"THE USE OF MODEL JETS FOR STUDYING ACOUSTIC FIELDS NEAR JET AND ROCKET ENGINES"

by

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Analytical prediction of the sound pressure field near large jet and rocket engines is not generally possible for complex configurations of exit nozzles and adjacent structure. Considering the present state-of-the-art, the influence of complex bounding surfaces and nozzle design is most readily determined experimentally. The use of scale model jets for this approach is discussed and the scaling principles reviewed. A scale model facility developed for studies of the noise field around multi-engine jet aircraft is considered and its validity examined. For the same exit conditions, it is shown that a model jet can duplicate near field sound levels of the B-52 within an accuracy of ± 3 db. The application of this facility to the development of a noise suppressor for reduction of near field noise levels on the B-52 wing surfaces is discussed. Other model facilities for simulation of the noise field around afterburning engines and rocket engines are also considered.

ACOUSTIC SCALING OF JETS

Since the advent of the jet engine as a means of aircraft propulsion, the structural designer of airframes has been concerned with a new source of structural loadings--the random noise pressure generated by the turbulent jet exhaust. As jet engines have increased in size and performance, this additional structural load has increased in significance, in some cases to the point where it determines the basic design features of structural surfaces which are located adjacent to the jet exhaust. A multi-engine aircraft which has its engines located forward of wing surfaces presents a particularly challenging problem to the structural designer and the acoustical engineer. Once the acoustic environment of the structure is defined, proper structural design and sonic testing of prototype configurations can be accomplished and a reliable structural configuration achieved. The determination of the acoustic environment near a jet engine for a variety of spatial arrangements of structure relative to the jet has not been possible by any general theoretical method. It is only within the last few years that the basic analytical description of the "near noise field" of a jet has been attempted (Ref. 1, 2, 3). At present, it is possible to make reasonable predictions of the noise levels in the near field for relatively simple configurations, such as a single non-afterburning turbojet exhausting over a simple flat panel (Ref. 4, 5). A useful tool for studying the more complex situation is a scale model jet.

Since it is not yet possible to define all the characteristics of the near field in terms of known or measurable parameters of the jet exhaust, it is currently assumed that a valid acoustic scale model of a jet noise source must duplicate these parameters. The exit velocity and gas density are generally recognized as the principle variables which determine the intensity of the noise field. This logically follows from the concept that jet noise obtains its acoustic energy from the kinetic energy (proportional to jet density x velocity^3) of the turbulent exhaust. Beyond this assumption of the essential origin of the noise, no attempt is made here to establish the true mechanism or efficiency of noise generation. Much more is known, of course, about the origin of jet noise than is considered here. Other papers have covered this subject very well. For this study it is assumed that it is necessary and sufficient to duplicate the jet density and velocity to achieve a valid acoustic model of a jet.

There is one additional consideration that should be mentioned. High temperature jets, particularly rockets, may generate noise by fluctuations of the exhaust temperature (Ref. 6). Thus, thermal energy may also act as a source of acoustic energy. Efficiencies and radiation characteristics are not well defined for this source of noise. This implies that accurate models of afterburning and rocket engines must also duplicate the thermodynamic and combustion processes of their full scale counterparts as closely as possible.

The basic scaling principles of the acoustic model jet are illustrated in Figure 1. The principles enumerated are not new and are presented here only to illustrate the foundation upon which the succeeding work is based. The basic equations numbered in Figure 1 state:

(1) The mean square pressure at a given frequency in the field of a sound source is proportional to the source strength times a near field and directivity weighting function, and inversely proportional to the square of the path length.

(2) The frequency of the source is characterized by the ratio of a typical source velocity to a typical source dimension.

(3) The source intensity can be defined uniquely in terms of the kinetic energy terms, velocity and density.

(4) For similar gases, typical dimensions and velocities within the jet, normalized by exit diameter and exit velocity respectively, will be functions of dimensionless position.

When these concepts are combined, an expression for the mean square pressure is found in terms of a set of dimensionless ratios times a measure of unit source intensity. The product of frequency times jet diameter is also a function of similar dimensionless ratios. Thus, a simple set of ratios of source dimension to observation distance are sufficient to equate the sound fields around two jets which differ only in their size. Based on this concept, a model jet facility has been used extensively by Boeing to study the near field sound levels around the B-52 airplane engines.

MODEL B-52 FACILITY

The acoustic model of the B-52, shown in Figure 2, consists of an accurate 1/10 scale model built of 1/4 inch steel plate, representing the lower surface of a B-52 wing, including flap well, flaps, and one half of the aft fuselage surface; and a dual jet assembly to simulate either inboard or outboard engine pods. This dual jet exhausts two streams of hot air whose exit conditions are monitored with conventional pressure and temperature pickups to maintain the same exit conditions as for the full scale B-52 engines. The air is heated by a kerosene burner system which can be closely regulated to give very stable operating conditions for prolonged tests, if necessary.

Acoustic measurements were taken on the wing, flush with the under surface, and at the same locations used for full scale tests. As shown in Figure 3, a 5/8 inch diameter condenser microphone was secured at appropriate test point locations by a magnetic holder. A pitot tube, shown in position on the wing, was used for measurements of total pressure in the jet. The acoustic instrumentation consisted basically of the microphone, a low-noise pre-amplifier, a set of high quality fixed octave band filters, and a damped voltmeter for manual readout. Data could be obtained over an equivalent full scale frequency range of 15 to 2400 cps for 45 test points in less than 1 hour. The model test procedure permitted valuable data to be obtained at approximately 1% of the cost of comparable full scale tests.

To illustrate the validity of the model technique, the data in Figure 4 show how the total power radiated by the model jet is readily scaled in frequency and magnitude to correspond to the full scale data. Figure 5 illustrates how near field sound levels on the model wing agree with the full scale data (Ref. 7). For paired comparisons of over 50 test points measured just once each for model and full scale, the standard deviation of the differences is between 2 and 3 db. It is particularly important that the highest accuracy is ordinarily found at the frequencies where the octave band level is highest. To illustrate the agreement as a function of position on the wing, Figure 6 compares contours of levels in the peak 150-600 cps band for model and full scale. The complex shape of the contours is matched quite well over most of the wing surface. The success of this experimental method led to its extensive application in a program for development of a B-52 noise suppressor.

SUPPRESSOR DEVELOPMENT

Early in the development of noise suppressors for use on commercial transports it was established that a noise suppressor that reduced community noise from the engine also provided a large amount of noise reduction in the near field (Ref. 8). It was decided, therefore, to investigate the possibility of developing a noise suppressor for the B-52 airplane which would have, as its primary purpose, suppression of noise in the near field to reduce sonic excitation of the B-52 wing structure. This was to be achieved without measurable loss of airplane performance. An empirical analysis of simple Greatrex-type nozzles (Ref. 9) indicated that a 3-lobe configuration should provide maximum reduction in the 150-300 and 300-600 cps bands in which the maximum sound levels and panel resonances occur.

After extensive model tests, covering about 30 different designs, a final 3-lobe canted-nozzle, shown in Figure 7, was selected for full scale tests. Parallel model studies were also conducted by Aerodynamic and Propulsion groups to insure a final configuration compatible with all design requirements.

The results of the acoustic tests are summarized in the lower left hand corner of Figure 8 which shows the average suppression, as a function of frequency, for two typical test points on the wing. The final configuration is shown as Nozzle A. Full scale and model suppression data are seen to be quite comparable. The other model, Nozzle B, is the same as A except that the exit plane is perpendicular to the jet axis.

