM 602

N69-28850	
(ACCESSION NUMBER)	(THRU)
17	1
(PAGES)	(CODE)
NASA CR-#98476	33
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

WYLE LABORATORIES

TESTING DIVISION, HUNTSVILLE FACILITY

[redacted]

S07-55814

research report

WYLE LABORATORIES - RESEARCH STAFF

TECHNICAL MEMORANDUM 68-12

ESTIMATE OF NUCLEAR TECHNOLOGY ENGINE TEST STAND SOUND POWER AND SPECTRUM

By

D. E. Cuadra and R. C. Potter

Work Performed Under Contract NAS8-21260

August 1968

WYLE LABORATORIES
RESEARCH DIVISION, HUNTSVILLE FACILITY

COPY NO. 50

TABLE OF CONTENTS

INTRODUCTION

In a preliminary test run of the Nuclear Technology Engine, at reduced hydrogen flow rate, it was realized that the structural integrity of an adjacent shielding wall (of corrugated aluminum) might be endangered by noise levels in the design flow rate case.

The purpose of the present exercise has been to estimate the total sound power level, and the spectrum of the power, for both the test case already run and the design case. From these, the sound pressure levels at points on the wall can be estimated.

Heat from the nuclear reactor is used to heat the propellant (hydrogen). In the case of tests run within the atmosphere, the hot hydrogen mixes and burns with the atmospheric oxygen. In the test setup as described to us, the efflux includes steam from an ejector, premixed with the hydrogen, and ejected through a circular exit of 4.33-ft diameter.

Since both combustion and jet mixing occur in the atmosphere aft of the exit, it was not apparent which noise source would dominate, and estimates have been made for both mixing noise and combustion noise. By these results, as well as the observations of previous experimenters, combustion noise is expected to be the dominant source.

1. JET MIXING NOISE

The correlation of Cole et al. (Reference 1) was used to predict the mixing noise:

$$PWL = 78 + 13.5 \log_{10} W_m, \text{ dB, re: } 10^{-13} \text{ watts}$$

where W_m = jet mechanical power, watts

= $0.676\ TV$,

T = thrust, lbs = $\frac{w}{g} V$

V = exit velocity, ft/sec

w = exhaust weight flow, lbm/sec

Two conditions were given - a test case and a design case:

Case	Hydrogen Flow (lbm/sec)	Steam Flow (lbm/sec)
Test	6	137
Design	77	137

For these two cases, the resulting jet mechanical powers and sound power levels were:

Case	Jet Mechanical Power (watts)	Sound Power Level (dB, re: 10^{-13} watts)
Test	6.75×10^6	170
Design	1.81×10^8	190

Before leaving Cole et al, it is of interest to note that, while their (code numbered) rocket engines probably did not include any hydrogen-fueled engines - not in 1957 - they did explore the effect of the case when combustion noise is dominant, by adding a flame-inhibiting chemical. The effect of the additive was to delay the combustion process and thus lengthen the external combustion flame. They found that rockets with re-ignition in the exhaust are substantially noisier than those without. They also found that oscillations in the flame front caused large increases in the near-field SPL, though not in the far-field SPL, and power. A stabilizing surface, providing a region of low-speed air to which the flame could attach itself, was found to decrease the near-field SPL as much as 15 dB in the low-frequency bands.

If flame-front oscillations were observed in the test run of the nuclear engine, a flame stabilizer may be necessary, since the wall will be in the near-field and may experience SPL's significantly higher than those predicted from a sound power calculation.

2. COMBUSTION NOISE

Combustion noise was calculated by a method based on the experiments of Smith and Kilham (Reference 2), whose results are generally supported by the other experiments cited (References 7 and 8).

