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PREDICTED ACOUSTICAL PERFORMANCE OF THE S-IC SOUND SUPPRESSOR

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

DEFINITION OF SYMBOLS

Symbol	Definition
λ	linear scale ratio, model to prototype
db	decibel; unit of level denoting the ratio between two quantities proportional to power. Number of decibels corresponding to the ratio of two amounts of power is 10 times the logarithm to the base 10 of this ratio.
Hz	cycles per second
re	with reference to
microbar	one dyne per square centimeter; unit of pressure used in acoustics
N	newtons, unit of force in International System of Units
N/m^2	newtons per square meter, reference pressure used in acoustics
lbf	pound force (English system)
v	velocity, feet per second, meters per second
l	length, reference length, meters, feet
g	gravitational constant, $9.80665\ m/s^2$ ($32.17398\ ft/s^2$)
Fr	Froude number, $= \frac{v^2}{1 \cdot g}$

PREDICTED ACOUSTICAL PERFORMANCE OF THE S-IC SOUND SUPPRESSOR

SUMMARY

Results of tests on dynamically similar models of 1:7 and 1:20 scale are used to predict the performance of a sound suppressor for the S-IC static test facility.

The overall sound power reduction is expected to be 22 decibels, with a minimum suppression of 13, 16, and 20 decibels at the octave band mid-frequencies of 1, 2, and 4 Hz, respectively.

INTRODUCTION

The high-intensity sound generated by today's high-thrust rocket powerplants is undesired in populated areas close to missile test sites. When the large test stand for the S-IC booster rocket was under design at the Marshall Space Flight Center at Huntsville, Alabama, in 1962, a sound pressure level of 110 decibels (re 2×10^{-5} N/m^2 or 0.0002 microbar) was set up by Test Laboratory as a threshold level, not to be exceeded in a neighborhood residential area only 4.2 kilometers (2.60 miles) away from the test site. The major annoyance and possible structural damage is caused by the low-frequency sound below 100 Hz, therefore, the design requirements specified also that the low-frequency sound should be particularly well supressed; less emphasis was to be placed on the high-frequency sound. Recognizing the difficulties in the relatively unknown area of low-frequency sound suppression, the required degree of sound suppression was stated as a minimum of 10 decibels within each octave band of center frequencies of 2, 4, 8, and 16 Hz. A sound suppression program which was initiated in 1962, culminated in the design criteria for a sound suppressor for the S-IC test facility. The operational characteristics and the acoustical performance of these criteria were determined through operation of two experimental models. The actual sound power spectrum of the S-IC first stage (or booster stage) is shown in Figure 1.

One model (Fig. 2), geometrically similar to the prototype at a linear scale of 1:19.54 (nominally 1:20), used a cluster of five engines of 17 790 newtons (4000 lbs) thrust each, or a total thrust of 88 950 newtons (20,000 lbf). These engines were dynamically similar to the F-1 engine. With a mass ratio of eight in a model for the flow of additive water to propellant flow, the model was also dynamically similar to the prototype sound suppressor. Assuming the same acoustical conversion efficiency, and the same effectiveness of the additive water in exchanging momentum with the gas flow, this model may be considered to be a true acoustical model. It was set up and operated at the Components and Sub-systems Test Division of Test Laboratory.

The second model (Fig. 3) used a cluster of five engines with a thrust of 122 340 newtons (27,500 lbf) each, or a total of 611 340 newtons (137,500 lbf) thus representing a linear scale of 1:7.45 on the basis of thrust ratio. This model was erected at the Sound Suppression Test Stand of the Systems Test Division of Test Laboratory. It served primarily as a model for the determination of the operational characteristics of the water recirculation system. For this purpose, its mass ratio of additive water to propellant flow had to be designed for a value of eighteen according to the Froude scaling law. This model is, therefore, not a dynamically similar model of the prototype with respect to the acoustic performance. However, the acoustical data obtained from this model show the effect of the higher water flow rate on the sound power spectrum of the prototype.

ACOUSTICAL SCALING

Theory and experiments show that for dynamically similar systems [2], the sound pressure spectra measured at similar positions are the same if measured in the same frequency bands, and if frequency is scaled inversely proportional to a characteristic length. This leads to a dimensionless frequency parameter defined by frequency times a characteristic dimension of the system (such as the engine nozzle diameter), and divided by a characteristic velocity. The model and the prototype rocket engines have practically the same specific impulse (and exhaust velocity). If the same conversion efficiency is assumed for the model and the prototype, it follows that the overall sound pressures measured at geometrically similar points are the same, and that the sound pressure is scaled according to the thrust ratio (or as λ^2). The latter follows from the fact that total power is directly proportional to thrust.

Therefore, to scale sound power,

1. The octave-band sound power spectrum has to be shifted in frequency by a ratio of $1/\lambda$,

2. The individual power levels have to be increased by the addition of $10.\log(\lambda^2) = 20.\log(\lambda)$ decibels.

The total thrust of the five F-1 engines during test S-IC-08 was 33 970 000 N (7,637,000 lbf). This value has been used to determine the actual model scales and the proper value for scaling the model acoustical power levels.

MODEL TESTS

The 1:20 Model

A longitudinal cross-section of this model is shown in Figure 2, with gas velocities indicated at various locations. Also shown are four resonators with their theoretical resonant frequencies. These resonators are not a part of the prototype design; they were incorporated into the model for study purposes only. The model deviates also in details of the water storage for the additive water. In the prototype, the water storage is built into the sound suppressor structure with a capacity of 18 925 m^3 (five million gallons). For the model tests, the water was stored in a separate tank of 17 m^3 (4500 gallon) capacity, sufficient for a test time of 50 seconds, although normal test duration was 30 seconds.

