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NOISE CONTROL FOR AIRCRAFT ENGINE TEST CELLS AND GROUND RUN-UP SUPPRESSORS

Volume 1: Measurement and Analysis of Acoustical Performance

NORMAN DOELLING
RICHARD H. BOLT

AND
THE STAFF OF BOLT BERANEK AND NEWMAN INC.

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FOREWORD

This report was prepared by the firm of Bolt Beranek and Newman Inc. under Contract Nos. AF 33(616)-3335 and AF 33(616)-3938, for the Bioacoustics Branch in support of Project 7210, "The Generation, Propagation, Action and Control of Acoustic Energy," Task 71708, "Reception, Transmission and Reduction of Acoustical Energy by Structures." Mr. R. N. Hancock was the task engineer. Technical supervision of the preparation of this report was the responsibility of Mr. R. N. Hancock, Capt. L. O. Hoeft, and Dr. H. E. von Gierke, Chief, Bioacoustics Branch, Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

This is the first of three volumes concerning physical aspects of noise control in aircraft engine test cells. Volume 2 deals with design and planning for noise control and volume 3 presents a technical justification for many of the procedures described in the first two volumes, where justification is not found elsewhere in the literature of acoustics. The first of these studies was initiated in 1955 and the third was completed in 1959.

The suggestions and criticisms of Mr. A. C. Pietrasanta of Bolt Beranek and Newman Inc. and Capt. L. O. Hoeft have been of great help in preparation of this report.

The WADC technical report number identifying this series of documents was assigned by Wright Air Development Center before it was redesignated Aeronautical Systems Division.

A companion report, technical documentary report number AMRL-TDR-62-134, Influence of Noise Control Components and Structures on Turbojet Engine Testing and Aircraft Ground Operation, has been written by Bonard E. Morse and the staff of Kittell-Lacy, Inc., El Monte, California, under Contract AF 33(616)-5789, for 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

ABSTRACT

This volume is the first in a series of three volumes concerned with the physical aspects of noise control in aircraft engine test cells and ground run-up suppressors. This volume presents recommended procedures for the measurement of noise control effectiveness. Three classes of measurement procedures are described. The first class is concerned with the description of the acoustical effectiveness of a facility as a whole. Such descriptions may be used to compare facilities with one another or to determine if a facility has met a given criterion. The second class of measurements is used to determine the most economical way of improving the noise control design of an existing facility. The third class of measurements is used to describe the acoustical effectiveness of individual noise control components.

PUBLICATION REVIEW

This report has been reviewed and approved.

Jos M Quashnock
JOS. M. QUASHNOCK
Colonel, USAF, MC
Chief, Biomedical Laboratory

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Volume One - Measurement and Analysis of Acoustical Performance

SECTION I
INTRODUCTION

The United States Air Force is conducting a program of acoustical evaluations of aircraft engine test cells and aircraft ground run-up suppressors. Under this program, detailed measurements have been carried out on more than twenty test cells and four ground run-up suppressors. The results of the program obtained to date, together with relevant information from other sources, are summarized in three volumes:

1. Measurement and Analysis of Acoustical Performance.
2. Design and Planning for Noise Control[18/]
3. An Engineering Analysis of Measurement Procedures and of Design Data[19/]

These three volumes deal only with the physical aspects of noise control. Information concerning the psychological and physiological problems of criteria for noise control is contained in other Air Force reports[1-6/].

The present volume describes three measurement and analysis procedures that are designed to answer respectively the following three questions:

1. How can the gross acoustical behavior of a test facility be measured in an objective manner so that

it can be compared with other test facilities, and so that the noise field in and around the facility can be described in a quantitative manner?

2. How can an existing test facility design be improved in the most economical manner?
3. What are the noise reduction characteristics of the individual components of a test facility?

The answer to the first question is provided by the measurement of general acoustical performance. This measurement procedure provides gross descriptions of the acoustical effectiveness of a test facility as a unit. No information is gained concerning the performance of individual components. Two sets of measurements are required to obtain information that can be used for comparing the acoustical effectiveness of different facilities. One set of measurements is made around an unsuppressed aircraft or engine, and the other set is made around the same aircraft or engine located in the test facility. The difference between the sound pressure levels (appropriately averaged) obtained from the two sets of measurements describes the noise reduction characteristics of the facility.