It was found that by canting the exit plane by 10°, as illustrated in the lower right of Figure 8, the supersonic jet exhaust was deflected downward about 5°. This effect has been previously observed by others working on controlling flow of supersonic jets (Ref. 10). The amount of jet deflection was determined on the model by measuring the total pressure in the stream at various stations below the wing surface. In the upper part of Figure 8, sample profiles obtained 7 1/2 nozzle diameters downstream for the standard nozzle, and for the straight and canted 3-lobe nozzles, are compared.

Because of the lift component of the deflected jet, no airplane performance loss is suffered with the canted nozzle. The important acoustic effect of this jet deflection has been to cause a very significant drop in low frequency sound levels on the wing. This is believed to be directly due to the increased distance of the wing from the pressure fluctuations which are not radiated as true sound but which are present in the form of a pressure field very close to the jet boundary. It should be noted that the decrease in low frequency sound is generally too great to be accounted for on the basis of a greater inverse square law attenuation due to increased source-to-wing distance. Unfortunately this phenomenon was not explored further. However, it does serve to illustrate the need for highly accurate positioning of any model surface to be located near the jet boundary.

The spatial variation of suppression in the important 150-600 cps band is shown in Figure 9 in the form of contours of constant suppression. As with all other models tested, the suppression is a minimum near the exit plane and is a maximum 5 to 10 nozzle diameters downstream.

The data shown in Figure 9 are from full scale measurements, however model data were essentially the same with maximum suppression about 2 db lower. Since the model can simulate only two engines at a time, determination of sound levels for four engines was made by adding decibel-wise the sound pressure levels measured from the inboard pod with the sound pressure levels measured from the outboard pod for each test point. The model data of Figure 6 were obtained in this manner. This was found to be a successful procedure and was verified by a full scale test which demonstrated the additive property of near field sound levels from two independent sources.

OTHER MODEL FACILITIES

The success of the B-52 model technique justified the development of models to explore the sound fields around more advanced engines.

The use of multiple afterburning engines is considered to be the next logical step in propulsion of air breathing bombers. A small scale model of an afterburning engine was therefore designed and built (Ref. 11). A unique high-temperature, water-cooled kerosene burner, shown in Figure 10, was used to heat an ambient air supply up to 3300°F. This provides an exit velocity of about 3200 ft/sec. and a thrust of 280 lbs. which allows the burner to be used as a 1/10 scale model of many afterburning engines. The burner can be operated for long periods over a wide range of temperatures and exit velocities at or below the maximum values. A limited amount of full scale afterburner sound level data is available for comparison with model scale data.

One such comparison is shown in Figure 11 for a single test point 7 nozzle diameters from the jet axis in the plane of the exit of a J-75 afterburning engine (Ref. 12). The model data agree well with full scale at the lower frequencies which are usually most important in sonic vibration. The discrepancy at the higher frequencies is believed to represent the influence of the turbine in generating high frequency sound levels at this location, which, of course, are not duplicated in the model. Comparison of model and full scale data at other points forward of the exit plane show a similar pattern. The facility is considered to be a very useful device for exploring the noise in the near field of afterburning engines.

In order to provide early estimates of the noise environment around rocket vehicles at launch, small solid propellant rockets have been used to study a variety of launch pad configurations. A typical model test firing is shown in Figure 12. This is a small model of a typical 4 nozzle configuration. The jet is exhausting directly over a simple conical blast deflector. The spoked exhaust pattern in the ground plane illustrates the peculiar flow pattern of a multi-nozzle engine. This type of information can be of definite value in obtaining a better understanding of the character of the launch environment and in developing means of noise reduction.

The acoustic measurements are being taken, in this case, with small high-frequency crystal microphones shock mounted on a fixed holder next to the model. Due to the short duration of the rocket firings, all data are tape recorded and played back into graphic level recorders to obtain a suitable time-averaged sound level. Data recorded in this fashion at the exit plane of two different scale models fired horizontally are compared in Figure 13 to equivalent full scale data taken under the same conditions. The scale factor, in this case, could not be considered as the ratio of the physical exit diameters because of the varying nozzle design. Instead, a scale factor equal to the square root of the thrust ratio is used. The 1/22.5 scale model data differ considerably from full scale in the low frequencies but the remaining model data agree very well. The meager full scale rocket data suitable for comparison with model tests prevents a more searching inquiry into scaling concepts for rockets at this time. More full scale and model tests are being conducted which will assist in demonstrating more clearly the validity of these simple model rockets for acoustic tests.

As the future brings the development of larger propulsion systems, the use of models for investigation of acoustic environment will assume even greater practical and economic significance. A continuing program is being carried out by the Boeing Airplane Company to explore this technique for providing more accurate definition of environmental loads on vehicle structure, equipment, and crew.

REFERENCES

1. Ribner, H. S.: "Strength Distribution of Noise Along a Jet", J. Acoust. Soc. Am., Vol. 30, p. 876, Sept. 1958.

2. Powell, A.: "Similarity and Turbulent Jet Noise", J. Acoust. Soc. Am., Vol. 31, p. 812, June 1959.

3. Dyer, I.: "Distribution of Sound Sources in a Jet Stream", J. Acoust. Soc. Am., Vol. 31, p. 1016, July 1959.

4. Franken, P. A., Kerwin, E. M., Jr., and the Staff of Bolt Beranek and Newman, Inc.: "Methods of Flight Vehicle Noise Prediction", WADC Technical Report 58-343, 1958.

5. Eldred, K.: "Prediction of Sonic Exposure Histories", pp. 396-415 in "Fatigue of Aircraft Structures", WADC Technical Report 59-507, 1959.

6. Cole, J. N., et al: "Noise Radiation from 14 Types of Rockets in the 1,000 to 130,000 Pounds Thrust Range", WADC Technical Report 57-354, 1957.

7. Morgan, W. V.: "Model Acoustic Development of 3-lobe Suppressor Nozzle for B-52", Boeing Airplane Co. Test Report T2-1568, 1958.

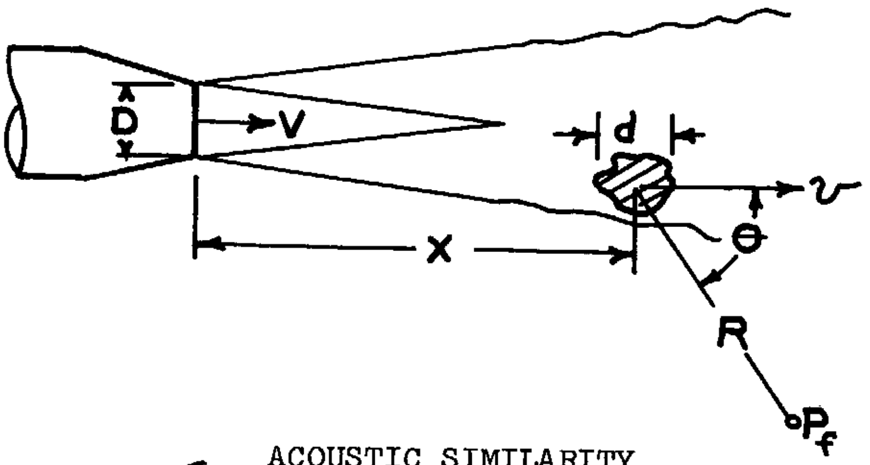
8. Withington, H. W.: "Silencing the Jet Aircraft", Aeronaut. Eng. Rev., Vol. 15, p. 56, April 1956.

9. Greatrex, F. B.: "Jet Noise", Preprint No. 559, Inst. Aeronaut. Sci., June 1955.

10. Fraser, R. P., and Rowe, P. N.: "Supersonic Jet Deflection", J. Royal Aeronaut. Soc., Vol. 62, Jan. 1958.

11. Bateman, D. A., and Wilson, G. P.: "Model Afterburning Engine for Acoustic Research", Boeing Airplane Co. Document D2-2435, 1958.

