# GENERAL SESSION II

## CHARACTERISTICS OF NOISE FIELDS

Chairman: I. Dyer

# TYPES OF PRESSURE FIELDS OF INTEREST IN ACOUSTICAL FATIGUE PROBLEMS

by

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## SECTION I

## INTRODUCTION

The first step in the analysis of the response of structures or equipment to fluctuating pressure fields is the description of the important characteristics of the pressure input. Such a description of the types of pressure fields encountered can be done in various ways and normally in this process some simplification is made either by approximating the actual environment by a theoretical description which can be handled satisfactorily mathematically or by selecting certain characteristics of the physical quantity for measurement as they are dictated by the interest in the effect of this quantity, by instrumental limitations or economic reasons. Therefore the resulting descriptions of pressure fields around aircraft structures are always only an approximation. Various amounts of information have been lost in this process depending on the specific purpose or application. It is important to emphasize this point since the majority of the information available on noise fields around aircraft and missiles was accumulated for purposes other than acoustic fatigue problems.[1*] Therefore the general, long time average characteristics of noise sources which are derived from far field measurements have been studied in detail for application in noise control work, whereas, for example, the statistical aspects of the noise and its space correlations have been neglected. Investigation of the latter properties of the noise fields was not started until recently when acoustic fatigue problems required this knowledge.[2, 3] Other papers in this symposium will deal with the limited data, which were recently obtained on these specific aspects. This review of the types of pressure fields of interest in acoustic fatigue problems will only give a brief introduction to their characteristic properties, their significant variables and to the problems limiting our knowledge. For detailed engineering information on the application of available data, a more exhaustive study of the references is necessary. Some of the data on noise fields presented in this paper were selected from experiments recently conducted and constitute rather specific examples of studies to obtain some of the information still missing. They cannot do justice to the large number of programs oriented toward similar goals.

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*Superscripts indicate references.

After a characterization of the types of pressure fields of interest, the discussion will be concentrated on the pressure fields around free jets and in boundary layers. The near and far fields around propellers will not be covered since they can be calculated even for forward speed conditions with fair accuracy[1] and constitute a minor problem with respect to sonic fatigue compared to jet noise. For jet noise the prediction of the near field and its space correlation is still a problem. It is not done by starting the calculations with the cause for the pressure fluctuations, namely the turbulent flow, since the detailed parameters of the specific flow regime are not known, but rather by extrapolation from existing measurements and by the application of certain scaling laws. It is in this connection that the general classification of pressure fields given in the first section can be of assistance since it helps in estimating the limits of validity of the assumptions and extrapolation.

# SECTION II

## CHARACTERIZATION OF PRESSURE FIELDS

The pressure fields of interest with respect to sonic fatigue problems can be characterized in several ways. First, they can be grouped according to their time function. There are periodic pressure fields, random pressure fields and transient pressure loads. The most important example for the first type is the pressure field from propellers; random pressure fields are present in turbulent gas streams and the noise radiated from this turbulence has the same character. Transient pressures of importance are the sonic bang from supersonic aircraft, gun blasts and the starting transients from afterburners in jet engines and from rockets.

It is important to realize that in the normal long time average frequency analysis of the pressure-time history the information concerning the phase between the different frequency components has already been abandoned. This is done for the discrete frequency spectrum of periodic noises as well as for the continuous, broad band spectra of noises with random character. The distribution of the instantaneous amplitudes as a function of time can be quite different for two noises with the same frequency spectrum. The assumption, as made frequently, of a normal distribution for jet mixing and boundary layer noise is an approximation valid only within certain limits. The same source can exhibit, for example, a different peak distribution depending on the environment into which it radiates. In fig. 1 this is demonstrated for a wide band siren proposed for the laboratory simulation of wide band noise: the same source produces different peak to RMS-values in a reverberant room and in an anechoic room.[4] Similar effects must be expected, for example, for the sound pressure of a jet engine under free field vs. test cell or other reverberant environment conditions. The importance of the peak to RMS value and other statistical properties of a noise have been neglected only too frequently when a noise was simulated for certain tests: identical noise spectra of the actual and simulated environment were accepted as proof that the pressure fields were the same. For many conditions this is far from being correct. For acoustic fatigue tests, it is obvious that peak factor and space correlation are properties of the noise field which cannot be neglected. They should be identical for the test noise field and the actual environment, and future investigations may reveal that additional statistical properties must be included in a valid characterization of the noise field for such testing purposes.

A second characterization of the pressure fields can be made according to their field character: one has to distinguish between acoustic fields, in which the pressure disturbances propagate in the medium with sound velocity, and the source fields, such as turbulent areas, in which this is not the case. Mathematically the source field is an area where, for periodic disturbances:

$$\Delta p + k^2 p \neq 0$$

whereas in the acoustic field the wave equation holds

$$\Delta p + k^2 p = 0$$

( p = pressure, $k = \frac{2\pi f}{c}$ , f = frequency, c = sound velocity)

The pressure fluctuations in the source field are determined by the aerodynamic flow conditions and therefore their calculation or prediction would require the solution of the difficult turbulence problem for the specific flow. The acoustic field outside of the source field can be calculated, at least in principle, when the source field itself or the conditions at its boundary are known.[5] This is normally not too difficult if one is interested only in the acoustic field at a far distance from the source (i. e., when the distance r from the source is large compared to the dimensions of the source and large compared to the wave length). In acoustics the area in which this condition is fulfilled is called the far field. Unfortunately most acoustic fatigue problems take place close to the noise source where this condition does not hold. Whereas the pressure in the far field decreases with ($\frac{1}{r}$), the near field has terms containing higher powers of ($\frac{1}{r}$). These terms of higher order in ($\frac{1}{r}$) contain the frequency with a lower exponent. As a result the spectrum changes in the near field with the distance from the source. In addition, the near field is usually mathematically very difficult to calculate since complicated phase changes occur near the source area. These phase variations complicate experimental measurements and make it difficult to establish a simple description of the near field.

A third way of characterizing the pressure fields is according to the elementary acoustic sources which generate the acoustic field.[6] The three most basic sources, the monopole, dipole and quadrupole, have all been used in analyzing and describing aviation noise sources. Their basic characteristics are summarized in fig. 2. A monopole radiation, represented in the graph by a pulsating sphere, is connected with any periodic volume flow such as occurring in reciprocating engine exhaust, pulse jet engines, rough burning jets, etc. A dipole, represented by an oscillating sphere, always originates from a change in force; it is therefore the main noise source of propeller noise. Dipole sources have been used to represent the aerodynamic forces of the propeller blade, and this type of source is also present in boundary layer noise. Only one type of quadrupole, the lateral quadrupole, is illustrated in fig. 2. Other kinds exist and Lighthill has shown that noise generation by free turbulent jets is due to quadrupole sources.[5]

# SECTION III

## TURBOJET ENGINE AND ROCKET NOISE

The pressure fields of main interest in sonic fatigue problems are generated by jet engines with and without afterburners and by rocket engines. Although the intake and compressor noise of air breathing engines and the combustion noise of air breathing engines and rockets can give rise to local acoustic problems, the exhaust noise of these jet propulsion units is by far the most important noise source. It is generated by the turbulent flow of the jets and appears to be radiated by a mixture of lateral and longitudinal quadrupoles. The total acoustic power radiated by today's high thrust engines is in the order of several thousand kilowatts. This total acoustic power has been predicted theoretically to increase at least with the 8th power of a characteristic jet velocity and all experimental investigations confirmed this so-called "8th power law" to a surprising degree. In fig. 3 the results are summarized for the acoustic power radiated by small model jets of less than one inch diameter up to the largest rocket engines of several feet diameter and for velocities ranging from small subsonic velocities to high supersonic exit velocities. The rocket data points appear to deviate from the straight line. To some extent this is promising since it indicates that the efficiency of conversion of propulsion energy into acoustic energy no longer increases steadily with increasing velocity. Theoretical studies proposed that this efficiency might not exceed a limiting value in the order of 2%. On the other hand there are no signs of decrease in efficiency, i. e., the noise will further increase with increased thrust. The explanation for the deviation of the rocket data from the straight line in this figure is probably found in the fact that the supersonic portion of the gas stream radiates only negligible acoustic power; in other words, the jet velocity effective for acoustic radiation does not exceed the sound velocity in the flow. Insertion of the sound velocity instead of the jet velocity as characteristic velocity in the Lighthill parameter makes the rocket data fall on the straight line with the rest of the data. The justification for this is suggested by the near field contours of fig. 4; most noise of the jet engine is radiated from the first 6 nozzle diameters downstream of the nozzle; little noise is radiated beyond ten nozzle diameters. In contrast to this, the supersonic rocket radiates most noise from the mixing region aft of the supersonic core, i. e., 20 to 40 nozzle diameters downstream. The supersonic part of the jet radiates comparably little energy. Fig. 5 confirms this finding. Here the location of maximum sound pressure along the jet boundary is plotted versus the Strouhal number or dimensionless frequency. All frequencies of the jet engine have their maximum closer than 10 nozzle diameters, the high frequencies close to the nozzle, the low frequencies farther away. They have a distribution similar to the turbulence frequency in the jet stream. The few data points available on supersonic jets point toward maxima between 20 and 40 nozzle diameters.