A single set of measurements with the engine or aircraft in the test facility is required to determine a quantitative description of the noise field in and around the facility. These measurements can be used to determine the noise exposure to individuals near the facility, to determine the noise levels at distant locations, and/or to determine if a facility is acceptable to a purchaser. Procedures for carrying out and analyzing both sets of measurements are given in Section II. Either one set or both sets may be used depending upon the information required.

The answer to the second question is provided by the measurement and analysis of acoustical balance which is used to determine ways of improving an existing test facility. The results of this procedure show how much noise each major component (e.g., intake, exhaust, walls) of the test facility contributes to the total noise. Once the contribution from each component is determined, it is a simple matter to specify the amount of noise reduction that must be added to each component to improve the performance of the entire facility by a given amount.

The answer to the third question is provided by the measurement of the acoustical effectiveness of noise control components. Several methods of carrying out such measurements are given in Section IV. Selection of an appropriate method will be governed by the information required, the amount and type of measurement equipment available and/or the engine operating time that can be obtained.

Each of these three measurement procedures is presented individually in a self-contained fashion. The reader may select the measurement procedure appropriate to his particular problem without reference to the others.

SECTION II

PROCEDURES FOR THE MEASUREMENT OF GENERAL ACOUSTICAL PERFORMANCE

Aircraft engine test cells and ground run-up suppressors are designed to reduce noise in distant locations, where persons are not directly associated with the facility, and at close locations, where personnel associated with the facility normally work. Measurement procedures for determining general acoustical performance must correspondingly yield information relevant to both of these regions.

The distant-field measurements are designed to provide objective data about the noise reduction characteristics and noise levels in areas surrounding a test facility. The prescribed measurement procedure is applicable to both test cells and to suppressors.

The close-field measurements are designed to provide objective data about the noise reduction characteristics and noise levels in areas where personnel associated with the operation of the test facility may be located. Two measurement procedures are prescribed, one for test cells and one for suppressors, since these facilities present slightly different problems.

A. Distant-Field Measurements

1. General Discussion of Measurement Procedures

General acoustical performance in the distant field of a test facility is described in two ways. One way is called the insertion-loss noise-reduction method. When this method is applied, measurements of sound pressure level* are made around the unsuppressed aircraft or engine in an open field.

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*Sound pressure level (SPL) = 20 $\log_{10} p/0.0002$, where p is the sound pressure in microbars.

Measurements of sound pressure level are then repeated at the same positions relative to the aircraft or engine, when the aircraft or engine is located in the test facility. The difference between the sound pressure levels measured under these two conditions is defined as the insertion-loss noise reduction.

Another method of describing general acoustical performance is by means of measurements of sound pressure level with the engine in the test facility only. These measurements provide a description of the noise field around the test facility.

Each of these methods has certain advantages. The insertion-loss method provides a useful basis for comparing or classifying the general acoustical performance of test facilities in the distant field. Because the same engine is used for both sets of measurements, the noise characteristics of the engine are, for all practical purposes, eliminated as an independent variable.

For many purposes, the noise field around an engine or aircraft in a test facility is of more importance than the noise reduction characteristics of the test facility. The noise levels around the facility must be known for estimating community reaction to noise from the test facility, for estimating speech communication conditions in buildings surrounding the facility, for determining if a test facility is acceptable to a buyer, and for other noise control problems. For such purposes, the noise-field method is a useful description of acoustical performance.

The noise-field method does not provide a good basis for comparing or classifying test facilities because the noise levels at all positions around the facility depend upon the noise output of the engine under test, as well as the noise reduction characteristics of the test facility.

Noise level measurements are prescribed on a circle enclosing the entire facility for both methods of measuring general acoustical performance. The practice of describing general acoustical performance in the distant field by the noise reduction at a single point 45° from the jet stream axis is of limited usefulness. Measurements at 45° alone do not tell enough about acoustical performance. Noise problems may exist at any angle relative to the jet stream axis. If measurements are to be generally useful, they must be made entirely around the test facility, not only at one angle.