12. Sutherland, L. C., and Morgan, W. V.: "Sound Levels in Forward Quadrant of J-75 Engine", Boeing Airplane Co. Test Report T2-1452, 1958.



NOISE SOURCE CHARACTERISTICS

Dimension	d	cm
Velocity	v	cm/sec
Density	ρ	gm/cm^3
Source Intensity	Q_f	watts/cm^2
Sound Frequency	$f = \frac{c}{\lambda}$	cps

ACOUSTIC SIMILARITY

$$\underline{\text{GIVEN}}\begin{cases} P_f^2 \sim \dfrac{\left[Q_f \cdot d^2\right] A\left[\frac{R}{\lambda}, \theta\right]}{R^2} & (1) \\ f \sim \dfrac{v}{d} & (2) \\ Q_f \sim B\left[\frac{1}{2}\rho v^3\right] & (3) \end{cases}$$

JET FLOW SIMILARITY

$$\underline{\text{AND}}\left\{\begin{aligned} \frac{d}{D} &\sim F\left[\frac{X}{D}\right] \\ \frac{v}{V} &\sim G\left[\frac{X}{D}\right] \end{aligned}\right\} \quad (4)$$

$$\therefore \begin{cases} P_f^2 \sim \left[\dfrac{1}{R/D}\right]^2 \; A\left[\dfrac{R}{D}\cdot\dfrac{V}{C}, \theta\right] \; B'\left[\dfrac{1}{2}\rho V^3\right] \\ f\cdot D \sim H\left[\dfrac{X}{D}, V\right] \end{cases}$$

Fig. 1 - Jet Noise Scaling Principles

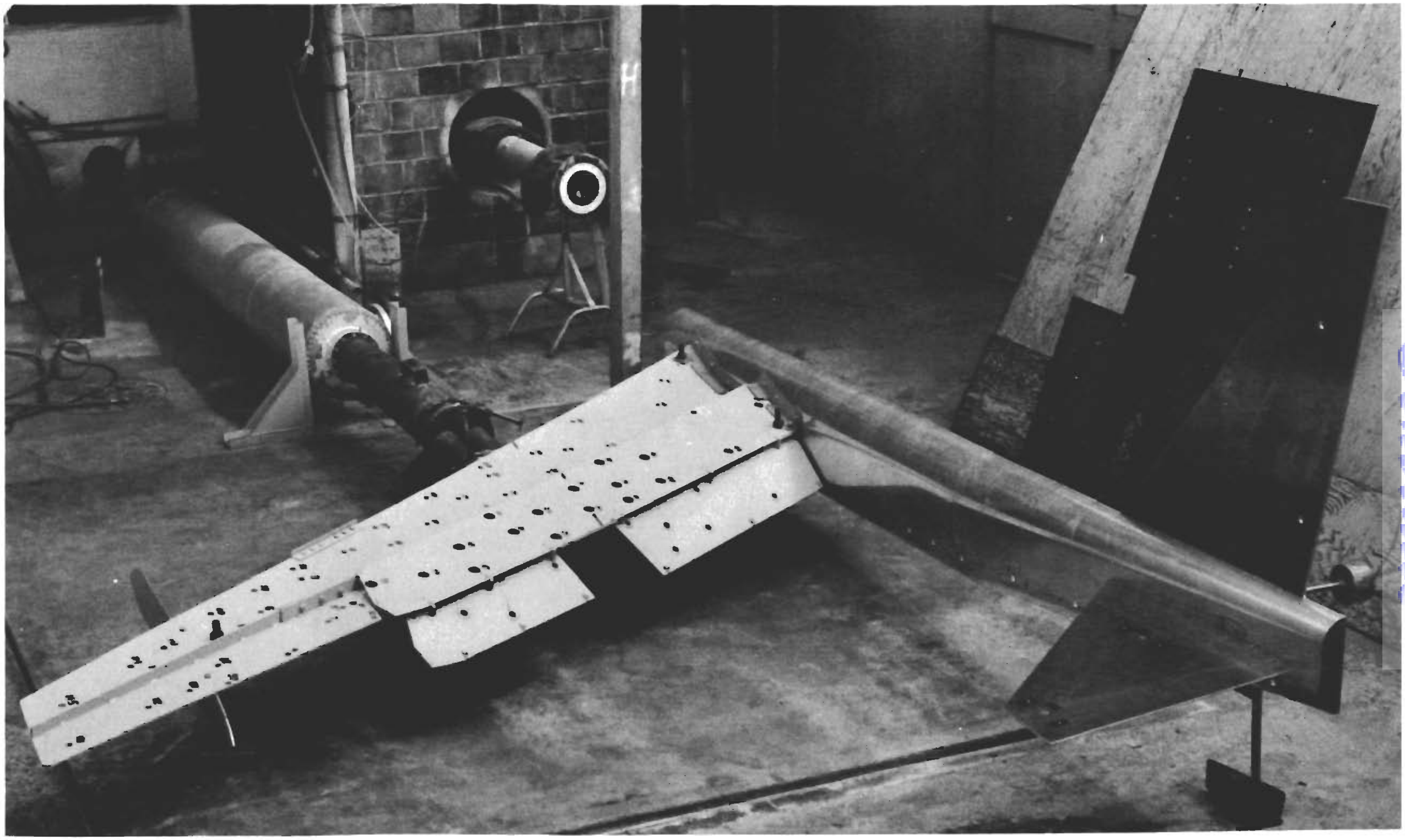


Fig. 2 - 1/10th Scale Model B-52 (Inboard Engines)