The total noise power radiated by all jet streams follows one normalized characteristic spectrum, which is shown in fig. 6. It has been found valid for jets of 2 inch diameter at low supersonic velocities as well as for rocket jets of 25 inch diameter, Mach number 3, and temperatures of 4000° F. The establishment of this generalized spectrum is not only important for theoretical considerations but also supplies the correct scaling laws for conducting noise reduction and noise distribution experiments with small model jets and model aircraft structures rather than with full scale jet engines, rockets, and flight vehicle configurations.

It is not yet possible to generalize the near noise field of jet and rocket engines to an extent which makes the prediction of near field contours and spectra and of the pressure cross-correlation between different points possible with an accuracy approaching the prediction of sound pressure levels in the far field. A more detailed analysis of the source strength distribution along the jet stream,[12,13] which can be derived by combining fig. 5 and fig. 6, and of the near field which radiates such a distribution might finally lead to the capability to predict all desired quantities. Until such time the near field environments must be measured in detail. The results of such measurements, as for example the overall SPL contours of fig. 4, can then be used to extrapolate expected changes brought about by small changes in engine parameters by making use of the general characteristics of jet noise.

The data on jet and rocket noise discussed so far apply to the engine at rest. In flight the nozzle exit moves with respect to the surrounding medium and a change in all characteristics, power output, power spectrum, directivity, and near field contours must be expected due to this motion. Although a decrease of the noise output due to the lower relative velocity between jet and surrounding medium must be expected and several measurements up to Mach number .6 to .8 indicated such a trend for the jet noise, no data useful as general guide to predict changes in the near field have been published. Under most circumstances it appears safe to assume that for constant engine conditions the maximum loads occur during static operations.

# SECTION IV

## JET NOISE SUPPRESSION

It might appear somewhat beyond the scope of this introductory talk on pressure fields to elaborate on jet noise suppression. But since this symposium will deal at length with the various possibilities of reducing the responses of structures, the possibilities of reducing the exciting pressure fields must at least be mentioned. In many situations where sonic fatigue problems occur it might be more advantageous to apply a weight penalty in the form of noise suppressors than in the form of stiffened or dampened structures. Only careful analysis of the overall design can reveal which method is most effective. So far, in-flight noise suppressors--as, for example, the two types used on commercial jet airliners (fig. 7)--were developed mainly to reduce the noise on the ground from the aircraft in flight; but the sound pressure levels at the aircraft structure are also reduced by most noise suppressor designs. Their use could be particularly advantageous since they are most effective in reducing the low frequency bands of the spectrum by diffusing the large original jet into many jets of smaller dimensions which, according to fig. 6, have the maximum of their noise radiation at higher frequencies. In fig. 7 the effectiveness of the noise suppressors in reducing far field sound pressure levels is demonstrated; fig. 8 demonstrates near field noise reductions at the trailing edge of a wing for pod mounted engines below the wing. It is obvious that a reduction in structural vibration response obtained by design changes equivalent to that which would be obtained by a sound pressure level reduction of 17-19 db in the structurally critical frequency bands (150-1200 cps) would involve considerable weight increase. Whether it would have been comparable, larger, or smaller than the suppressor weight cannot be answered without going into details of the design. There have been cases where in-flight noise suppressors have been developed and tested solely for structural reasons. As mentioned before, the maximum sound pressure levels from jet propulsion occur under static conditions. Noise suppressors used during ground operations alone, i.e., stationary, not in-flight suppressors, could therefore reduce the maximum peak loads; whether they could increase the fatigue life of the structure to any noticeable degree is questionable in view of the longer time acoustic flight loads and will depend on the vehicle characteristics. No extensive studies on this subject have been published.

For rocket propelled missiles neither ground nor in-flight suppressors have been used, since the high rocket exhaust temperatures make designs similar to those used on jet engines impractical. The missile is definitely exposed on the ground and in the early flight phase to the highest acoustic loads; with increasing flight speed the rocket noise has been observed to decrease approximately inversely proportional to the square of the flight speed. Since the highest structural loads on the missile occur on the launch pad and since launch noise reduction is also desirable to reduce exposure of personnel and communities in the vicinity, a study of the effect of various types of blast deflectors on rocket noise was recently undertaken.[16] Simple deflectors and configurations similar to those presently used on launch pads were investigated in model scale using small rocket boosters as the noise source. The normalized spectrum of fig. 6 justifies the application of these data to larger rockets and actual missile launch pads. Some of the configurations studied are indicated in fig. 9. The tests, accomplished with 1000-lb. solid fuel rockets, were conducted under free field conditions with equipment as illustrated in fig. 10. Because many of the deflection devices were asymmetrical about the rocket's longitudinal axis, it was necessary to measure the sound distribution at all angles around this axis. This was accomplished with the setup of fig. 10 by measuring the sound distribution in the ground plane for various positions of the deflector, obtained when the latter was turned with respect to the longitudinal axis. The acoustic power spectra for some of the various configurations are summarized in fig. 11. It is clear that whenever the rocket flow impinges upon the ground or any type of deflector its acoustical power is reduced, particularly in the lower frequency bands. Thus, the deflector is influencing the flow and hence its noise in a manner similar to the jet diffusion noise suppressors. The greatest reduction in power is obtained when the nozzle is closest to the deflector. This beneficial effect of the deflectors for far field noise is unfortunately for many configurations accompanied by an increase of the sound pressures in those near field areas where a missile structure would be located. In fig. 12 these near field pressures are plotted for various rotationally symmetrical deflectors; in these cases the sound pressures at a hypothetical missile surface were increased 10 db and more above the level observed for the free rocket without deflector. These examples make it obvious that most presently used blast deflector configurations are acoustically not advantageous as far as the acoustic load on the missile during static firings is concerned. The examples make it equally clear that caution is necessary in the application of noise data obtained under free field conditions (figs. 3-6) to conditions where the acoustic source itself is modified due to an altered flow field of the exhaust gases.

SECTION V

# BOUNDARY LAYER NOISE

In addition to the noise generated by gas jets the boundary layer noise has become of increasing importance. In high-speed aircraft and missiles the noise pressure load to which the major portion of the surface of the vehicle is exposed is due to the pressure pulsations in the boundary layer, not the noise caused by the jet propulsion system. The latter may cause acoustic pressure levels in localized areas close to the jet exhaust which are higher than the levels ever reached by boundary layer pressures, but the areas exposed to boundary fluctuations are by order of magnitude larger in most designs. Noise levels inside jet aircraft or missiles at high speed are therefore usually determined by either boundary layer noise or internal noise sources such as secondary power units, air conditioning systems, etc. Several studies on boundary layer noise have been reported which were useful for the engineering prediction of noise levels to be expected. However, all these previous studies calculated the noise levels at the surface of the aircraft skin from the noise levels measured inside the aircraft by considering the noise reduction through the skin. This procedure gives only an average, effective noise level at the skin. In addition these earlier studies were restricted to speeds below approximately 500 mph. In order to provide more extensive and precise experimental data,[17] a special microphone which is mounted completely flush with the skin of an aircraft was developed and calibrated over the whole pressure and temperature range of interest. Up to ten microphones of this type were distributed over the fuselage and wing of a supersonic aircraft and connected to a special recording system. The flight test program was conducted at several altitudes through the transonic range up to Mach 1.2. Some of the results are shown in fig. 13. In general the SPL increases, as in earlier studies, monotonously with increasing speed. The increase in SPL continues through the transonic range with only occasional signs of local shock waves or changes in the local flow over the microphone position. Changes in the local flow conditions are assumed to account for such dips in the SPL curves as are illustrated for the middle position on fig. 13. The OASPL at the surface correlates best with the dynamic stream pressure and appears to have a constant ratio to it of approximately $6 \times 10^{-3}$ (fig. 14). Wind tunnel tests on boundary layer noise at NASA resulted in the same ratio. The earlier inflight noise studies of boundary layer noise measured from inside the aircraft resulted in a steeper increase of SPL with velocity (approximately with the 2.75th power). This discrepancy must probably be attributed to the questionable application of standard transmission loss data to the boundary layer noise case and to the study of isolated noise bands instead of an attempt to recognize the general shape of the spectrum. Unfortunately the existing data are still too limited to obtain accurate information on a generalized spectrum.