Smith and Kilham measured the acoustic fields of small, low-speed turbulent flames. A correlation between generated acoustic power and a grouping involving jet exit velocity, jet exit diameter, and burning velocity was given, together with data on the efficiency of conversion of thermal energy to acoustic energy for two fuels tested. The acoustic power generation was correlated by

$$P \sim (UDU_b)^2$$

where P = acoustic power
U = exit velocity
D = exit diameter
U_b = burning velocity

Ranges of the energy conversion efficiency (thermal to acoustic), $\eta_t = 1.2 - 4.3 \times 10^{-8}$ for propylene-air and $2.7 - 8.2 \times 10^{-8}$ for ethylene-air (at near stoichiometric mixtures) were measured, and η_t is noted to rise rapidly with flow rate (i.e., thermal energy).

From Reference 3, the burning velocities for ethylene-air and for propane-air are about 60 cm/sec and 40 cm/sec respectively. This provides a check on the idea of ratioing the energy conversion efficiency by the burning velocity squared. The additional ratioing by the jet velocity squared provides for the increases of η_t with thermal energy available. However, it is apparent that η_t cannot continue to rise indefinitely, and from the data of Putnam (Ref. 8) there appears to be some leveling off at a value of about 10^{-7} for turbulent diffusion flames without premixing.

Burning velocity is the speed at which a laminar flame front will propagate through a quiescent mixture of the fuel and oxidizer. It depends upon concentration, temperature, pressure, and the chemicals involved. We have assumed that the hydrogen mixes rapidly enough with the air to be in near-stoichiometric mixture, and since it enters the reaction at a high temperature, we have taken the upper end of the range of burning velocities given in Reference 4 for hydrogen-air mixtures:

$$5 < U_b < 10 \text{ meters/sec}$$

Using these assumptions and a heating value of 60,000 BTU/lbm for hydrogen to get the thermal release rate, one obtains:

Case	Hydrogen Flow (lbm/sec)	Thermal Power (kw)	Sound Power Level (dB, re: 10^{-13} watts)
Test	6	3.8×10^5	186 - 191
Design	77	48.8×10^5	209 - 214

The foregoing results are generally consistent with approximate results from natural gas well fires (Appendix B). An attempt was made to calculate combustion noise by the method of Reference 5, but inconsistent results were obtained and are not reported here.

3. SPECTRUM OF COMBUSTION ACOUSTIC POWER

The spectrum of the combustion acoustic power was scaled directly from the results of Figures 16 and 17 of Reference 6. It was indicated in this report that the scaling of acoustic power spectra was dependent to some degree on the jet exit density of the gas flows, and that a simple Strouhal number based on frequency, exit diameter and exit velocity was not sufficient. This leads to a problem for the case considered here, in that it is not immediately apparent what is the appropriate density to use for the combined stream and hydrogen flow. Hence, both spectra were examined.

The octave band power spectrum was calculated for each case and the values are given below and plotted in Figure 1. These results are based on the calculated maximum overall level of 214 dB, re: 10^{-13} watt. A 5 dB spread below these figures must automatically be included.

Octave Band Center Frequency (Hz)	Octave Band Combustion Acoustic Power (dB, re: 10^{-13} watt)	
	From Figure 16 Reference 6	From Figure 17 Reference 6
16	203	197
32	206	200
64	208	203
125	208	206
250	208	207
500	204	208
1000	199	206
2000	196	204
4000	193	201
Overall	214	214

4. SPECTRUM OF SOUND PRESSURE LEVEL ON WALL

The typical sound pressure level on the wall was estimated by assuming a concentrated point source of acoustic power at a point 60 ft from the wall.

No directivity was included, since the nozzle will be firing at an angle to the wall and the directivity will be such that the highest levels are recorded near 70 - 80 degrees to the jet stream direction. Hence the wall could easily be in the region of maximum level.

On this basis, and taking the mean result from the acoustic power spectrum of Figure 1, the estimated sound pressure level on the wall was determined. No attempt was made to estimate the frequency shift from the acoustic power spectrum to the sound pressure level spectrum, since no estimate of source distribution could be made. The process of combustion noise generation is not fully understood, and hence the parameters that determine source location by frequency cannot be presented. Until measurements of mean velocity within the flame are available or appropriate acoustic measurements made, this question will not be resolved.

In view of all these comments it is estimated that the spectrum given below represents the most conservative value. A range of up to 10 dB can be added to these results, giving an overall level of 158 - 168 dB, re: 0.0002 dyne/cm^2.