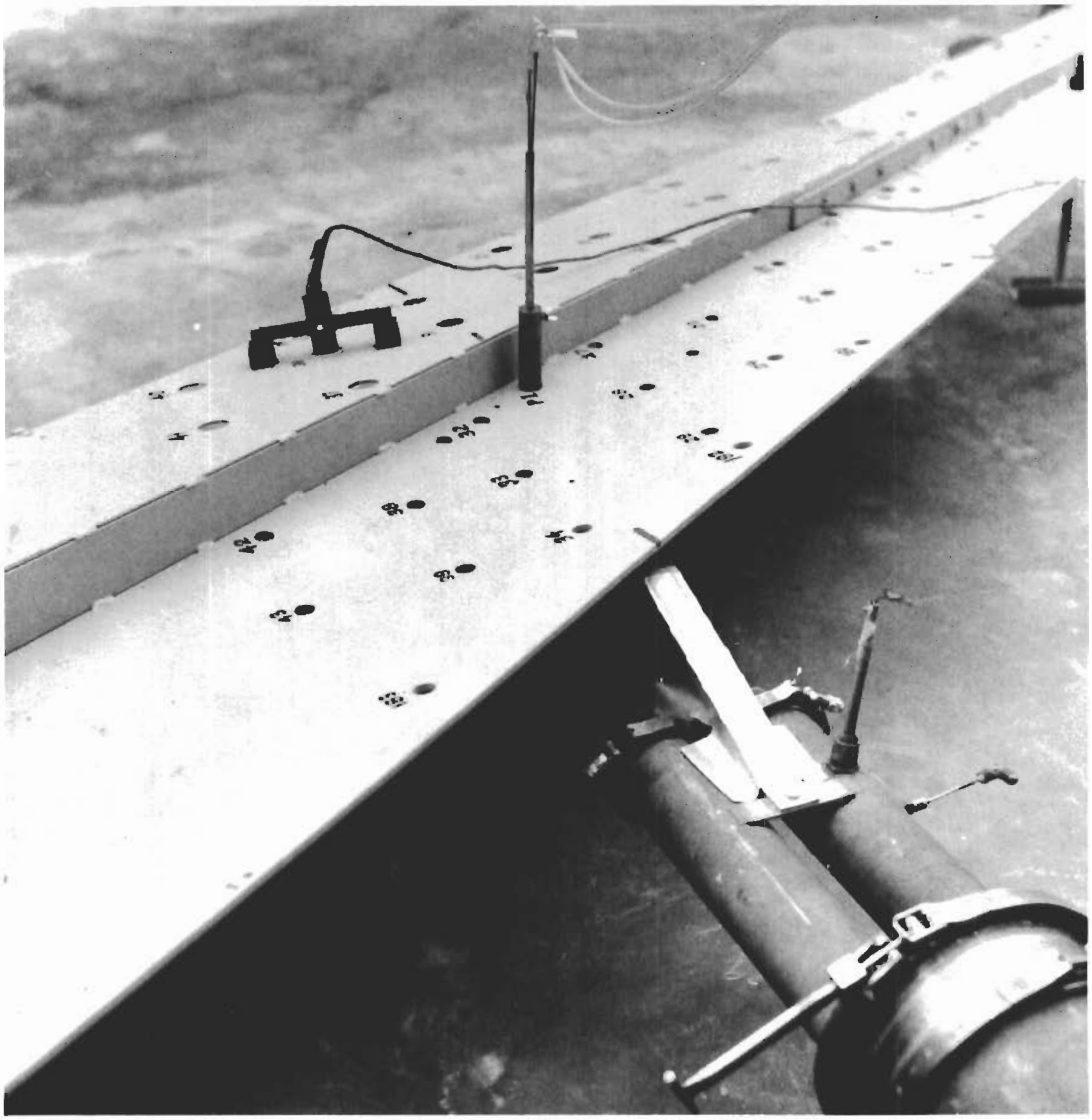
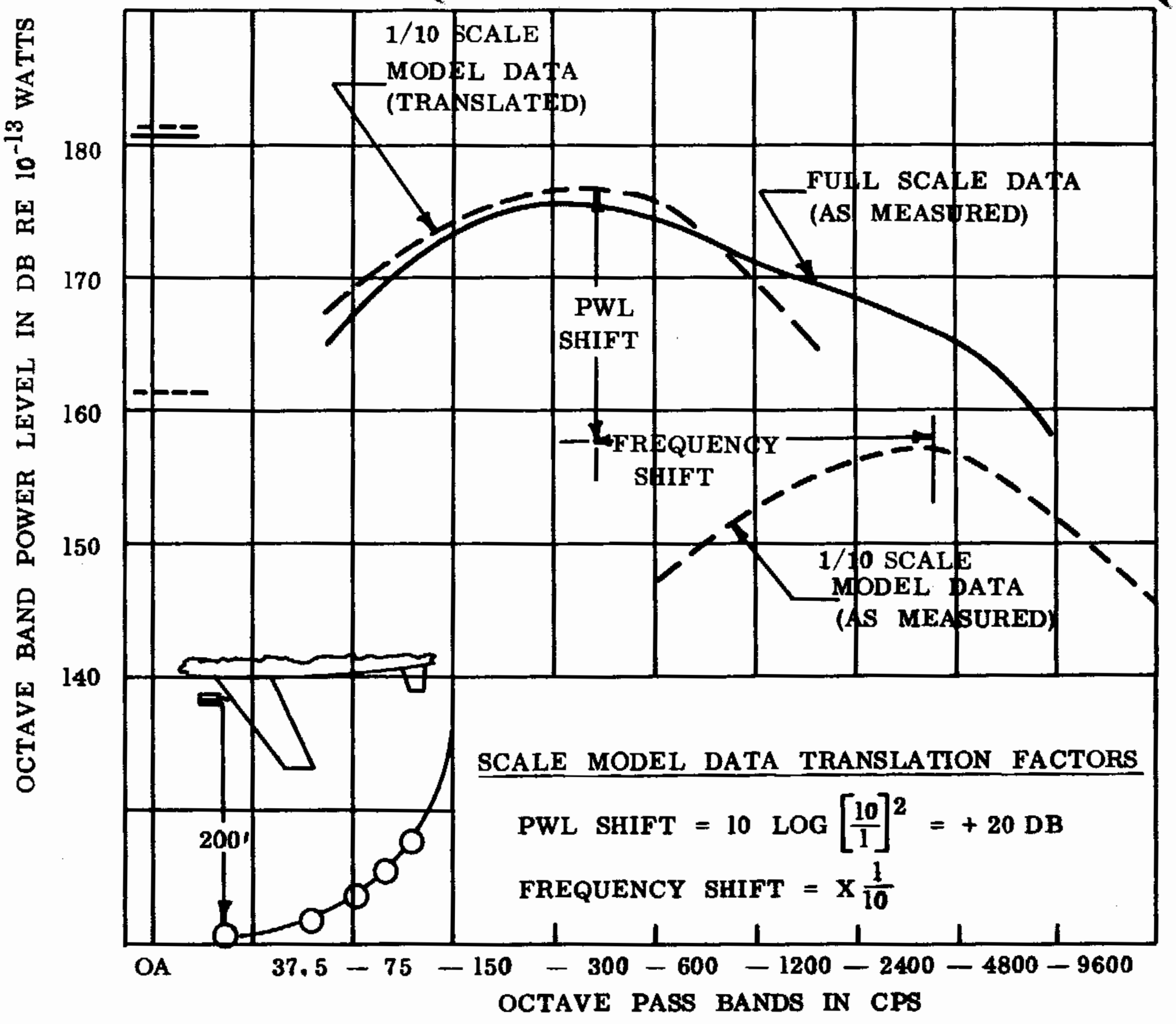


Fig. 3 - 1/10th Model and Instrumentation



SCALE MODEL DATA TRANSLATION FACTORS

PWL SHIFT $= 10 \text{ LOG } \left[\frac{10}{1}\right]^2 = +20$ DB

FREQUENCY SHIFT $= \text{X} \frac{1}{10}$

FIGURE 4 COMPARISON OF MODEL AND FULL SCALE OCTAVE BAND POWER LEVEL (2 J57-P43W ENGINES)