The acoustical performance of this model is shown in Figure 4. The overall sound power reduction amounts to 21 decibels, with relatively large suppression ratios at the low frequencies. To scale this spectrum to the S-IC size sound suppressor for a value of $\lambda = 1{:}19.54$, the frequency shift amounts to more than four octaves ($19.54 = 2^4 \times 1.22$), while the sound power of the individual octave band has to be increased by 25.74 or 26 decibels. Figure 5 shows this scaled spectrum cross-plotted against the measured power spectrum of the S-IC booster. It can be seen that the unattenuated "base line" of the 1:20 model is in very good agreement with the S-IC power spectrum, except for the peak power at 8 and 16 hertz octave mid-frequency. Because of this close overall agreement, it can be assumed that the suppressed power spectrum obtained with this model represents to a high degree of probability the suppressed power spectrum to be expected from the S-IC sound suppressor. It may be mentioned here that the resonators in the model were designed for resonant frequencies of 14, 18, and 23 hertz. If scaled up by the linear scale factor of 1:19.54, these resonators would provide additional attenuation of the low frequency power around the one-hertz mid-frequency. However, the effect of these resonators in the model could not be determined with sufficient accuracy or certainty. The application of similar resonators in the prototype design is, therefore, not contemplated.

The 1:7 Model

A longitudinal cross-section of this model is shown in Figure 3. The basic structure was used in a previous program as a sound suppressor model for the H-1 engine. The structure as shown in Figure 3, modified for five engines of 122 340 newtons each, or a total thrust of 611 340 newtons, represents an overall linear scale of 1:7.45, or an area scale of 1:55.5 on the basis of gas flow rate. Inasmuch as a dynamically, or acoustically, similar model (1:20) was already available, it was felt that this 1:7 scale model should not be used to duplicate the acoustical performance, but that it would be of greater value to the program if used for a simulation of the dynamics of the water recirculation system. This model was, therefore, designed to be hydraulically similar to the prototype, but not acoustically similar. As a consequence, the deflector in this model was built at a scale of 1:4.25 (instead of 1:7), to better meet the hydraulic requirements of the system.

The Froude number of the prototype, based on deflector exit conditions is 285 (from v = 350 m/s or 1150 fps, l = 44 m or 145 ft, and $g = 9.81\ m/s^2$ or $32.2\ ft/s^2$). To obtain the same Froude number in the 1:7 model, the gas exit velocity at the model deflector had to be made equal to 130 m/s (425 ft/s). This required not only the larger deflector (at the 1:4.25 scale), but also a water-to-gas mass ratio of 18. Only 80 percent of the water flow is expected to participate in the momentum exchange between water and gas, the remaining 20 percent most probably will be found in the boundary layer of the gas flow along the walls and the ceiling. This is so because this water has lost its momentum due to impact and wall friction, and cannot be accelerated any more to the velocity of the core of the gas flow. It is finally lost through the drainage system. The acoustical performance of this model is shown in Figure 6. The band of suppressed sound power was obtained from seven test runs of 60 seconds and 30 seconds duration, respectively, with no essential structural modifications. The spread in sound power level of 2 to 3 db is believed to be typical for field measurements. The slightly wider spread at the low frequencies is a basic difficulty connected with low-frequency measurements. Part of the data spread may be attributed to atmospheric conditions at the time of the tests.

The unattenuated power spectrum, or "base line" of this model, was obtained by firing the 5-engine cluster into a dry deflector. The S-IC booster stage, however, is fired into a wet deflector with a water-to-gas mass ratio of close to unity. This water has an attenuating effect on the order of 3 decibels overall. Relatively speaking, the S-IC unattenuated power spectrum is, therefore, too low by 3 db, or the 1:7 model spectrum is too high by 3 db. The comparable power spectrum for the 1:7 model would be the one obtained from the existing five-engine cluster firing into a wet deflector, or from a cluster of one-half the thrust firing into a dry deflector. Since a dry deflector was used with the existing five-engine cluster powerplant, the scale for the projection of the model sound power spectrum into the S-IC size has to be chosen on the basis of one-half the thrust of the actual cluster. This is true only for the "base line." Figure 5 shows that this base line is in excellent agreement with the sound power spectrum of the S-IC booster.

The suppressed sound power spectrum of the 1:7 model has to be scaled, of course, on the basis of the full thrust of 611 340 N for this model. This scaled spectrum is also shown in Figure 5. Attenuation of the low frequency sound power at 4, 8, and 16 hertz could be as high as 31, 35, and 38 decibels, respectively. These high suppression ratios could be obtained in the prototype suppressor if the water flow rate of 1:18 could be accomplished. This is not quite possible in the S-IC test tower at MSFC because of cross-sectional limitations at the deflector exit, which allow only a mass ratio on the order of 1:8. The test tower at the Mississippi Test Facility, however, does not have this restriction, and would allow higher water flow rates; the design of the sound suppressor for this test facility should take this into account. Correspondingly, higher attenuation in the frequency range from 4 to 16 hertz can then be expected for the sound suppressor at Mississippi Test Facility.

CONCLUSIONS

Figure 5 shows the results of the model tests scaled to the power of the S-IC booster stage. Because of the very close agreement of the unsuppressed sound power spectra of both models with the sound power spectrum of the S-IC booster stage, it is postulated that the scaled performance of both models represents the true performance to be expected of the S-IC sound suppressor, if built according to the developed design criteria.