Octave Band Center Frequency (Hz)	Sound Pressure Level (dB, re: 0.0002 dyne/cm^2) Most Conservative
16	154
32	157
64	159
125	161
250	161
500	160
1000	156
2000	153
4000	150
Overall	168

5. CONCLUDING NOTES

This study has indicated the lack of knowledge concerning large-scale combustion noise. Questions that need answering include determination of the whole basic mechanism of combustion noise, the source distribution in the exhaust flame, and cause of the directivity of the resultant sound field.

It is concluded that for the hydrogen flow nuclear rocket, the combustion noise will be some 10 dB greater than the associated jet mixing noise. For the design case considered, the sound pressure level on the wall was estimated to be 158 - 168 dB, re: 0.0002 dyne/cm^2.

REFERENCES

1. Cole, J.N., Von Gierke, H.E., Kyrazis, D.T., Eldred, K.M., and Humphrey, A.J., "Noise Radiation from Fourteen Types of Rockets in the 1000 to 130,000 Pound Thrust Range," WADC TR 57-354, Dec. 1957.

2. Smith, T.J.B., and Kilham, J.K., "Noise Generation by Open Turbulent Flames," JASA 35, 715-724, May 1963.

3. Arnold, J.S., "Modulated Combustion (Dragon) Loudspeaker," JASA 38, 416-423, Sept. 1965.

4. Williams, F., "Combustion Theory," Addison-Wesley Co., 1964.

5. Ffowcs-Williams, J.E., "Possible Effects in Rocket Exhaust Noise," Wyle TM 67-8, Oct. 1967.

6. Manhart, J.K., Ailman, C.M., Lane, S.R., and Marsh, A.H., "An Acoustical Study of the Kiwi-B Nuclear Rocket," NASA CR-370, Jan. 1966.

7. Powell, A., "Noise Measurement of a Turbulent Gasoline Vapor Flame," JASA 35, 3, 405, 1963.

8. Putnam, A.A., "Noise Measurements of Turbulent Natural-Gas Diffusion Flames of 120,000- to 750,000-Btu/h Output," JASA 43, 4, 890-891, 1968.