The radius of the circle enclosing the test facility has been chosen to be 250 ft. At this distance, the measurement positions are <u>far</u> enough from the facility so that the measured insertion loss is valid for greater distances, but <u>close</u> enough so that atmospheric conditions will not unduly influence the acoustic measurements.*

The measurement positions, procedures, equipment, and the ambient conditions prescribed for both the insertion-loss and the noise-field methods are nearly identical except, of course, that measurements are not made around the unsuppressed engine for the noise-field method. In the following Sections distinctions between the two methods are made only for the few minor cases where they differ.

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* A more detailed account of the reasons for selecting a radius of the order of 250 ft is given in Volume Three of this report.

2. Acoustical Measurements

a. Measurement Positions. The measurement positions for the distant-field evaluation are on a circle whose radius is 250 ft. The center of the circle is located at the exhaust orifice of the jet engine both for the measurements in open field and for the measurements with the engine or aircraft in the test facility. Sound pressure level measurements are made at a height of approximately 6 ft above the ground in equal angular increments of 22-1/2° or less.

The number of measurements required may be cut in half if the test facility is symmetrical about the longitudinal axis of the engine. This will generally be the case for jet engine test cells and for suppressors on single engine aircraft. For large multi-engine aircraft, it will usually be necessary to make measurements around the entire circle. Measurements should be made on the "downwind" side of an axis of symmetry if measurements are made only over a semicircle.

The measurement system should be calibrated before and after the measurements, and as frequently during the measurements as is possible. The calibration must be made with an acoustic source which generates a known sound pressure level at the microphone. An electrical calibration of the sound level meter and octave band analyzer is not sufficient.

b. Measurement Equipment. Only a sound level meter and an octave band analyzer are essential for the acoustical measurements. The sound level meter and the octave band analyzer should meet the specifications set forth in the "American Standard for Sound Level Meters" Z24.3-1944, and "American Standard for an Octave Band Filter Set" Z24.10-1953, published by the American Standards Association, Inc., 70 East 45th Street, New York 17, New York.

The tolerances allowed in the above specifications are relatively large. If measurements by the noise-field method are being made for the purpose of satisfying an acceptance specification, the requirements for the measurement equipment should be more stringent than those noted here. (See, for example, reference 7.)

The operation of a sound level meter and an octave band analyzer is not discussed here. Anyone not familiar with operation of them should consult any one of References 8, 9, or 10. Measurement techniques and calibration procedures are described in detail in each of these references.

A tape recorder is useful because measurements can be made more rapidly than with a sound level meter and octave band analyzer. However, a tape recorder should never be used unless it has been specifically designed or modified for precision acoustical measurements[11].

Windscreens on the microphone are not necessary since the wind velocity must be less than 5 miles per hour during the measurements (see Section 2-d below).

c. <u>Data Records</u>. Analysis of the data is aided by a complete log of the measurements. The following information should be recorded in a log:

1. Sound pressure levels in octave bands of frequency, at each measurement position.
2. Ambient background SPL's in octave bands of frequency.
3. Engine operating condition.

4. A map of the measuring site, showing measurement locations and prominent geographical features.
5. Wind velocity; ambient temperature and pressure.
6. A schematic diagram of the measurement equipment with each part (including cables and their lengths) identified.
7. A complete list of types and serial numbers of all measurement equipment.
8. Personnel making measurements.

d. Conditions for Acoustical Measurements. The required ambient conditions and engine operating condition for the insertion-loss method and the noise-field method are somewhat different. The required conditions for each are discussed below.

Wind Conditions. Recent studies 12, 13/ show that the influence of wind velocity, wind velocity gradients, and temperature gradients will almost always be negligible at 250 ft from the noise source if the wind velocity, measured at 20 to 40 ft above the ground, is less than 5 miles per hour. Below 5 miles per hour the effects of wind will be negligible except under unusual temperature conditions (a strong temperature inversion). The probability of temperature inversion will be extremely small if the measurements are made slightly before or after sunrise.

Ambient Temperature and Pressure. The mass flow and thrust of a jet engine vary with the ambient temperature and pressure. The variations in mass flow and thrust, in turn, cause variations in the total noise power radiated from the engine. Thus, the total noise power radiated from an engine changes with ambient temperature and pressure 14/. At any location (or altitude) the noise power variations induced by atmospheric pressure fluctuations can be considered negligible, but the variations induced by temperature changes can be significant.