The spectrum of the 1:20 model, scaled to the size of the S-IC, exhibits an overall sound power level of 191 db, and thus affords an overall reduction of the radiated sound power by 22 decibels. The 1:7 model, scaled up to the S-IC size sound suppressor, has an overall sound power level of 187 db, and provides a sound power reduction of 26 decibels.

Although these overall power reductions are important in themselves as a measure of the overall performance of the system, the sound power reduction at the low frequencies, below 100 Hz, is the actual criterion for judging the effectiveness of the design and its principle of operation. The design specifications called for a maximum sound pressure level of 110 db (re 0.00002 N/m^2) at a distance of 4200 meters (2.60 miles).

In the Appendix it is shown that the sound pressure level (Lp) at a distance (r) due to a sound source of power (Lw) is obtained as

$$Lp = Lw - 20 \log r - 17.9 \quad \text{if r is given in meters} \qquad (1)$$

or

$$Lp = Lw - 20 \log r - 7.6 \quad \text{if r is given in feet} \qquad (2)$$

In these equations, the sound pressure level is referred to a pressure of 0.00002 N/m^2, and is based on the mean square sound pressure averaged over all directions. The sound source is hereby assumed to be in a free field and close to the ground which restricts the sound propagation to a hemisphere. For the same sound power, the sound pressure level is, therefore, higher by 3 decibels. The reference level for the sound power level Lw is 10^{-13} watts.

The sound pressure levels in the various low frequency octave bands, expected from test firings of the S-IC booster stage at a distance of 4200 meters, have been computed using equation 2. The results are given in columns 3 and 5 of Table I; they show that the requirement to suppress the low frequency sound has been met by a good margin not only at the very low frequencies, but even up to 250 Hz.

TABLE I. SOUND PRESSURE LEVELS EXPECTED AT 4.2 KILOMETER DISTANCE

Mid-Frequency Hz	Lw Octave Band Level re 10^{-13} watts	Lp re 0.00002 N/m^2	Lw Octave Bands Level re 10^{-13} watts	Lp re 0.00002 N/m^2
1	174 db	84 db	178 db	88 db
2	180	90	178	88
4	182	92	172	82
8	183	93	171	81
16	179	89	169	79
31.5	177	87	173	83
63	176	86	178	88
125	178	88	183	93
250	180	90	184	94