# SECTION VI

## SUMMARY

This review was intended to serve as an introduction to some of the following papers and discussions. The basic characteristics of pressure fields of interest in acoustic fatigue problems have been described and the latest data on the noise fields of specific interest, the turbo-jet and rocket noise and the boundary layer pressures were reviewed. It appears as if acoustic exposure histories can be predicted with fair accuracy if the flight and engine parameters do not deviate too much from the parameters of the engines and vehicle characteristics which were available when our present knowledge was accumulated.

As an example for the application of the material discussed in the present paper, the calculated overall sound pressure level at the nose cone of a missile is shown in fig. 16. The missile is approximately 100 feet long and is launched vertically by a rocket engine of 600,000 lbs. thrust. While at rest the rocket noise is at a level of over 150 dbs and decreases immediately when the missile leaves the ground. With increasing flight speed the rocket noise decreases until the missile reaches its maximum indicated airspeed at an altitude of approximately 50,000 ft. 65 sec. after launch. After this point the noise level decreases as the vehicle continues out of the atmosphere. Recent measurements obtained in such a missile indicate that our estimates as far as OASPL and spectra are concerned were not very far off.

For structural problems the space correlation of the noise fields and their statistical properties appears to be the main gap in our prediction capability. The following two papers will discuss these problems in more detail.

A recent attempt to arrive at a normalized boundary layer pressure spectrum[9] is shown in fig. 15. The non-dimensional frequency parameter indicates the dependence of the pressure spectrum at the vehicle surface upon the vehicle speed and also upon the boundary layer thickness. The latter fact makes the lower frequencies more pronounced at aft vehicle stations compared to forward stations. The spectrum observed at the vehicle wall will in addition depend upon the size of the pressure pickup since cancellation effects occur when the correlation of the turbulence pressure field decreases markedly over the length of a microphone diameter. This can result in a high frequency cutoff of the spectrum caused by the microphone size.[20] This spectrum presented in fig. 15 shows only the general trend of the non-dimensional spectrum; more measurements in the boundary layer are necessary to determine its relationships more accurately.

In spite of extensive theories on boundary layer noise, it appears as if extrapolation of experimental results as the ones presented offer at the moment the only possibility of predicting boundary layer noise for practical cases.

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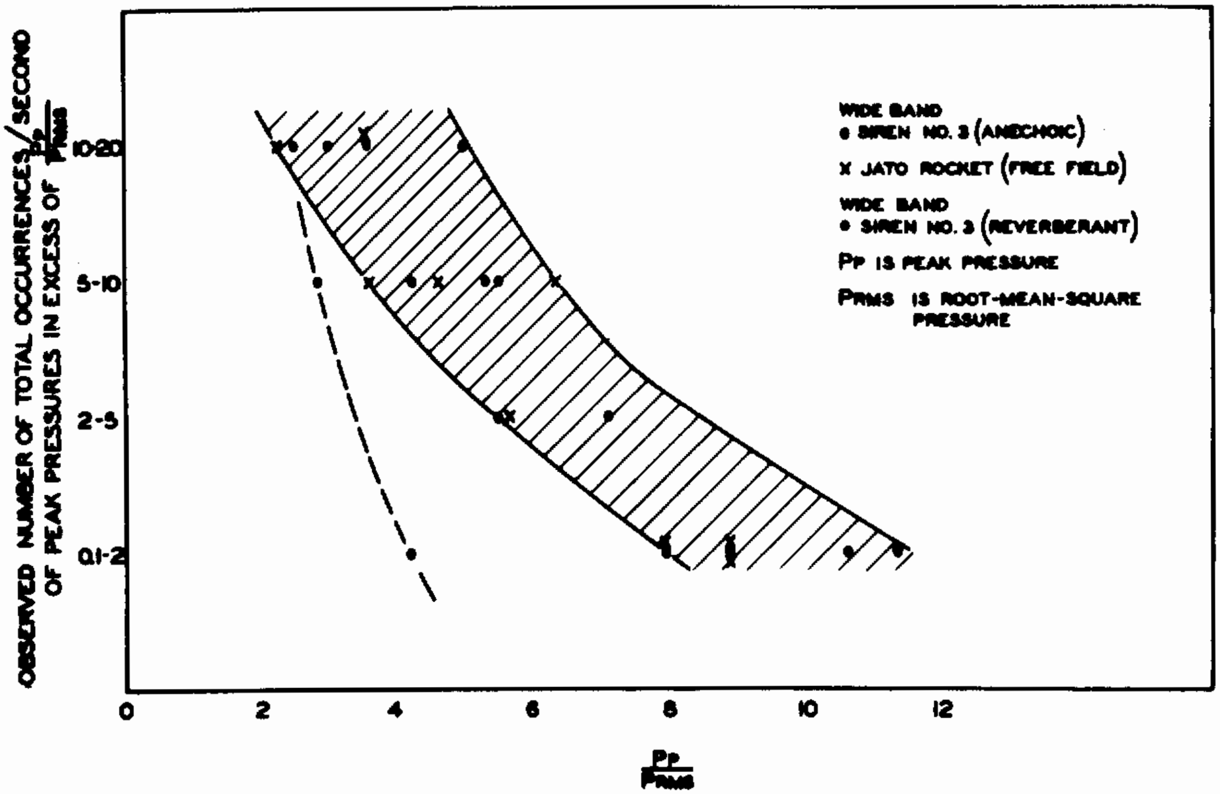



Fig. 1. - Peak pressure distribution of rocket noise (free field) and of the noise of a wide band noise siren (anechoic and reverberant environment) (from ref. 4).

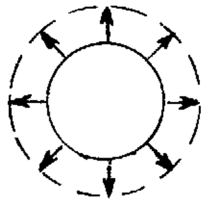
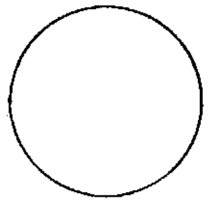
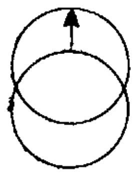
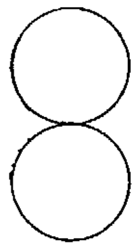
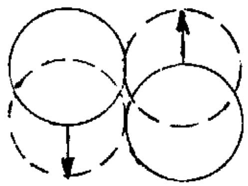
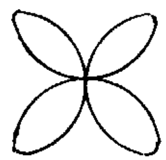
| SOURCE | | REPRESENTS CHANGE IN | RADIATION PATTERN | RELATIVE ACOUSTIC EFFICIENCY | SOUND ENERGY FUNCTION OF- |
|---|---|---|---|---|---|
| type | name | | | | |
|  | MONOPOLE | VOLUME |  | 1 | $\rho A v^3 \left(\frac{v}{c}\right)$ |
|  | DIPOLE | FORCE |  | 1/13 | $\rho A v^3 \left(\frac{v}{c}\right)^3$ |
|  | QUADRUPOLE (LATERAL) | SHEAR |  | 1/1000 | $\rho A v^3 \left(\frac{v}{c}\right)^5$ |

**Fig. 2.** - Some properties of basic acoustic sources ( $\rho$ = density of air, A = area, v = velocity of flow, moving body, or jet, i.e., velocity responsible for noise radiation, c = sound velocity). The relative efficiency of noise generation is indicated for a frequency having a wave length twice the circumference of the sphere (from ref. 7).