9. Private communication, C.N. Segnar, Chief Engineer, Standard Oil of Texas, Houston, Texas, July 24, 1968.

10. Private communication, Red Adair, Red Adair Co., Inc., Houston, Texas, July 25, 1968.

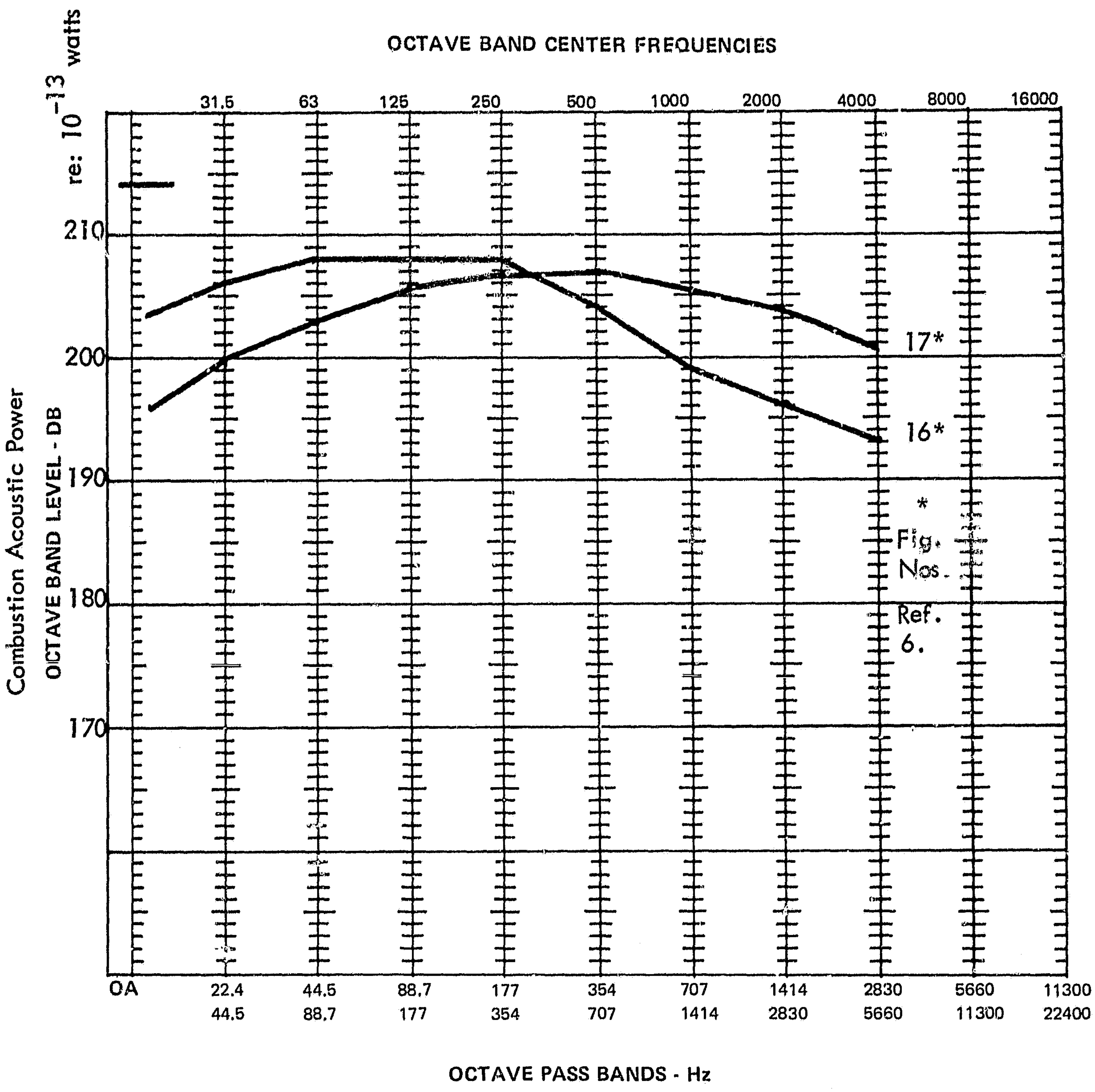

Figure 1: Spectrum of Combustion Acoustic Power (Design Case)