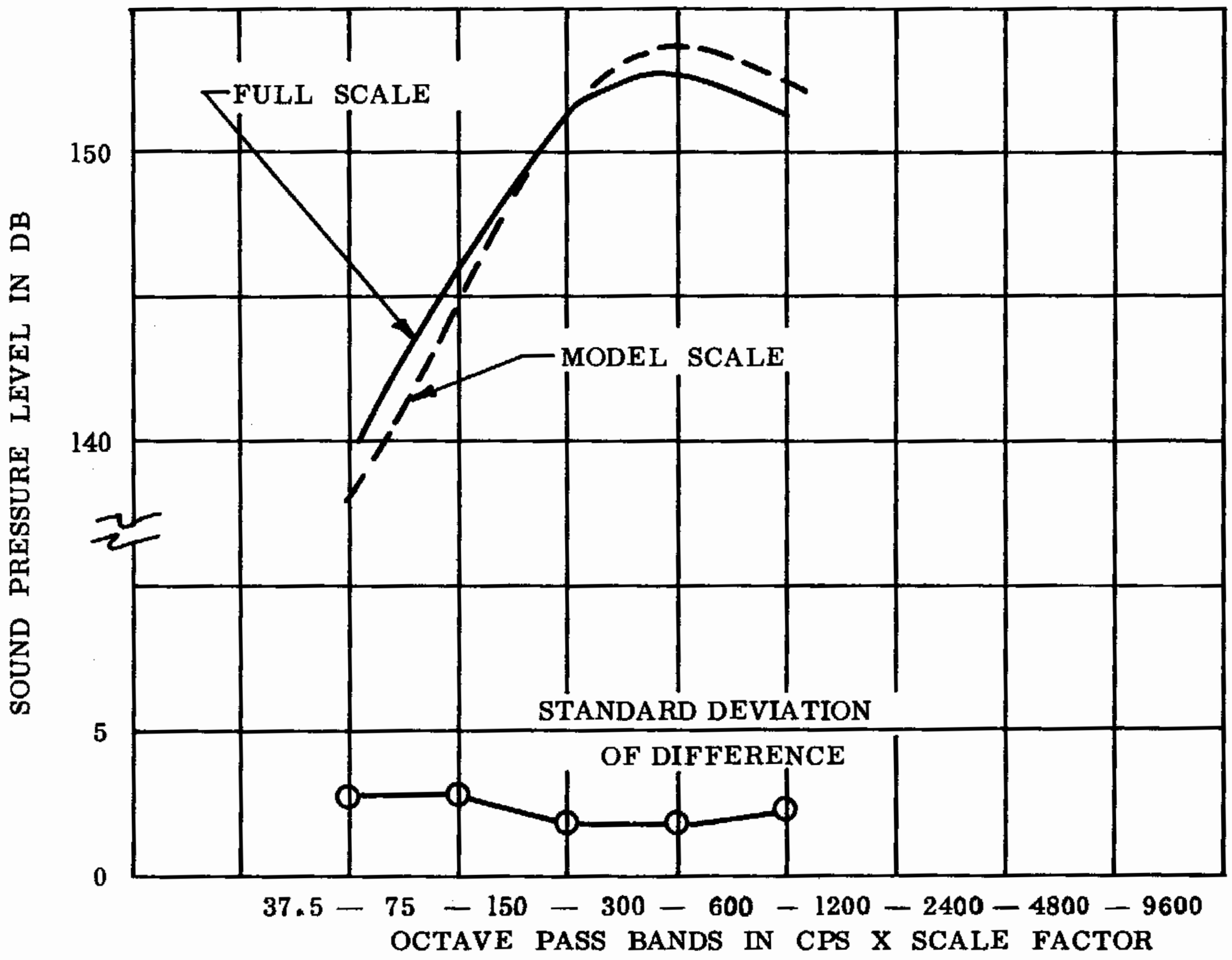


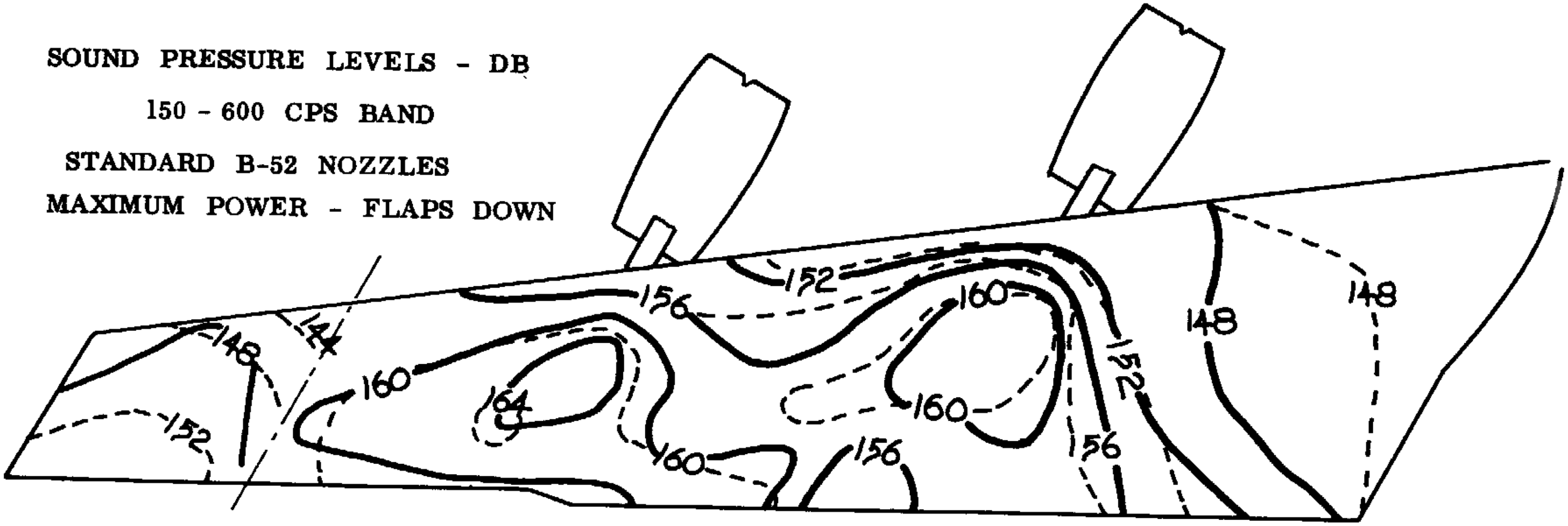
FIGURE 5 COMPARISON OF MODEL AND FULL SCALE AVERAGE SOUND LEVEL ON WING FOR 52 TEST POINTS