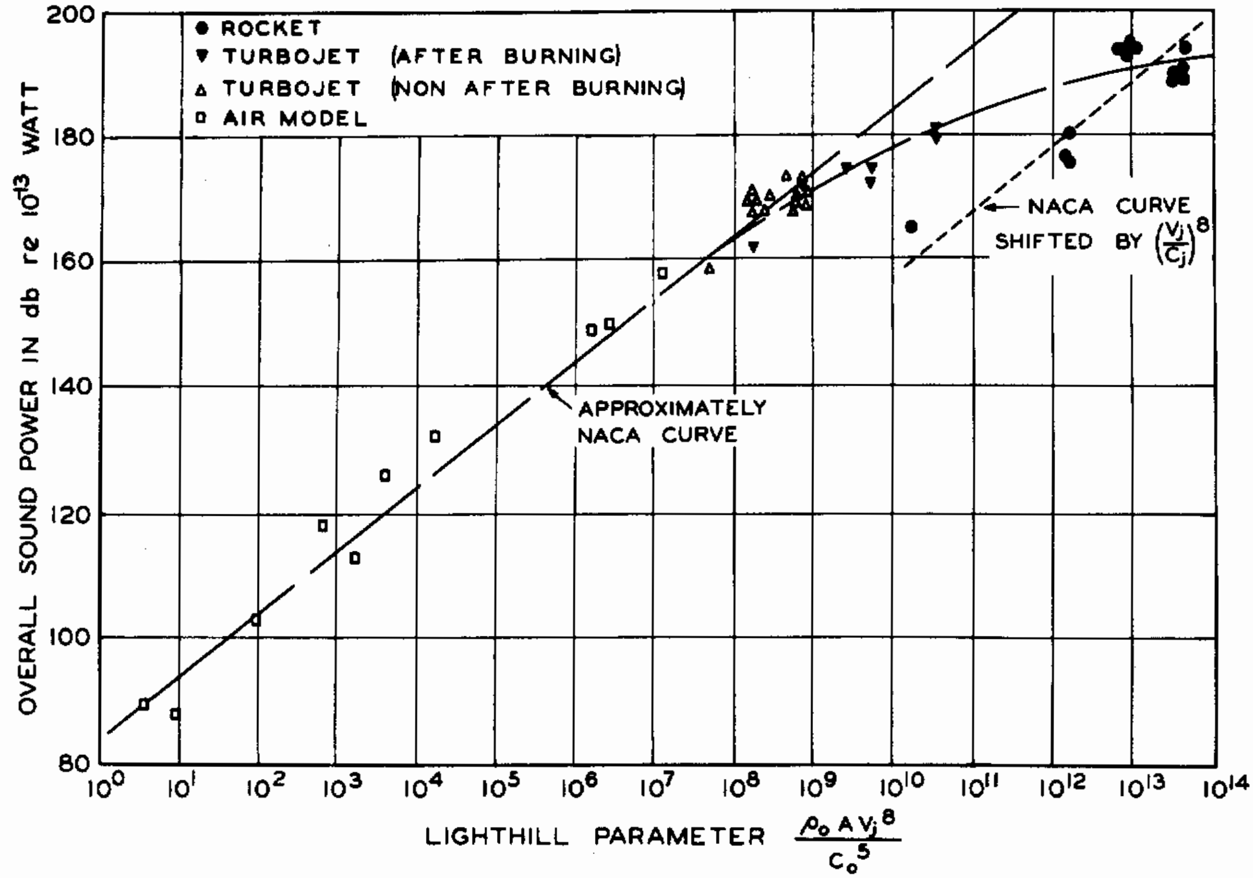



Fig. 3. - Overall sound power of model jets, turbo-jets, and rocket engines as a function of the Lighthill parameter (A = cross sectional area of the jet, $v_j$ = jet exit velocity, $\rho_o$ = density of ambient air, $c_o$ = sound velocity in ambient air, $c_j$ = sound velocity in gas jet) (data from ref. 1, 8, 9, 10, NACA curve from ref. 10).

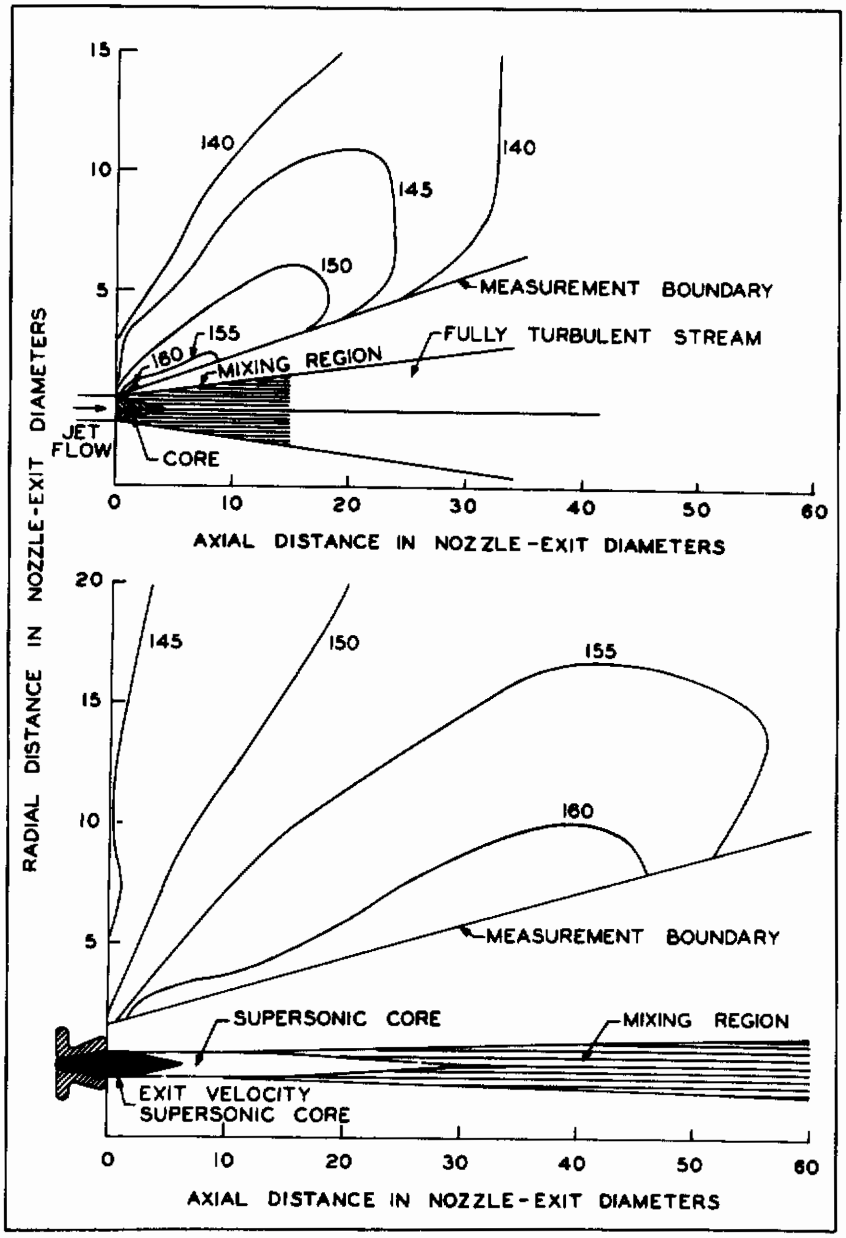



Fig.4. - Comparison of the near field sound pressure level contours in db re 0.0002 dyne/cm$^2$ of a turbo-jet engine (above) with the near field of a JATO rocket (below) (turbo-jet engine parameters: thrust 9600 lbs., jet velocity 1850 ft./sec., nozzle pressure ratio 2.2, nozzle exit diameter 1.85 ft. JATO rocket parameters: thrust 1000 lbs., jet velocity 6000 ft./sec., nozzle pressure ratio 60, nozzle exit diameter 0.22 ft.).

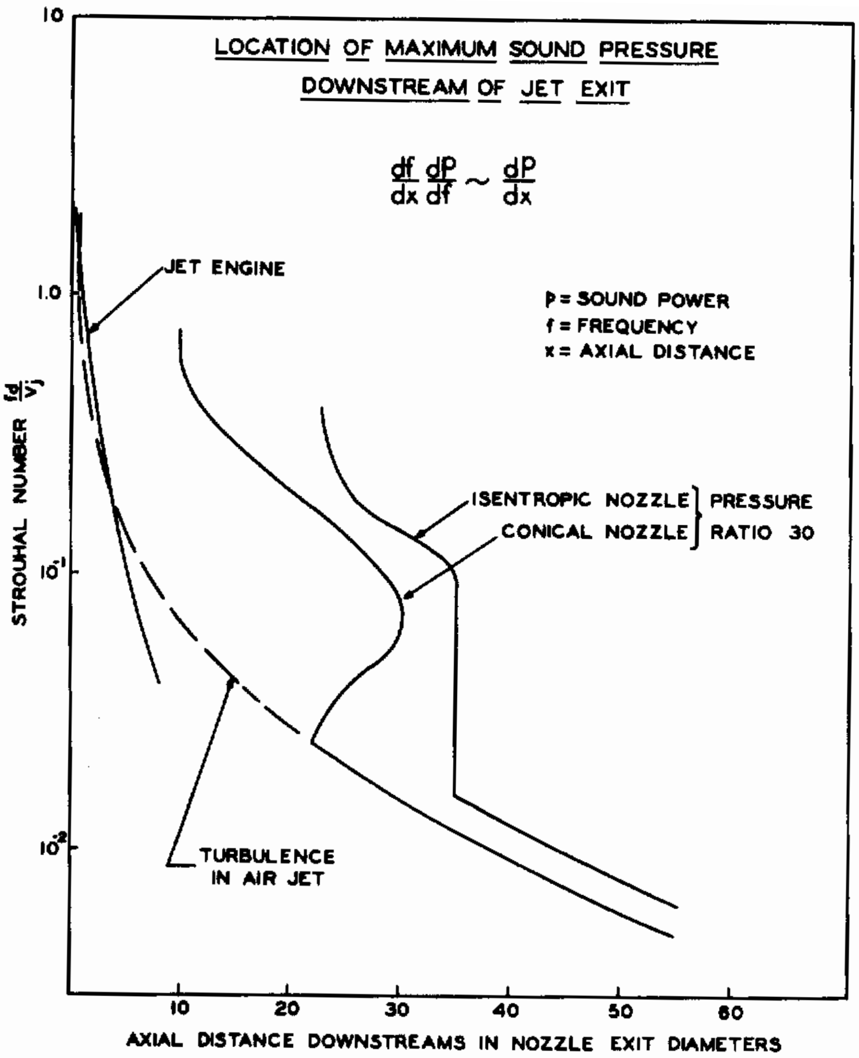



Fig.5. - Dimensionless frequency (Strouhal number) as a function of the apparent source position for turbo-jet engine and supersonic nozzles and of the peak longitudinal turbulent velocities of a subsonic air jet (d = jet diameter, $v_j$ = jet exit velocity) (from ref. 10 and 11).