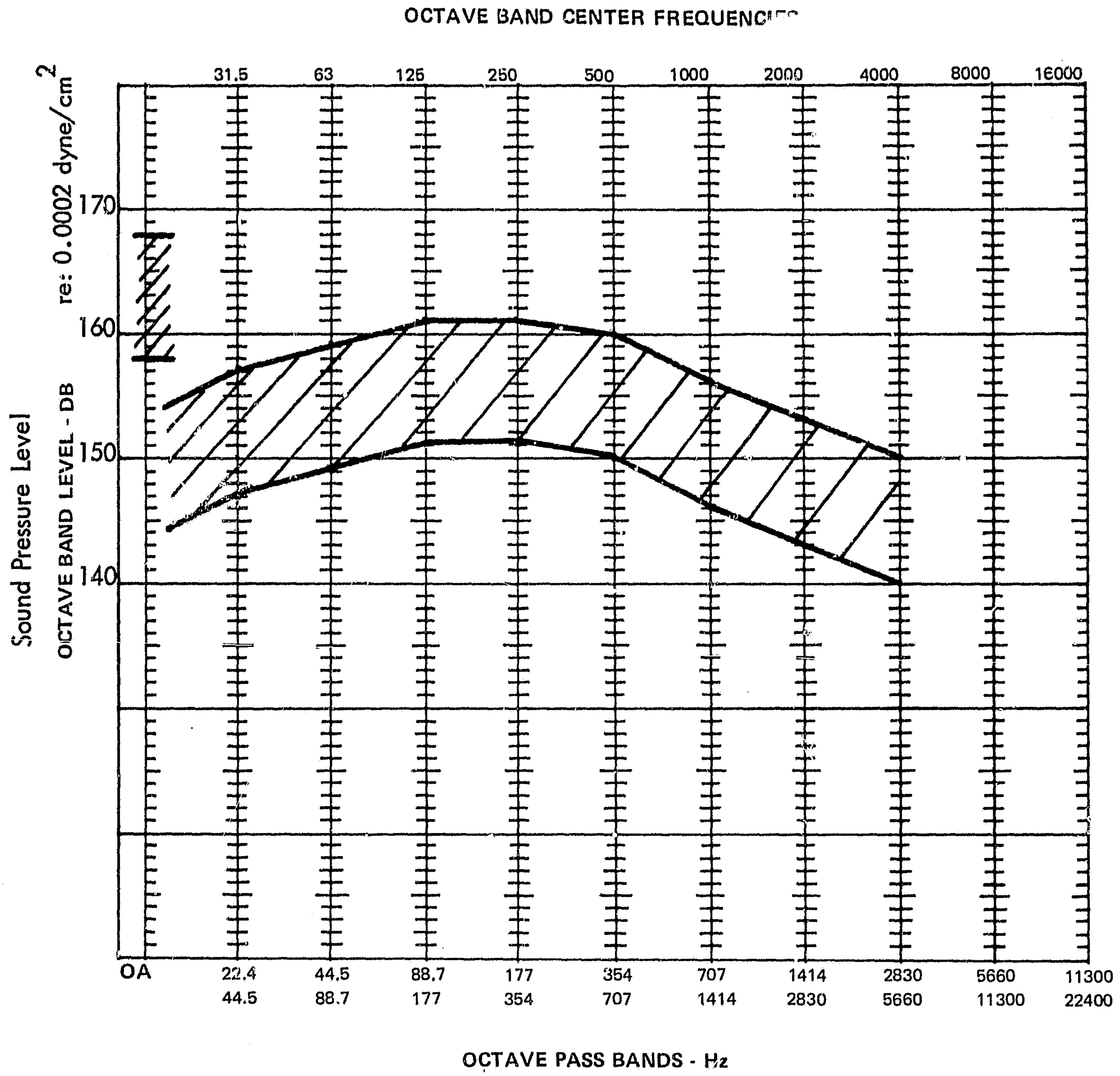

Figure 2: Spectrum of Estimated SPL on Wall

APPENDIX A

Some Physical Considerations Regarding the Sound Power Level and Spectrum of Combustion Noise as Compared with Jet Noise

Two of the key questions bearing on prediction of noise from a burning rocket exhaust are:

1. Is combustion noise or the jet noise dominant?
2. If the combustion noise is dominant, at what characteristic frequency (wavelength) does the sound power spectrum peak?

By the Ffowcs-Williams method of estimating an upper limit for combustion noise (Ref. 5), the sound power level calculation rests on an assumption for the dominant wavelength. The effect of this assumption is profound, since the acoustic power is inversely proportional to the square of the wavelength.

The experimenters of References 1, 2 and 7 have commented on: (a) the relative noise produced by a burning jet compared with the same jet without burning, and/or (b) the typical wavelength of the combustion noise. Some of their comments are collected here.

Cole, et al. (Reference 1), explored the effect of combustion in one external exhuast by adding a flame-inhibiting chemical. The effect of the additive was to delay the combustion process and thus lengthen the external flame. They found that rockets with re-ignition in the exhaust are substantially noisier than those without. Further, in cases where large oscillations in the flame front occurred, they measured large increases in the near-field SPL (15 dB at the low-frequency end), although these increases were not measured in the far-field SPL and power. Therefore, combustion noise was certainly dominant in their rockets whenever an extensive flame occurred, and low-frequency near-field SPL's (experienced by a nearby structure) can be significantly higher than would be predicted by any sound power calculation.

Powell (Reference 7) measured the noise of a Primus burner (exit diameter 0.050-inch), producing a turbulent diffusion flame and 1.4 kw thermal power. He found an energy conversion efficiency η_t (thermal power to acoustic power) of 3 x 10^{-9}, measured octave band levels peaking in the 300 - 600 Hz band, and noted that "The wavelength of the frequency at the spectral maximum is many times any characteristic dimension of the turbulent combustion zone".