SOUND PRESSURE LEVELS - DB

150 - 600 CPS BAND

STANDARD B-52 NOZZLES

MAXIMUM POWER - FLAPS DOWN



— FULL SCALE CONTOURS
--- 1/10 SCALE MODEL CONTOURS

FIGURE 6

COMPARISON OF MODEL AND FULL SCALE B-52 SOUND LEVELS

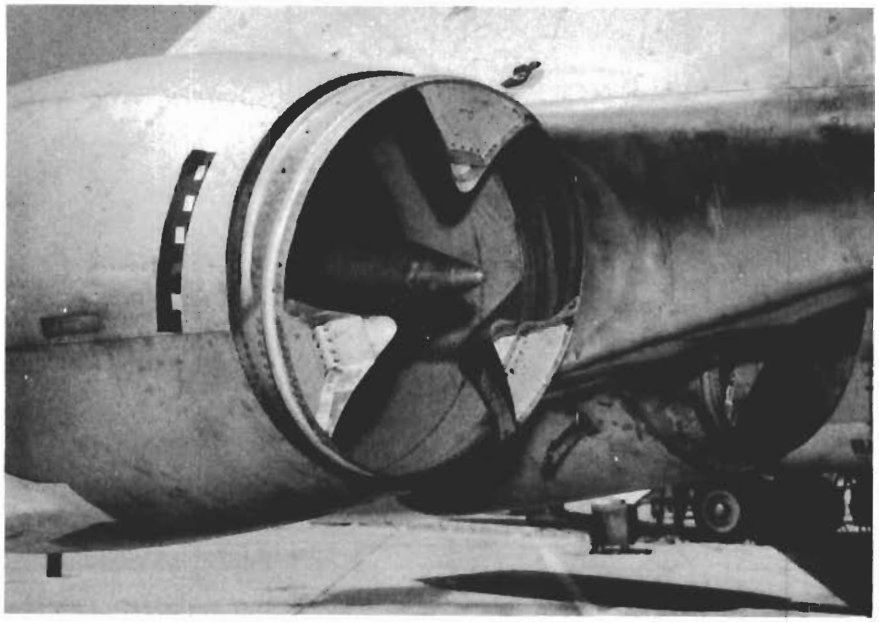


Fig. 7 - Supressor Nozzle Installed on B-52

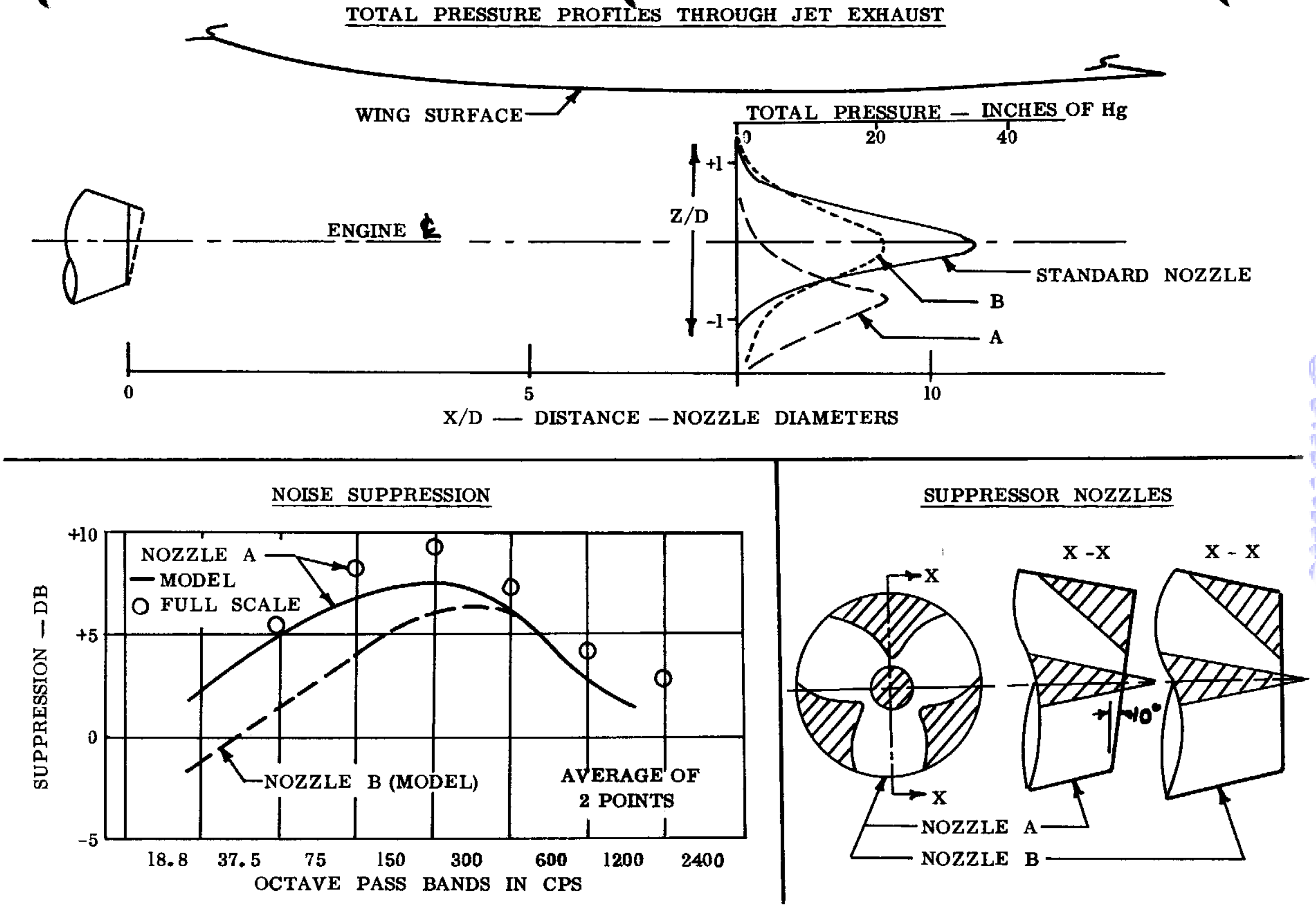