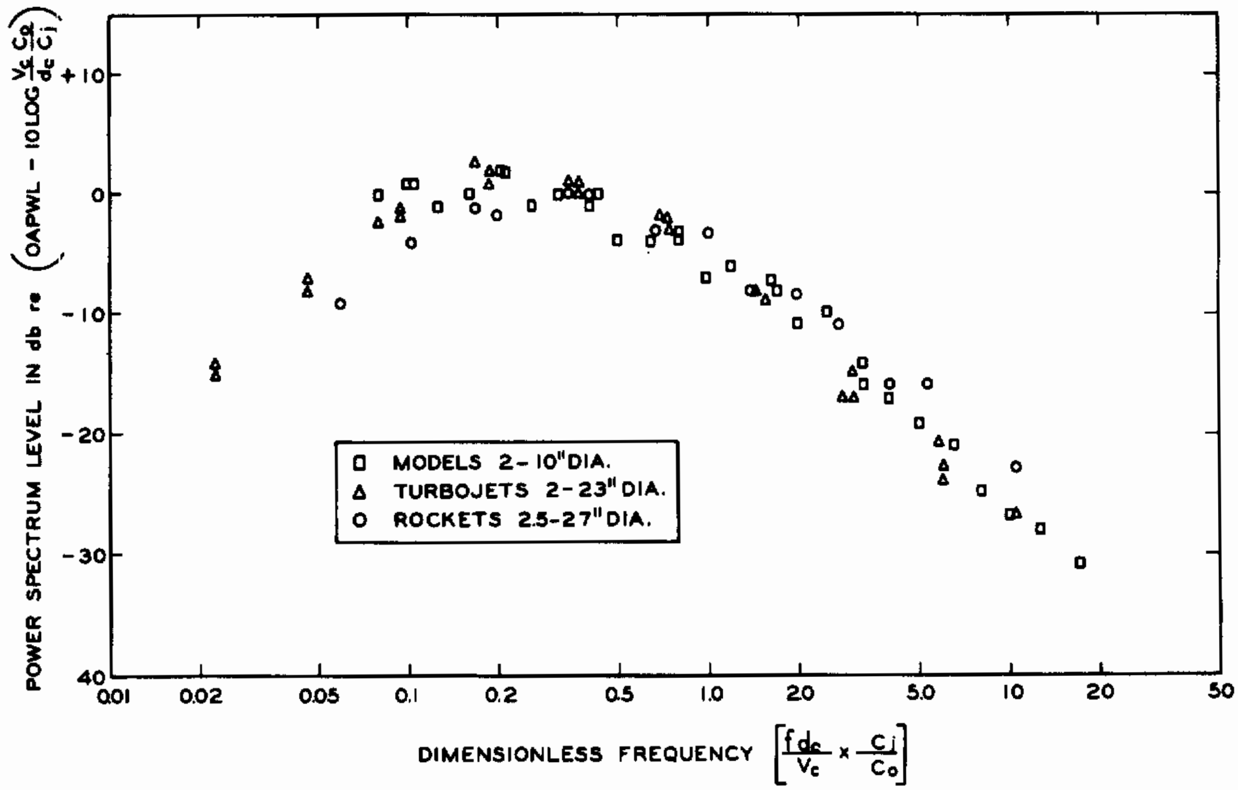



Fig.6. - Power spectra of rockets, turbo-jets, and model air jets, normalized with the modified Strouhal number (OAPWL = overall sound power level, f = frequency in cps, $d_c$ = characteristic diameter in feet, $v_c$ = characteristic velocity in ft./sec., $c_j$ = sound velocity in jet in ft./sec., $c_o$ = sound velocity in ambient air in ft./sec.)(from ref. 1 and 9).

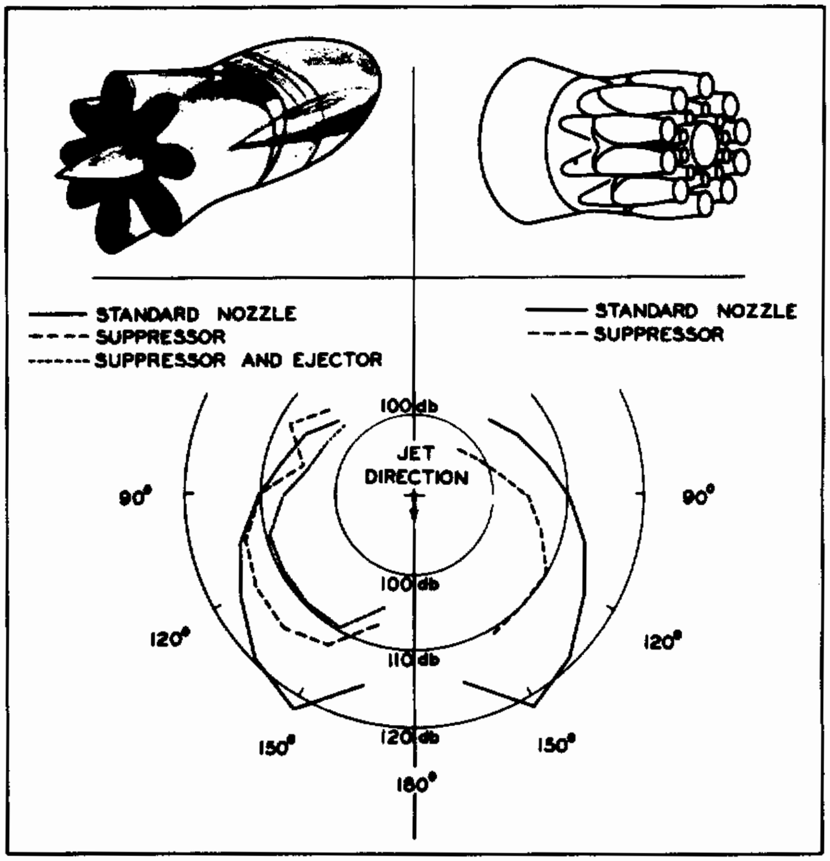



Fig.7. - In-flight noise suppressors for turbo-jet engines. The noise reduction (as measured on a 200-foot arc) achieved by the use of the 8-lobe and 21-tube suppressor on a J57 engine is illustrated on the lower half of the figure. Suppressors such as the ones demonstrated have thrust losses between 2% and 6% and add several hundred pounds to the engine weight (based on ref. 14).