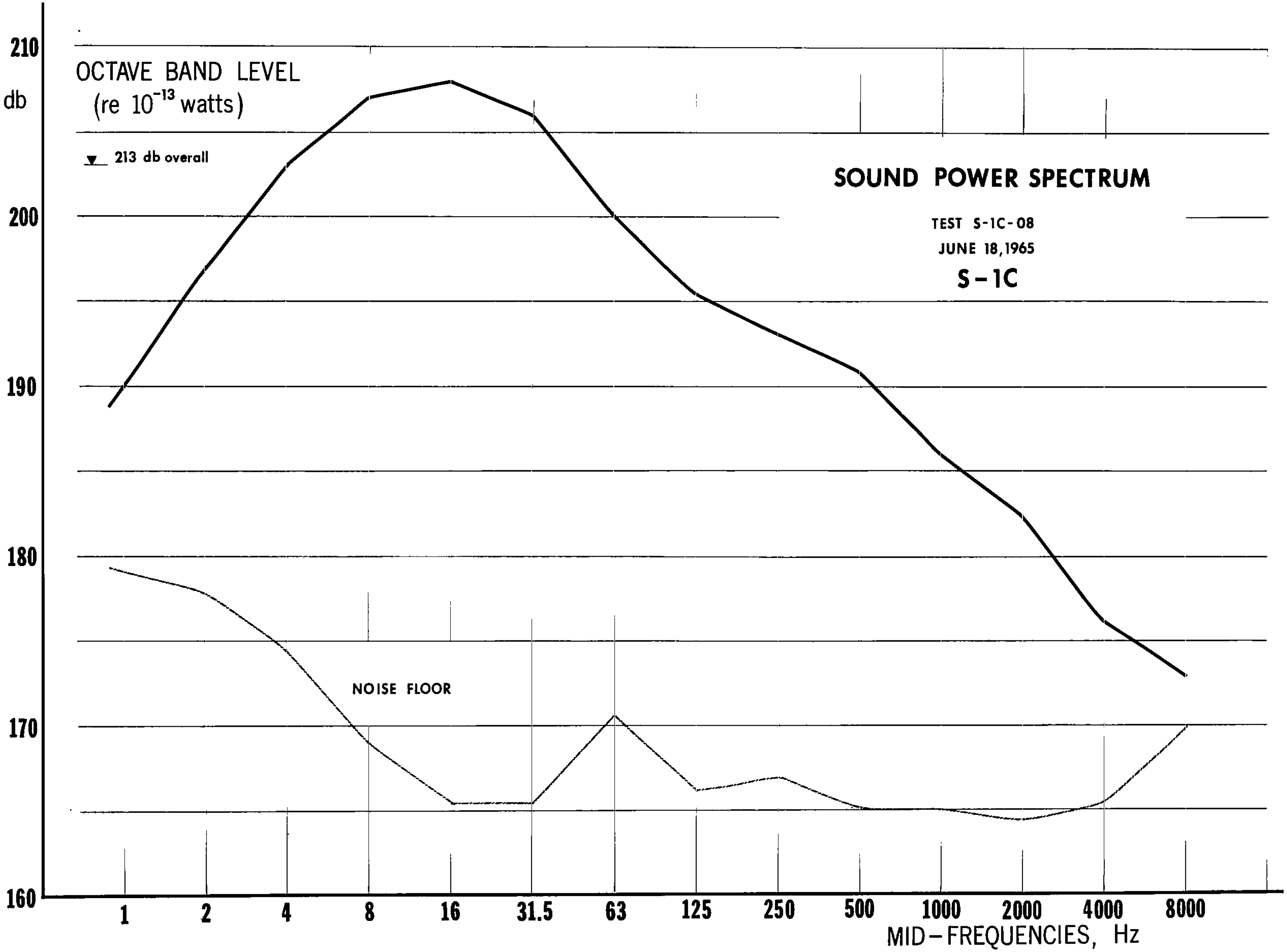

FIGURE 1. SOUND POWER SPECTRUM OF THE S-IC STAGE

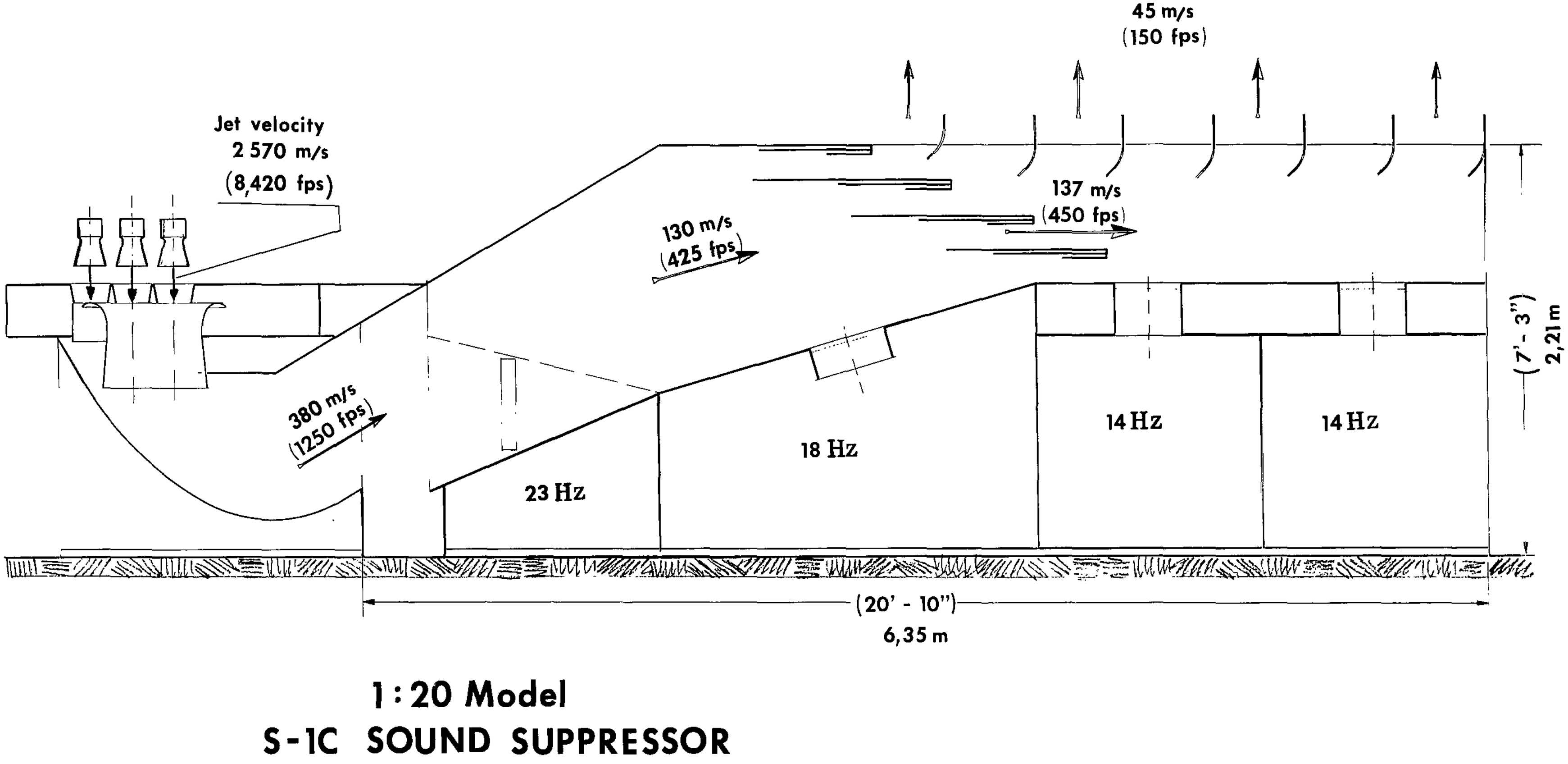

FIGURE 2. LONGITUDINAL CROSS SECTION THROUGH THE 1:20 SCALE MODEL SOUND SUPPRESSOR

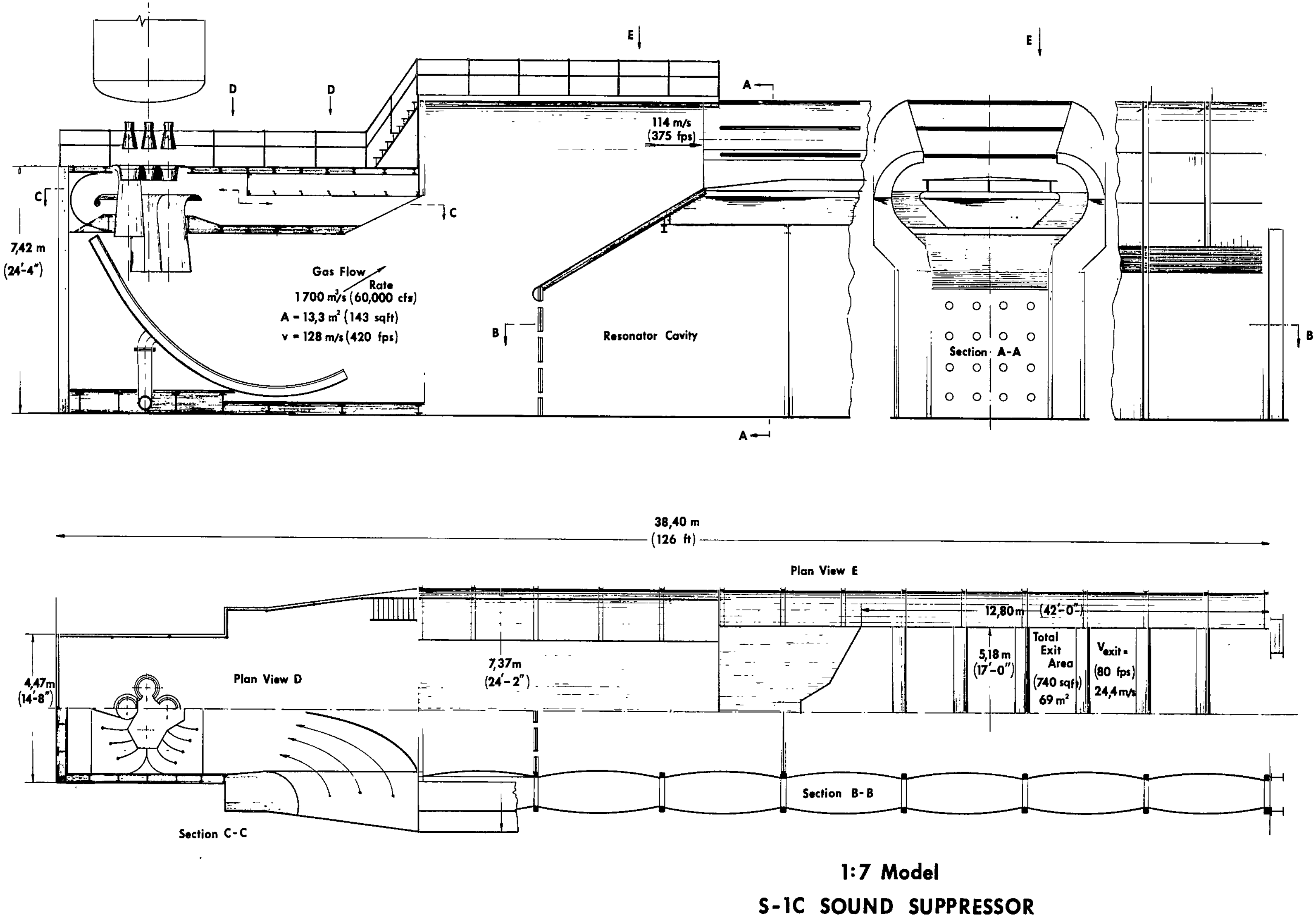

FIGURE 3. LONGITUDINAL CROSS SECTION THROUGH THE 1:7 SCALE MODEL SOUND SUPPRESSOR

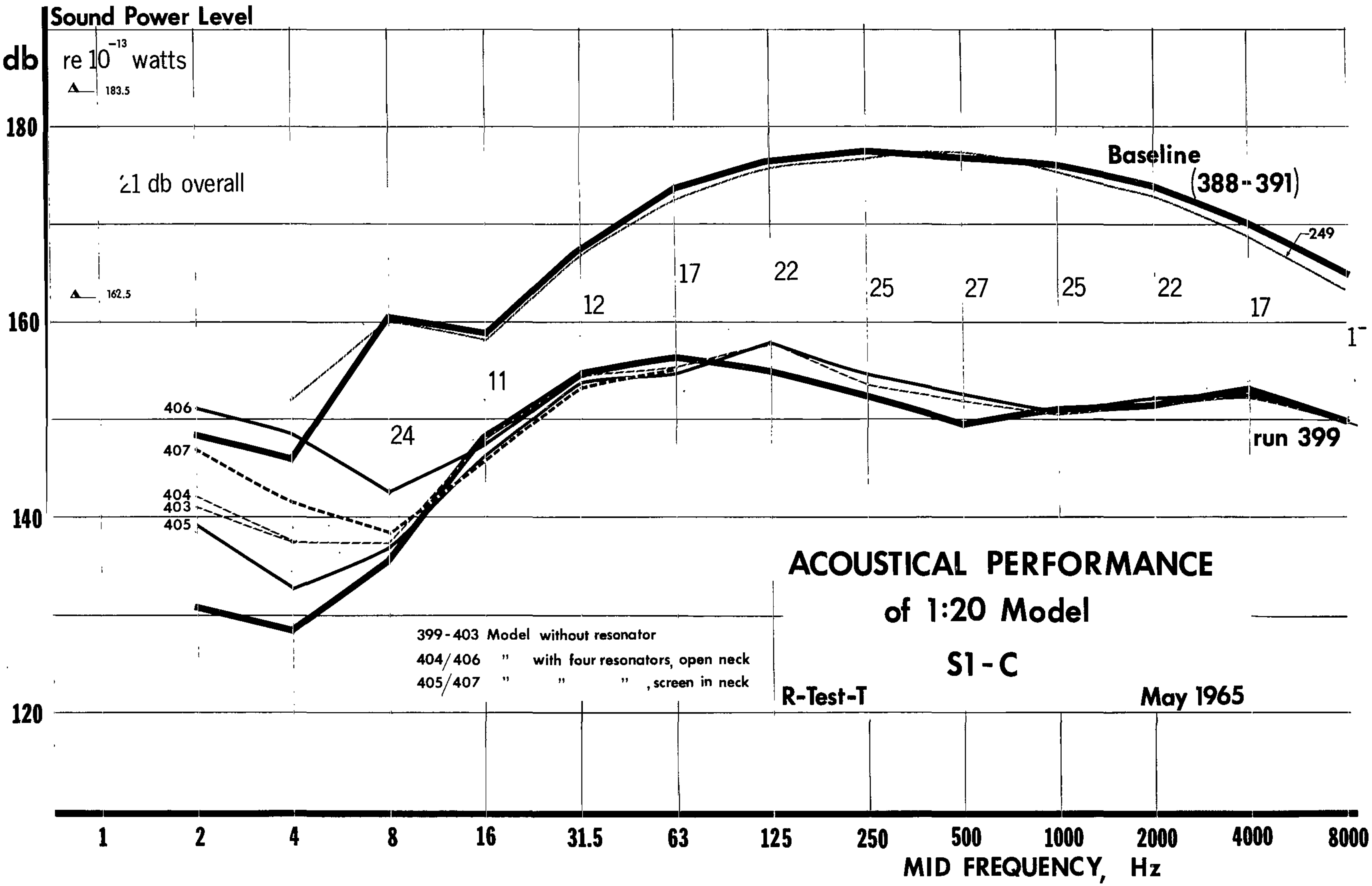