FIGURE 8 PERFORMANCE OF MODEL B-52 SUPPRESSORS

SUPPRESSION IN 150 - 600 CPS BAND - DB

FULL SCALE 3-LOBE B-52 SUPPRESSOR

MAXIMUM POWER CONDITION — FLAPS DOWN

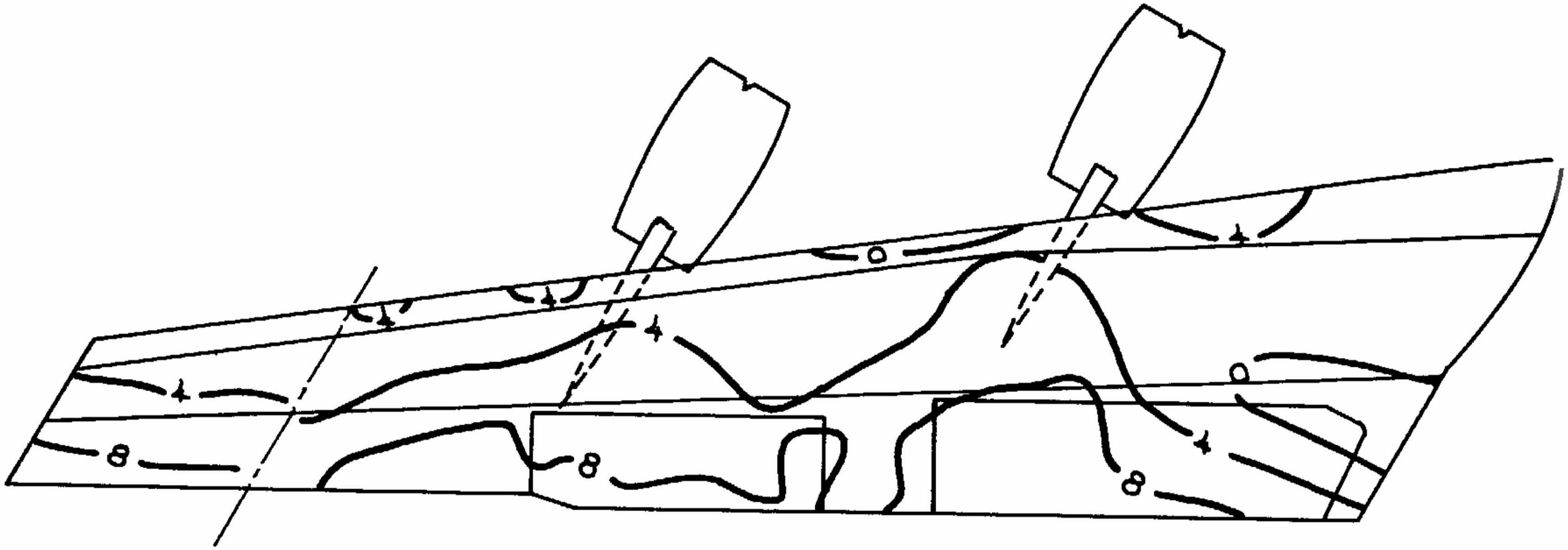


FIGURE 9

SUPPRESSION CONTOURS ON LOWER WING SURFACE

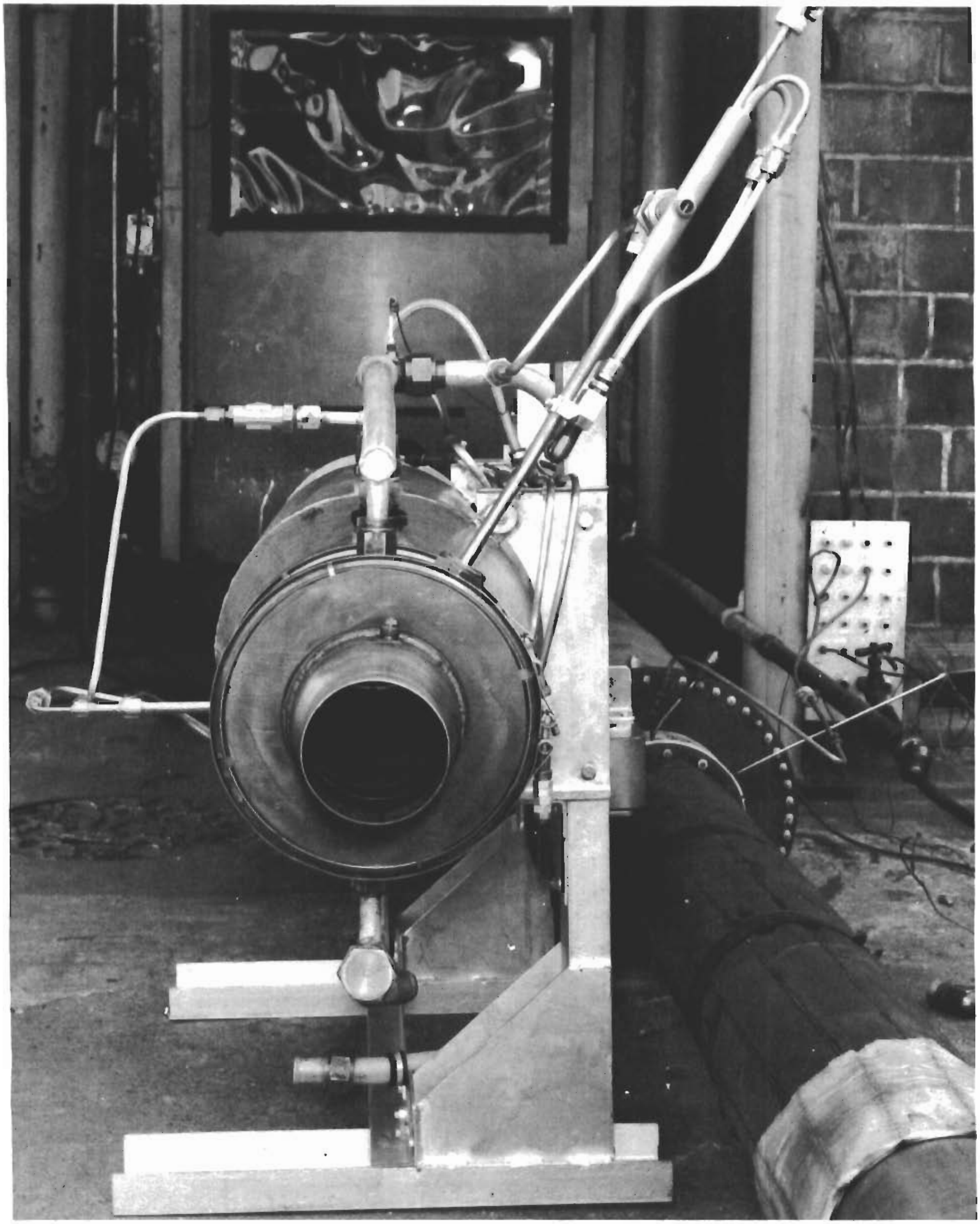