Smith and Kilham (Reference 2) concluded from their measurements of the noise field of premixed hydrocarbon-air flames that combustion noise could be considered to originate from monopole sources of various strengths and frequency distributed throughout the combustion zone, with the resulting sound field modified by refraction through the temperature gradient (peaking about 50 degrees from the axis). They obtained energy conversion efficiencies η_t (thermal to acoustic) ranging 1 x 10^{-8} to 3 x 10^{-8} and rising rapidly with efflux velocity. Regarding the typical wavelength of the combustion noise, we quote:

> "It was noted that a relationship existed between the most intense frequencies of combustion-noise spectra and the dimensions of the burner port, large-burner diameters having predominantly low-frequency content, and small-diameter burners high-frequency content. The peak frequencies of combustion noise were found to be related to burner dimensions, the wavelengths of the maxima being approximately 70 to 100 times the burner-port diameter, depending on the type of fuel gas, since the wavelengths of maximum intensity also appear to be inverse functions of the combustion velocities of the stoichiometric air-gas mixtures. The dependence of wavelength on diameter differs greatly from the case of jet noise, where the wavelength of the peak frequency was found to be only 3 to 4 times the jet diameter.
>
> From the foregoing observations, it is proposed that the peak frequency of combustion noise (arising from any burner system) may be expressed as a constant nondimensional frequency, or Strouhal number, in terms of the exit diameter, flow and combustion velocities, and the frequency maximum, but further research will be required to determine the exact form of this expression."

Additional comments on the relative levels and spectra, comparing burning gas jets with the same jets nonburning, were made by Putnam (Reference 8), working with natural gas opposing jets that formed a spherical flame region. He found that the noise produced by unlighted fuel jets peaked at a frequency of 10,000 Hz and gave low intensities compared with the same jets ignited. Further, when the jets were ignited, the dominant frequency shifted to the 100 to 500 Hz range. Energy conversion efficiencies ranged roughly from 2×10^{-8} to 10^{-7}. Putnam also concluded that the sound field produced was characteristic of monopole-type sources in the flame.

Of course, all these cited results are for flow rates and energy release rates much lower than for a burning hydrogen rocket exhaust. However, qualitative confirmation of the relative level of combustion noise and of its dominant frequency range for the case of much larger burning jets is available from witnesses of natural gas well "blowouts" (References 9 and 10). When a new well is being drilled in regions of high underground natural gas pressure, occasionally the blowout prevention devices fail and a "wild well" occurs, producing a large natural gas flame. This flame must be blown out with explosives, after which the same gas jet continues (nonburning) until the well is finally capped. Witnesses report that one burning gas jet is "extremely noisy, much noisier than the same jet after the flame is put out", that the combustion noise is audible for distances of 8 - 10 miles and produces complaints and threats of legal action from residents within a radius of 5 miles. Those who move in close to blow out the flame and cap the well report severe body vibrations, dizziness and earth vibrations. The frequency content of the unlighted jet is similar to that of a jet aircraft takeoff (broadband but peaking at a definite frequency), whereas the same jet with combustion shifts to a "rumbling roar", a very uneven sound of much lower frequency content and apparently much more broadband in nature.

From the results of all the above noted experimenters and observers it is apparent that, in a gas jet with combustion - - even including the large, high-speed (up to Mach 6) jets produced by natural gas well fires - - it is the rule rather than the exception that:

1. The combustion noise dominates the jet noise.
2. The combustion noise spectrum is typically of lower frequency content than the jet noise from the same setup without burning.
3. Combustion noise is from a completely different generation mechanism than jet noise and is probably monopole in nature.