Both sets of insertion-loss measurements should be made within a short period of one another to minimize the effects of temperature changes. Alternatively, the two sets of measurements must be made at approximately the same ambient temperature (i.e., within 20° F).

If the noise-field method is used there are no special limitations on ambient temperature and ambient pressure. However, it must be borne in mind that the sound pressure levels around the test facility will vary with temperature and pressure. The sound pressure levels measured in Denver in August, for example, will not be the same as the sound pressure levels measured in Boston in December, even though the same aircraft engine is used. The difference between the sound pressure levels measured in Denver and Boston can be calculated by the methods given in Reference 14 if the temperature and pressure are reported with the sound pressure level values.

Engine Operating Condition. Measurements of general acoustical performance should be made at military power and at maximum afterburning condition for insertion-loss and noise-field measurements.

If the measurements are made to satisfy an acceptance specification, it is necessary that the measurements be made at the operating conditions stated in the specification. However, if engine operating time is severely limited at high power ratings, the insertion-loss measurements may be made at about 95% of maximum engine operating condition without a significant change from the values obtained at military power.

If engine operating time at afterburning condition is limited, measurements can be made at only a few of the distant-field measurement positions. For example, measurements could be made at 0°, 90° and 135°. These data can be compared with the data obtained at military power to determine roughly the change in the noise field between military power and afterburning.

3. Analysis and Presentation of Data

a. Immediate Evaluation of Data in the Field. Before leaving the measurement site, the data should be reviewed to assure that no errors have been made in reading the instruments. Errors that are integral multiples of 10 are easily made when using a sound level meter and octave band analyzer. A useful way to find such errors is to plot the sound pressure levels in octave bands of frequency as a function of angle about the engine. Errors can then sometimes be noticed as an unusually large change in SPL, which occurs in only one octave band at only one measurement position. The measurement should be repeated if there is any doubt when reviewing the plots of sound pressure level versus angle.

b. Presentation of Data. In some cases, the measured data will be influenced by obstacles within or near the 250 ft circle. If these obstacles are not parts of the test facility or aircraft, then the reported data should not reflect the effects of the obstacles. In Appendix A, some methods for dealing with the effects of obstacles upon the measured data are presented. If obstacles exist, then the data should be corrected or eliminated according to the methods outlined in Appendix A before proceeding with the presentation of data.

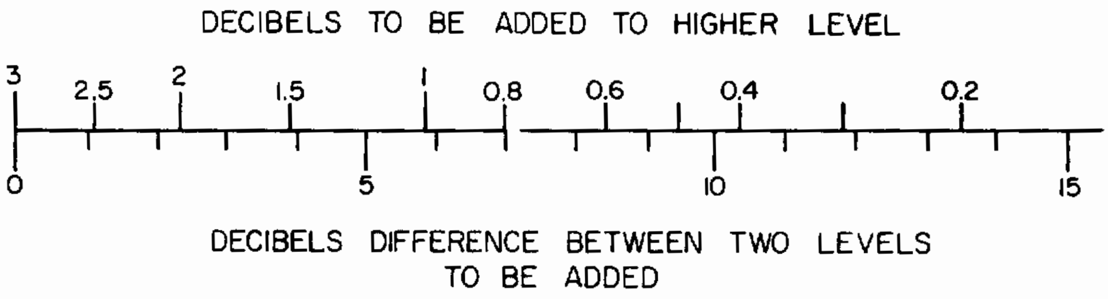
There are several methods of presenting data. For noise field measurements, a plot of sound pressure levels versus angle from the jet stream in each octave band provides information about distant-field noise conditions from which sound pressure levels at other distances can be found (see Section 4 below). These plots should preferably be made on a rectangular-coordinate system and not on a polar-coordinate system.

For insertion-loss measurements, the noise reduction in octave bands is presented as a function of angle around the aircraft. These data provide a description of the distant-field noise reduction characteristics of the facility. The insertion loss at each angle is found by subtracting the sound pressure levels measured with the suppressor in place from the sound pressure levels measured without the suppressor.

The plots of sound pressure level or noise reduction as a function of angle in each of the eight octave bands may be used in the solution of many noise control problems. However, the large amount of information contained in these graphs makes rapid comparison or classification of test facilities somewhat difficult. Certain averaging techniques are therefore recommended to obtain more easily used descriptions of general acoustical performance.