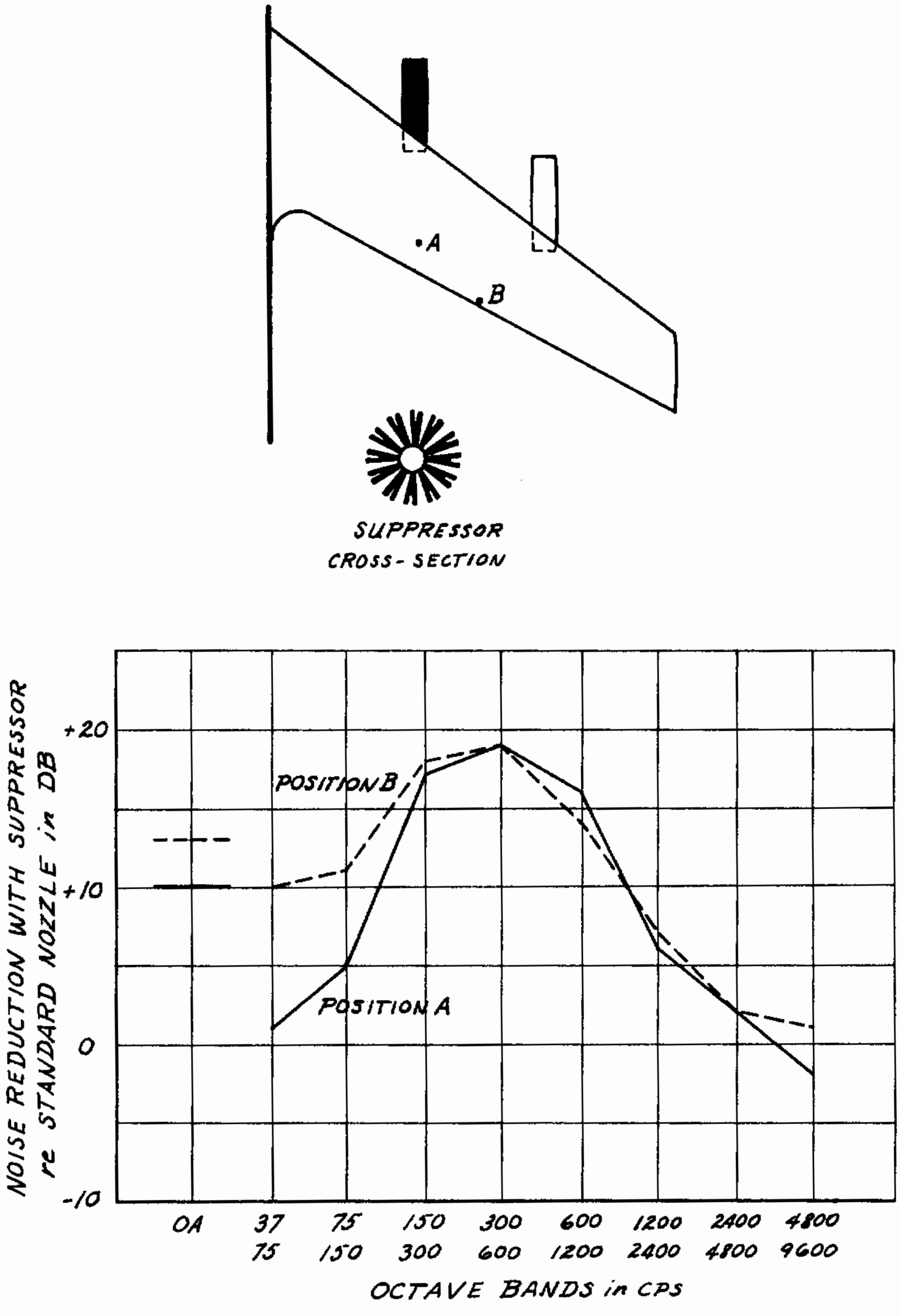



Fig.8. - Examples of sound pressure level reductions at wing positions achieved with experimental noise suppressor. In this case the reduction in acoustical excitation could be obtained by thrust reduction of approximately 50 per cent instead of by use of the suppressor (based on ref. 15).

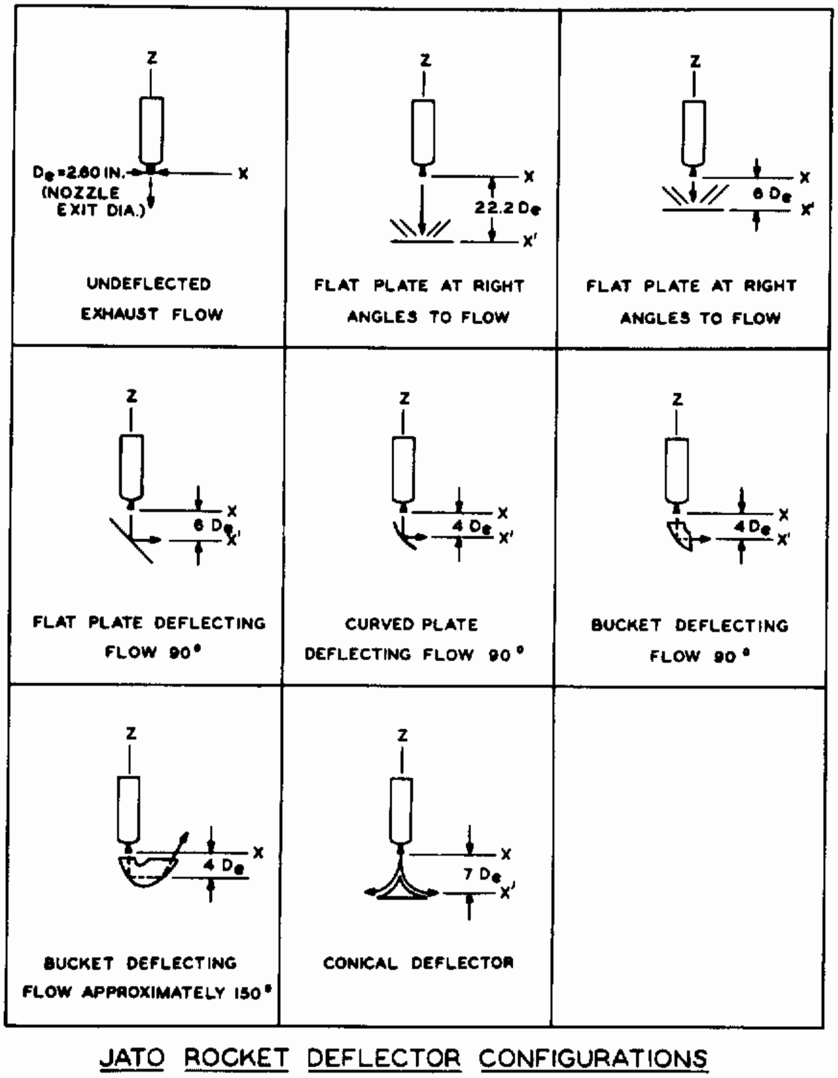



Fig. 9. Various launch pad configurations and jet deflectors tested on a 1000-pound thrust rocket.

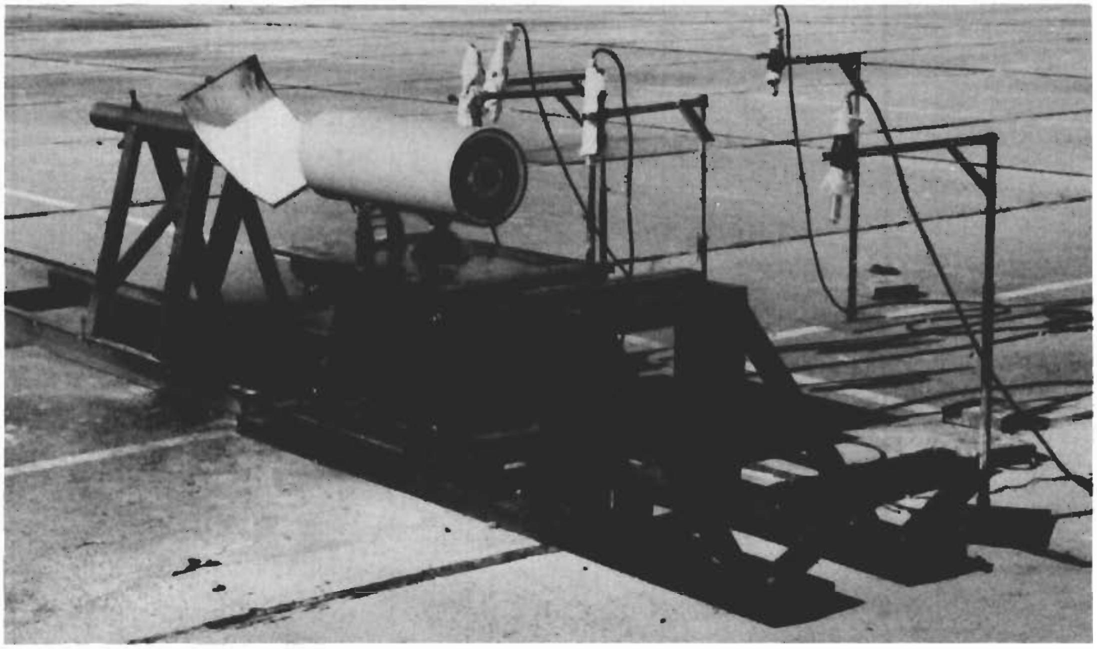


Fig.10. Rocket in horizontal firing stand with curved plate deflector. (Only the microphones in the near field are visible in this picture.)