FIGURE 4. ACOUSTICAL PERFORMANCE OF THE 1:20 SCALE MODEL

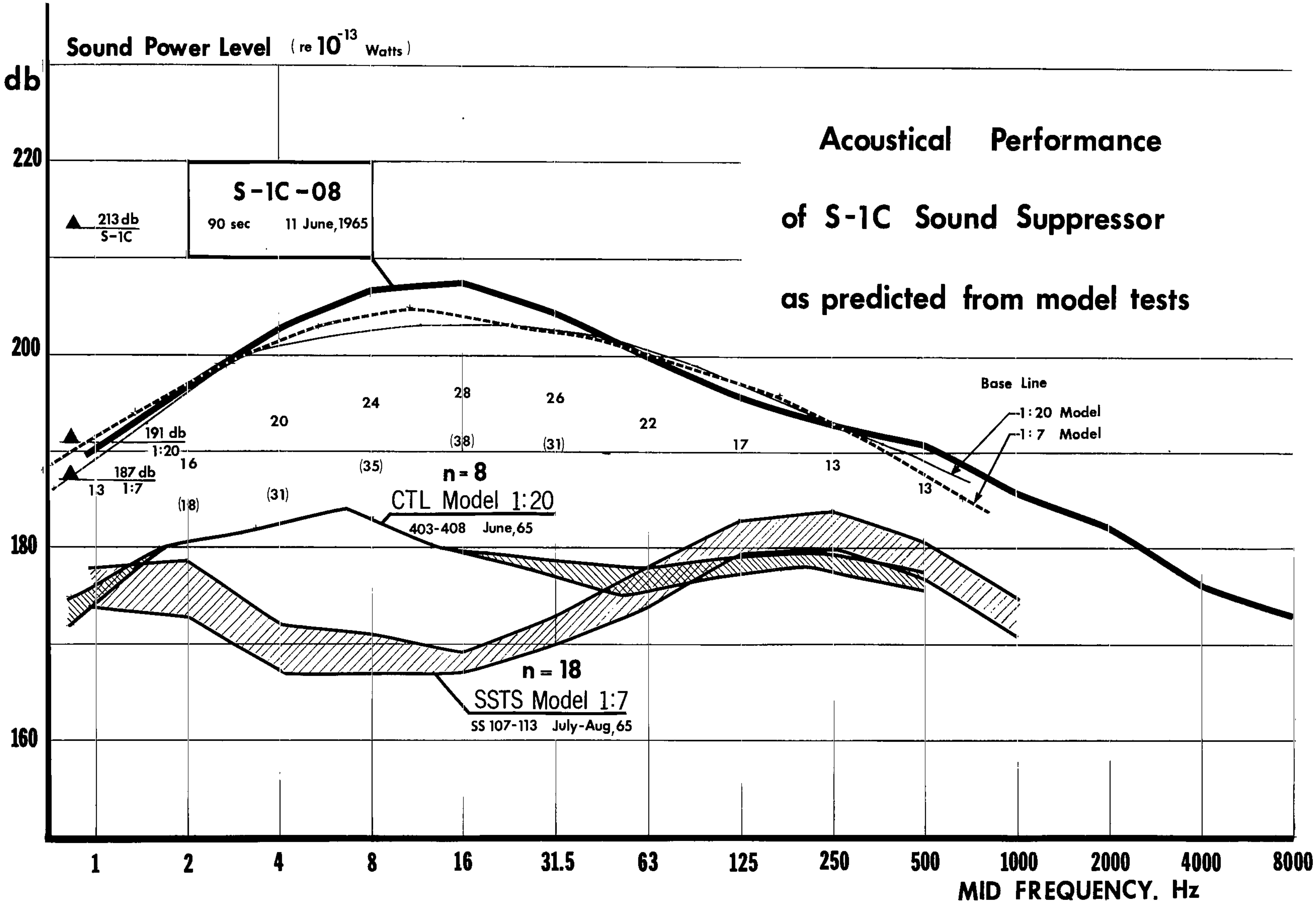

FIGURE 5. ACOUSTICAL PERFORMANCE OF THE S-IC SOUND SUPPRESSOR AS THE SCALED-UP MODEL PERFORMANCE

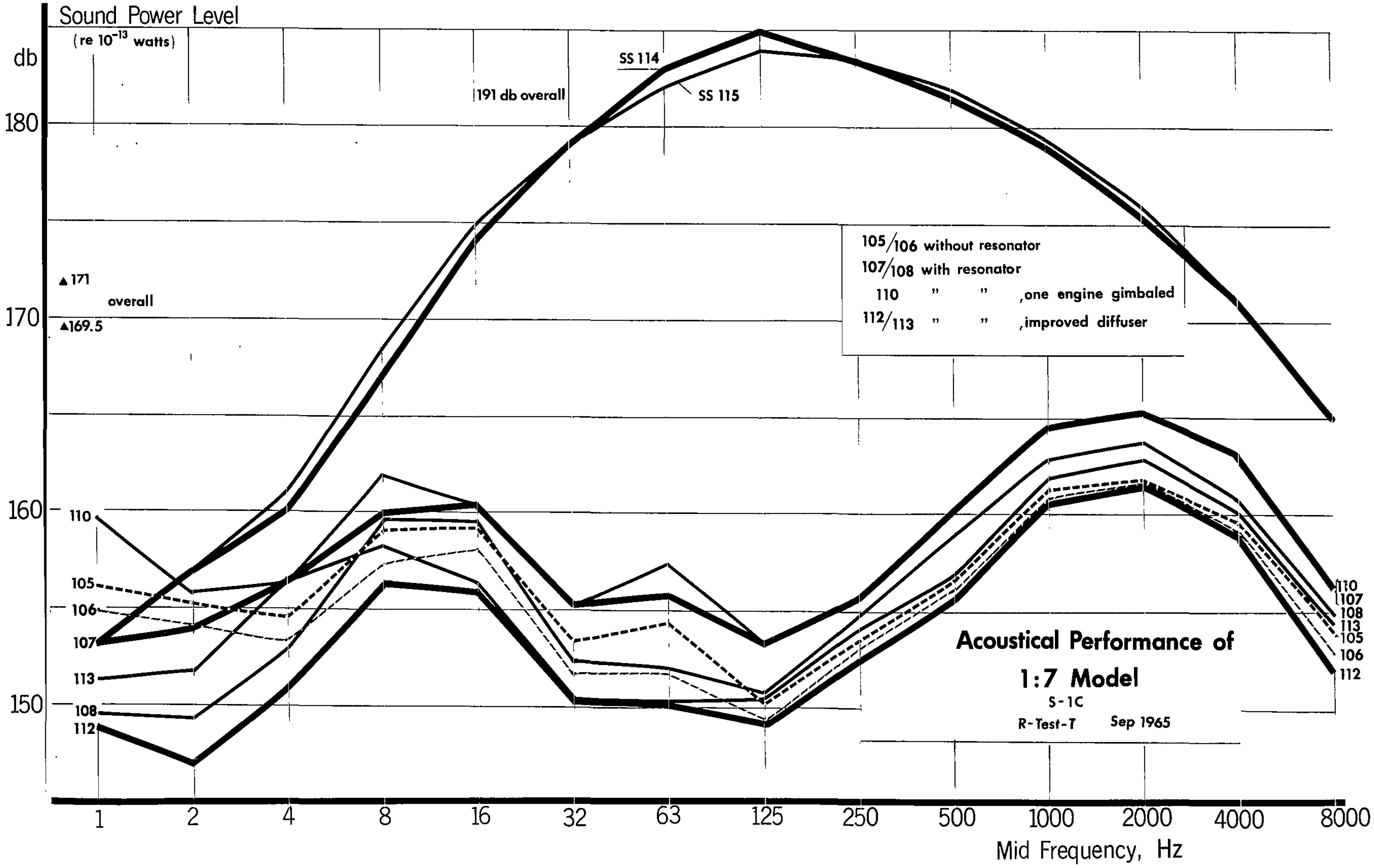

FIGURE 6. ACOUSTICAL PERFORMANCE OF THE 1:7 SCALE MODEL

APPENDIX

An ideal point source of acoustic power (W) radiates sound energy uniformly at an average intensity in all directions. Assuming this sound source to be located at the center point of a sphere of radius (r), the average sound intensity passing through each unit area of the surface of the sphere is of the amount

$$J_1 = \frac{W}{4\pi r^2} \quad . \qquad \text{(A1)}$$

Also, in a free field, where both the particle velocity (v) and the sound pressure (p) are in phase, the sound intensity in the direction of propagation is

$$J_2 = \frac{p^2}{\rho \cdot c} \quad . \qquad \text{(A2)}$$

Here, ρ is the density of the medium, c is the velocity of sound propagation through the medium, and the product $\rho \cdot c$ is the characteristic impedance of the medium. p is the mean square (rms) value, or the effective sound pressure, not its instantaneous value p(t).