Having drawn these conclusions, it is worthwhile to consider why they should be so. On comparing the expressions for total sound power generation by monopoles, dipoles, and quadrupoles, one finds that the power generated is related to characteristic frequency and to propagation speed in the medium as:

$$W_S \sim \omega^2/c \quad \text{, monopole}$$

$$W_D \sim \omega^4/c^3 \quad \text{, dipole}$$

$$W_Q \sim \omega^6/c^5 \quad \text{, quadrupole}$$

This means primarily that monopole sources generate sound more efficiently at low frequencies than do dipoles or quadrupoles, and so on. As a secondary effect, the sound power generated by dipoles and quadrupoles is more affected by changes in propagation speed (as due to heating of the nearby air by a very large flame) than is the sound power generation by monopoles.

Now, jet noise without surfaces present is generally agreed to be quadrupole-type generation; with surfaces present, it would become dipole-type generation (corresponding to the fluctuating force produced by pressure fluctuations on a solid surface); and combustion noise (based on results from all experiments referenced) appears to be monopole-type generation (corresponding to volume fluctuations).

Therefore, in any given jet including heat release, if one were to increase the jet velocity while keeping the rate of heat release constant, one should expect the spectrum shape to shift slowly from the (combustion noise dominated) low-frequency spectrum (like that from Kiwi-B hot hydrogen runs) to the typical jet noise spectrum. If there were surfaces present, such as an exhuast deflector, the spectrum shape would finally peak at a lower frequency corresponding to dipole sources, compared to that for quadrupole sources.

Considering the fact that the dimensionless spectrum used here (Reference 6, Figure 17, hot flow hydrogen, Kiwi-B) was based on data from a vertical (upward) firing and no surfaces present, it naturally should be expected to have less low-frequency content and more high-frequency content than data from the same engine with exhaust deflectors present. This is confirmed by reduction of experimental data for chemical rocket engine noise (private communication, R-AERO-AUA, MSFC). It is felt that the free upward firings reported in CR-370 are more representative of NASA's present engine setup than any data involving exhaust deflection. Further, it is concluded that when combustion noise is dominant, a generally lower frequency content should be expected than when jet noise is dominant.

APPENDIX B

Oil Well Fires

When an oil field under pressure is drilled, occasionally the escaping gas will catch fire. This fire is put out by explosives before the well can be capped. This phenomena produces a jet of gas at high speed vertically upward that is initially burning, and then not burning. It resembles a rocket and allows a qualitative assessment of the noise of combustion relative to jet mixing noise.

Conversations with Mr. Red Adair, Red Adair Company, Inc., and Mr. C. N. Segnar, Chief Engineer, Standard Oil of Texas, produced the following observations. When the well was burning, the noise could be heard 8 - 10 miles away, and complaints and threats of legal action were made at distances of 5 miles. The noise when burning is characterized by very low frequency sound, which is both airborne and groundborne and causes dizziness and body vibration. The level decreases as the flame is extinguished and the noise shifts to higher frequencies. In this case it was described as resembling jet engine noise.

The gas flow is supersonic, and up to 6 Mach diamonds have been observed in the flow. The gas stream expands 4 to 6 times the pipe diameter on leaving the pipe end.

On the basis of these observations and parameters for the oil well flow, the noise due to the combustion and jet mixing can be estimated.

If 80 dB were measured at 10 miles, then the source power, assumed radiating hemispherically, and including a correction for atmospheric absorption, calculates to be 205 dB, re: 10^{-13} watts.

Putting the jet velocity at 3000 cps, the jet gas density at 0.0057 slugs ft^3 and the jet diameter at 4 feet (observed expanded flow diameter), the aerodynamic noise power calculates as 195 dB, re: 10^{-13} watts.

Using the same figures, the thermal energy release was calculated to be 1.2×10^{7} BTU/sec. This gives a noise power of over 210 dB, re: 10^{-13} watts, using the Smith and Kilham procedure.

These two results indicate that the combustion noise is some 10 dB greater than the jet aerodynamic mixing noise.

It is recommended that consideration be given to obtaining measurements from such oil fires. This would allow an immediate examination of combustion noise relative to jet mixing noise. Such oil fires are a not too uncommon phenomena in the high pressure fields of Texas, Louisiana, and the off-shore Gulf of Mexico oil fields.