Fig. 10 - 1/10th Scale Model Afterburner

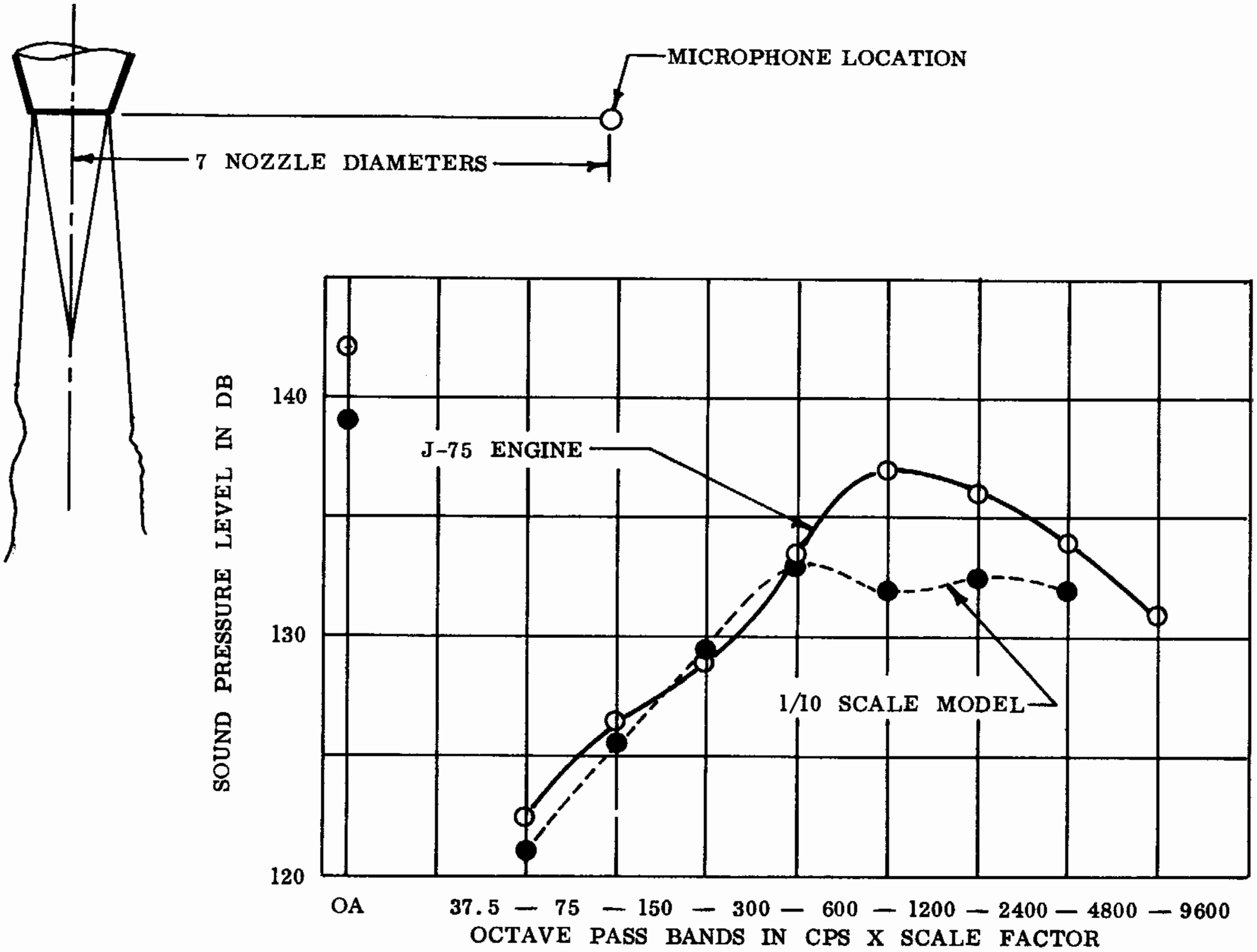


FIGURE 11 COMPARISON OF FULL SCALE AND MODEL AFTERBURNING ENGINES

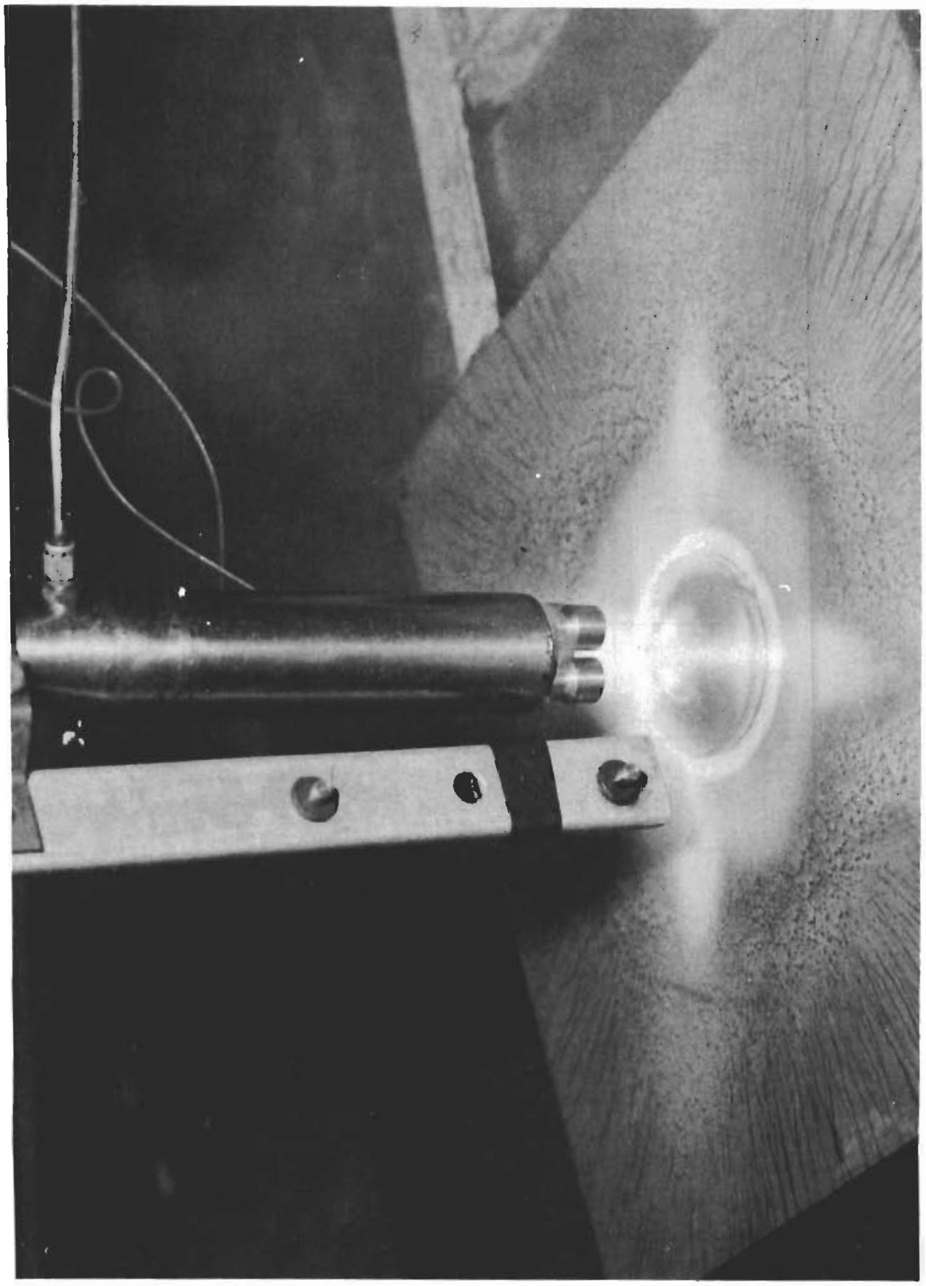


Fig. 12 - Acoustic Measurement During Model Rocket Firing

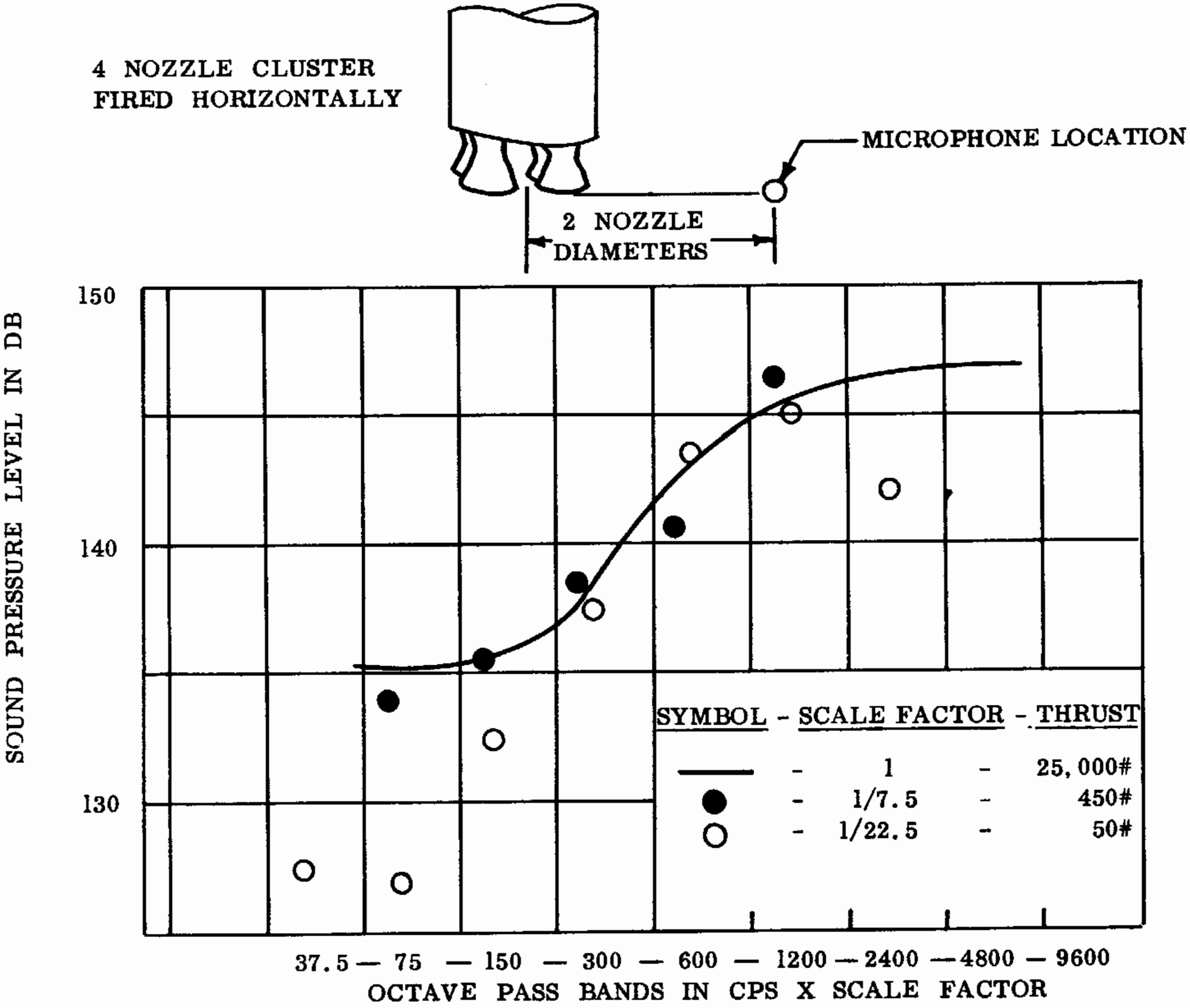


FIGURE 13 COMPARISON OF FULL SCALE AND MODEL ROCKETS