Since $J_1 = J_2$, it follows that

$$p^2 = \frac{1}{4\pi} \cdot W \cdot (\rho \cdot c) \cdot \frac{1}{\tau^2} \quad . \qquad \text{(A3)}$$

Equation (A3) can be rendered dimensionless by introducing the following reference values

$P_{ref} = 2 \times 10^{-5}$ newton/m^2

$W_{ref} = 10^{-13}$ watts

$r_o = 1$ meter

$\rho_o \cdot c_o = 407$ mks rayls (selected as standard value for T = 293°K and 0.751 meter barometric pressure)

With these values, equation (A3) assumes the form

$$\frac{p^2}{p^2_{ref}} = \left[\frac{W}{W_{ref}} \cdot \frac{\rho c}{\rho_o \cdot c_o} \cdot \frac{r_o^2}{r^2}\right] \cdot \left[\frac{1}{4\pi} \cdot \frac{W_{ref}}{p^2_{ref}} \cdot \frac{\rho_o \cdot c_o}{r_o^2}\right], \qquad \text{(A4)}$$

which may also be written in the form

$$10 \cdot \log \frac{p^2}{p^2_{ref}} = 10 \cdot \log [\mathrm{I}] + 10 \cdot \log [\mathrm{II}]. \qquad \text{(A5)}$$

It is obvious that each term in the two brackets is dimensionless; the term in the second bracket has a numerical value of 8.0971×10^{-3}.

Since $10 \cdot \log \frac{p^2}{p^2_{ref}}$ = sound pressure level = L_p in decibels

$10 \cdot \log \frac{W}{W_{ref}}$ = sound power level = L_W in decibels

and $10 \cdot \log (8.0971 \times 10^{-3}) = -20.92$

equation (A5) becomes

$$L_p = L_W + 10 \cdot \log \frac{\rho c}{\rho_o c_o} + 20 \cdot \log \frac{r_o}{r} - 20.92 \text{ db} \qquad \text{(A6)}$$

or

$$L_p = L_W + 10 \cdot \log \frac{\rho c}{\rho_o c_o} - 20 \log r - 20.92 \text{ db}. \qquad \text{(A6a)}$$

If the distance (r) is introduced in feet, then $r_o = 0.3048$ meter, $r_o^2 = 9.2903 \times 10^{-2}$ meters squared, and the numerical value of the term in the second bracket of equation (A4) becomes 8.71563×10^{-2}.

Then equation (A5) becomes

$$L_p = L_W + 10 \cdot \log \frac{\rho \cdot c}{\rho_o \cdot c_o} + 20 \cdot \log \frac{r_o}{r} - 10.60 \text{ db} \qquad (A7)$$

or

$$L_p = L_W + 10 \cdot \log \frac{\rho \cdot c}{\rho_o \cdot c_o} - 20 \log r - 10.60 \text{ db} \quad . \qquad (A7a)$$

Had the reference power been chosen to be 10^{-12} watts instead of 10^{-13} watts, the term in the second bracket of equation (A4) would be smaller by a factor of 10, and the resulting equation for the sound power would read

$$L_p = L_W + 10 \cdot \log \frac{\rho c}{\rho_o c_o} - 20 \cdot \log r - 10.90 \text{ db} \qquad (A6b)$$

for r in meters

and

$$L_p = L_W + 10 \cdot \log \frac{\rho \cdot c}{\rho_o c_o} - 20 \cdot \log r - 0.60 \text{ db} \quad . \qquad (A7b)$$

for r in feet

Equations (A6) through (A7b) are valid for a sound source in space, radiating uniformly into the full spherical space surrounding it. If radiation is restricted to a half sphere, as is the case for a sound source located on an infinitely large, solid, reflecting plane, the total sound power has to pass through half the sphere surface, thus doubling the intensity through each unit of area of that half space. Therefore, the numerical value of $4\pi r_o^2$ in the second bracket of equation (A4) is reduced to half, which causes the constant in equations (A6) through (A7b) to be larger by a value of 3 (+3 decibels). Thus, if radiation is restricted to pass only into the half-infinite space, the sound pressure level at a distance (r) from the source, and for the reference values of 2×10^{-5} N/m^2 for the pressure, and 10^{-13} watts for the power, is given by these formulas

$$L_p = L_W + 10 \cdot \log \frac{\rho \cdot c}{\rho_o \cdot c_o} - 20 \cdot \log r - 17.9 \text{ db (r in meters)} \qquad (A8)$$

$$L_p = L_W + 10 \cdot \log \frac{\rho \cdot c}{\rho_o c_o} - 20 \log r - 7.6 \text{ db} \quad (r \text{ in feet}) \quad . \qquad (A9)$$

Under normal atmospheric conditions, the value of $\rho \cdot c$ is so close to the reference value of $\rho_o \cdot c_o = 407$ mks rayls, that the term $10 \cdot \log \frac{\rho c}{\rho_o c_o}$ can be neglected. The final equations then assume the form as used for the computation of the sound pressure levels on page 6.

$$L_p = L_W - 20 \log r - 17.9 \quad (\text{db}) \qquad \text{for } r \text{ in meters}$$

$$L_p = L_W - 20 \log r - 7.6 \quad (\text{db}) \qquad \text{for } r \text{ in feet.}$$

REFERENCES

1. Acoustic Levels Resulting from Midfield Measurements Acquired During Test S-IC-08. Internal Memo of Test Laboratory, R-TEST-ICA-129-65 June 11, 1965.

2. Bies, D. A.; and Franken, P. A.: Notes on Scaling Jet and Rocket Noise. Journal of the Acoustical Society of America, Vol. 33, pp. 1171-1173, 1961.

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