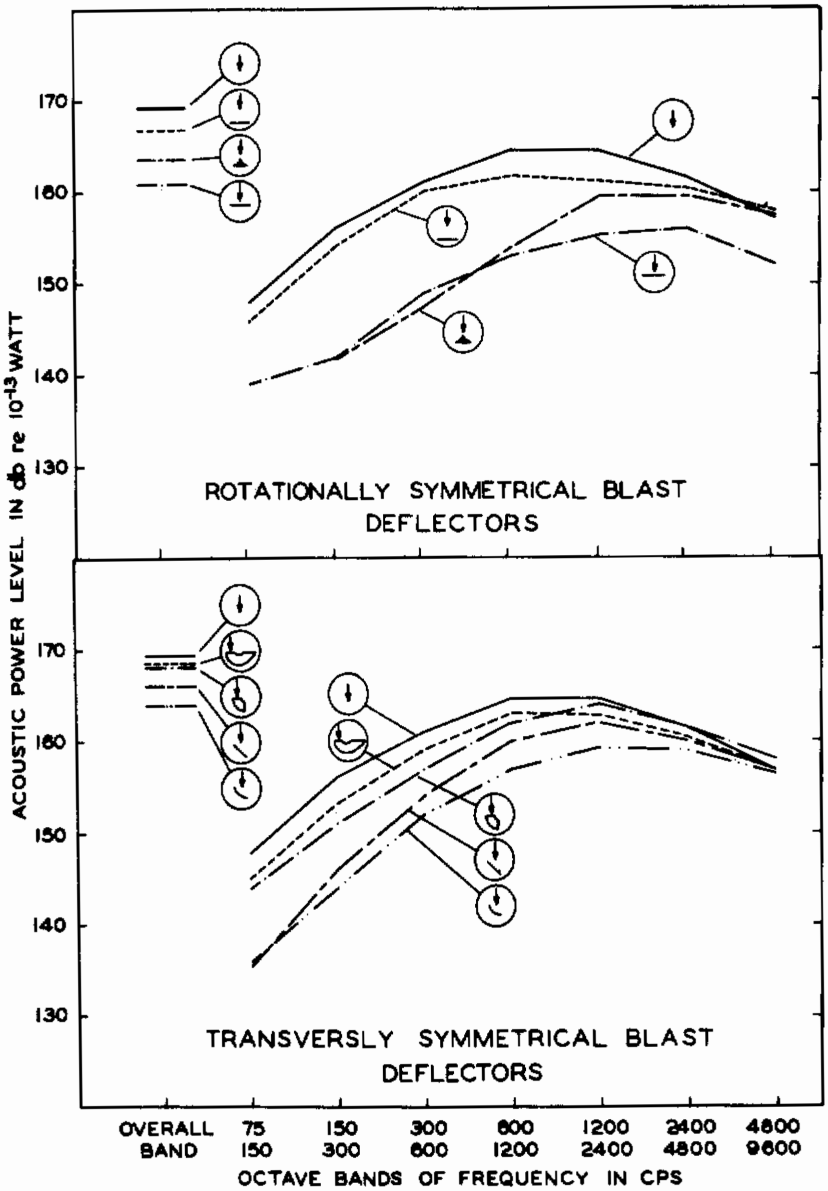



Fig. 11. Examples of the modification of rocket noise power spectra by blast deflectors. The nozzle exit diameter $d_e$ of the 1000-lb. thrust rocket was 2.60 in. The distance of the deflectors from the nozzle exit was approximately as follows: flat plate 22 and 6 $d_e$; conical deflector 7 $d_e$; flat plate at 45° to rocket axis 6 $d_e$; curved plate (deflecting flow 90°) 4 $d_e$; buckets (deflecting flow 90° and 150°) 4 $d_e$.

NEAR FIELD OVERALL SPL'S
ROTATIONALLY SYMMETRICAL DEFLECTORS

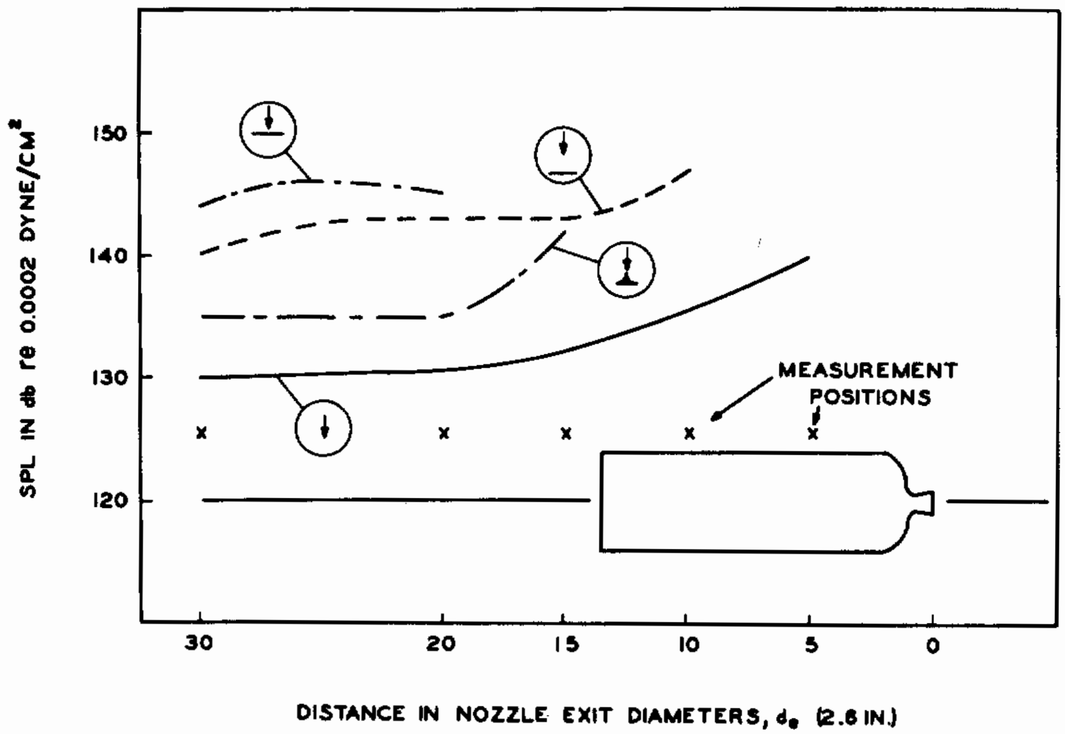



Fig.12. Near field overall sound pressure levels for the rotationally symmetrical deflectors. All deflectors caused an increase in near field SPL's.

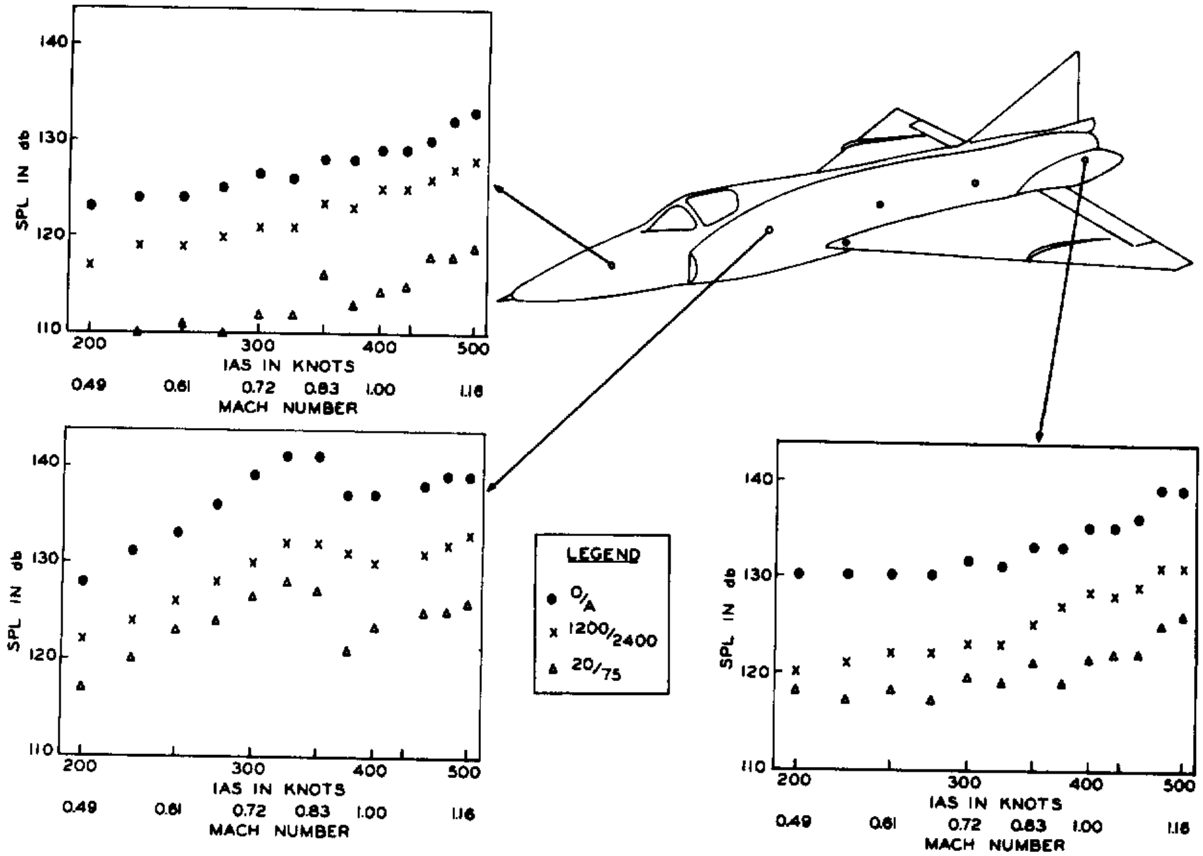



Fig.13. Boundary layer noise at 3 positions on a supersonic aircraft as a function of flight Mach number (from ref. 17).

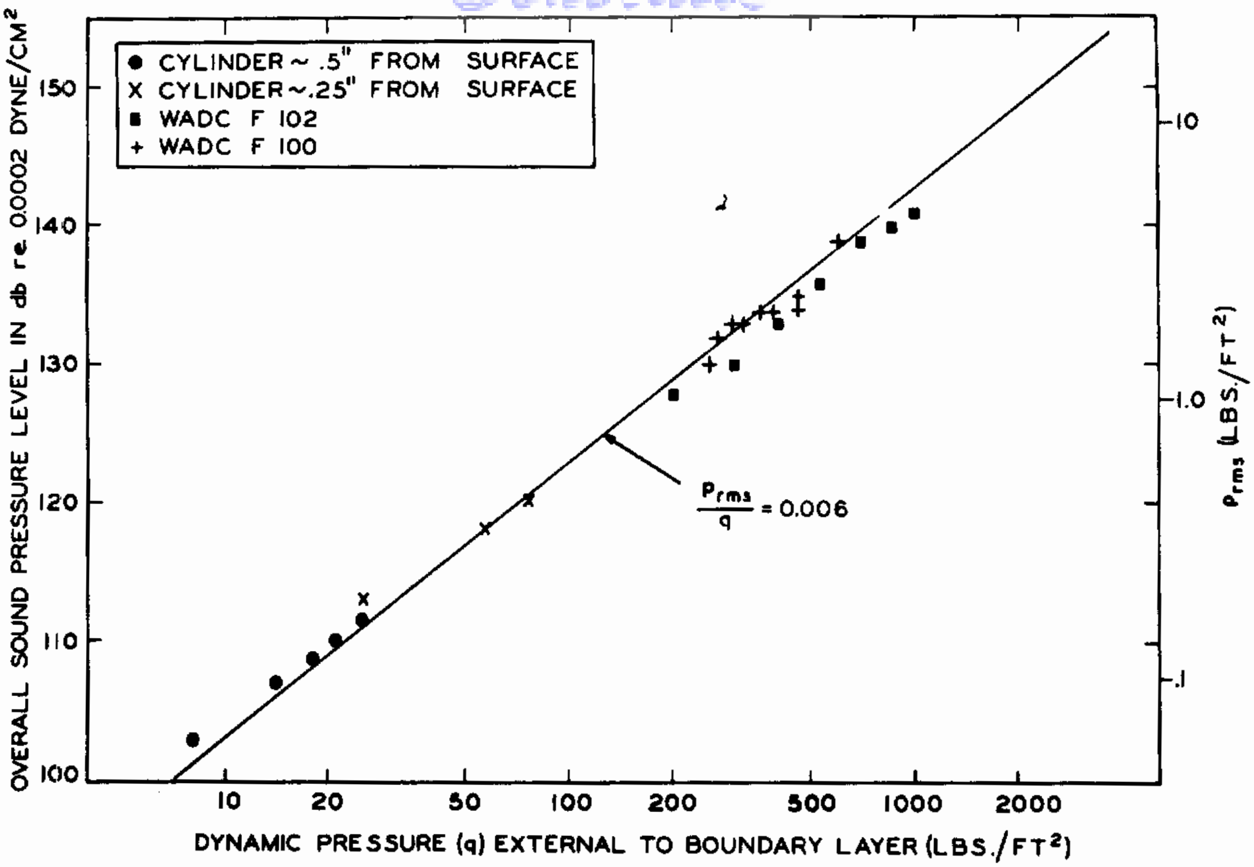



Fig. 14. Variation of overall sound pressure in boundary layer, $p$ rms, as a function of free stream dynamic pressure, $q$. (The rotating cylinder has a diameter of 8 in. The data marked F-102 were measured with a microphone mounted flush with the external surface of the aircraft; the data marked F-100 were measured with a microphone inside the aircraft and corrected to external sound pressure levels.) The straight line relating overall sound pressure level to dynamic pressure represents $SPL_{OA} = 83 + 10 \text{ Log } q$ in db re 0.0002 dyne/cm$^2$ (from ref. 9, 17, 18, and 19).

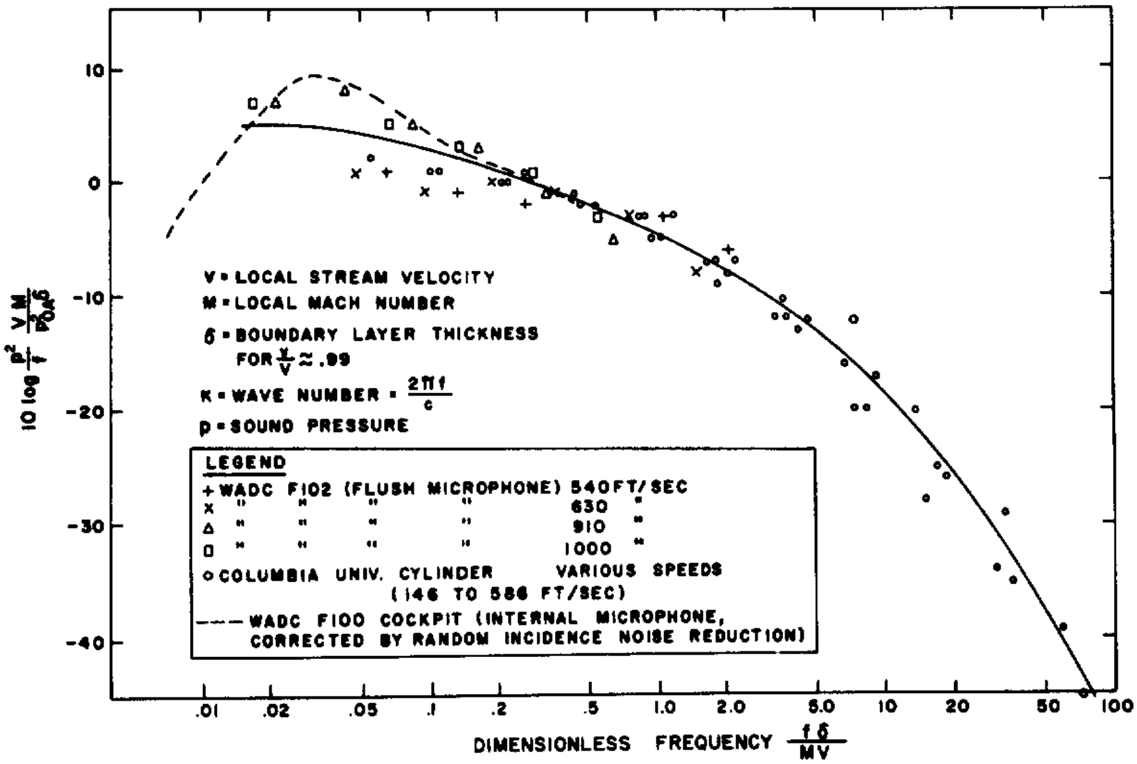



Fig.15. Normalized boundary layer spectrum (from ref. 9 based on ref. 17, 18, 19).

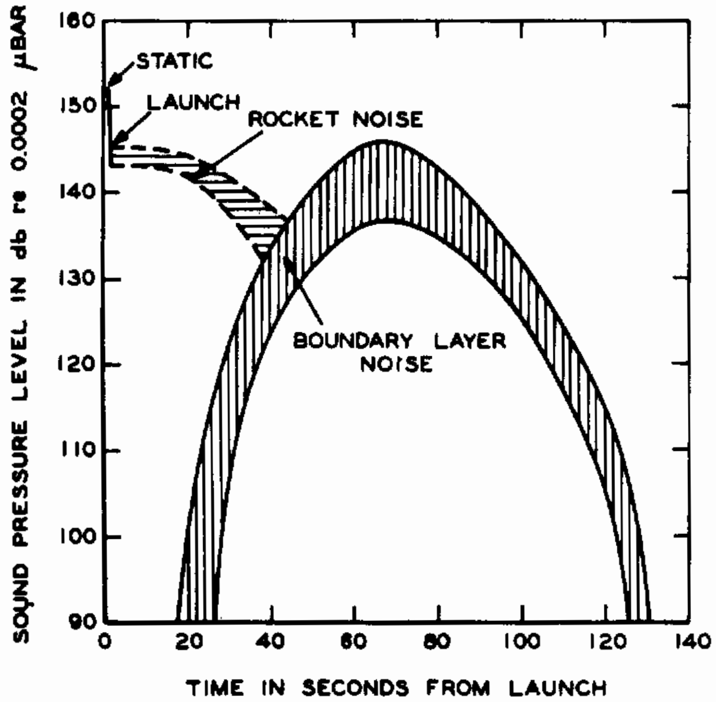



Fig. 16. Predicted overall sound pressure level at the surface of the nose cone of a large missile(approx. 100 ft. long, 600,000-pound thrust booster).