The average value of sound pressure levels at various measurement positions is found from the sound pressures that correspond to the average sound intensities at these positions, as follows:

1. Convert each measured sound pressure level to sound pressure, p, in dynes/sq cm;
2. Square the resulting sound pressures;



NOTE: ADD LEVELS TWO AT A TIME.

FIG. I LINE CHART FOR THE ADDITION OF SOUND PRESSURE LEVELS ON AN INTENSITY BASIS.

3. Find the average value of the squared sound pressures, $\overline{p^2}$;

4. Take the square root of $\overline{p^2}$;

5. Calculate the average sound pressure level in db re 0.0002 dyne/cm^2 from SPL = 20 $\log_{10}$ $(\sqrt{\overline{p^2}}/0.0002)$ db.

This process can be more simply accomplished by use of Fig 1. The average sound pressure level is found by adding the sound pressure levels by use of Fig 1 and then subtracting 10 $\log_{10}$ (n), where n is the number of measurement positions in the angular range over which data is to be averaged.

An average sound pressure level over the entire circle provides an adequate description of the noise field around most engine test cells. The average noise reduction, obtained from the average SPL's around the entire circle, provides an adequate description of the noise reduction characteristics of the test cell in the distant field. This average noise reduction is roughly a measure of the decrease in the total noise power radiated from the engine towards surrounding areas.

The average sound pressure level over the entire circle can provide a description of the noise field or noise reduction characteristics that is adequate for gross classification of ground run-up suppressors. However, the noise field around certain types of ground run-up suppressors may be quite directive. As a result, the sound pressure level averaged over the entire circle (or the average noise reduction over the entire circle) may not provide a meaningful approximation to the sound pressure level (or noise reduction) in many angular ranges. For example, a run-up pen may provide a large noise reduction in some areas and no noise reduction in other areas. The noise reduction averaged over the entire circle may be zero, although the average noise reduction in a large angular range may be about 20 db.

The averages for ground run-up suppressors are, therefore, made over angular ranges less than 360°. The average SPL and the average noise reduction taken over two angular ranges, 0° to 90°, and 90° to 180° from the nose of the aircraft, have been found to provide useful measures of general acoustical performance for engineering purposes. The averages in octave bands of frequency for the two angular ranges aid in rapid comparison and classification of test facilities and in the solution of many noise control problems.

In summary, the noise reduction and the noise field around most engine test cells can be adequately described by an average over the 250 ft circle. For ground run-up suppressors, these averages should be supplemented by averages over the angular ranges from 0° to 90° and from 90° to 180°. It must be remembered, however, that information which might be needed to solve a particular problem is lost in the averaging process. Therefore, a complete report on the general acoustical performance in the distant field should include plots of SPL or noise reduction as a function of angle in octave bands of frequency as well as the average values.

4. Relation of Measured Data to Acoustical Requirements at Other Locations

The noise reductions measured at 250 ft will generally be equal to the noise reductions at other distances. In fact, one reason for selecting a 250 ft radius was so that the noise reduction would be independent of distance beyond 250 ft.

The acoustical analysis of a noise problem may give, as an end result, maximum allowable sound pressure levels at some other distance, R. Figure 2 shows noise levels at a distance, R, relative to the levels at 250 ft. This figure can be used to translate the SPL requirement at R to the corresponding requirement at 250 ft or conversely to find the SPL at R when the SPL at 250 ft is known.

B. Close-Field Measurements

1. General Discussion

Close-field measurements of general acoustical performance are designed to measure the performance of the test facility at positions normally occupied by personnel associated with the aircraft or engine. Because crew positions in engine test cells and around ground run-up suppressors are very different, it is necessary to present two procedures for close-field measurements; one for test cells and one for ground run-up suppressors.

The noise-field method of measuring general acoustical performance in the close field is usually used to obtain data relevant to speech communication conditions or relevant to the total noise exposure of personnel with reference to the possibility of damage to hearing.

Selection of appropriate measurement positions is simple for test cells, because the crew positions there are well defined. The selection of appropriate measurement positions for ground run-up suppressors is more difficult, and necessarily somewhat arbitrary, because crew positions are not well defined. In the close field, sound pressure level measurements are made on a rectangle which encloses the aircraft in order to provide a description of the average noise levels in the general area

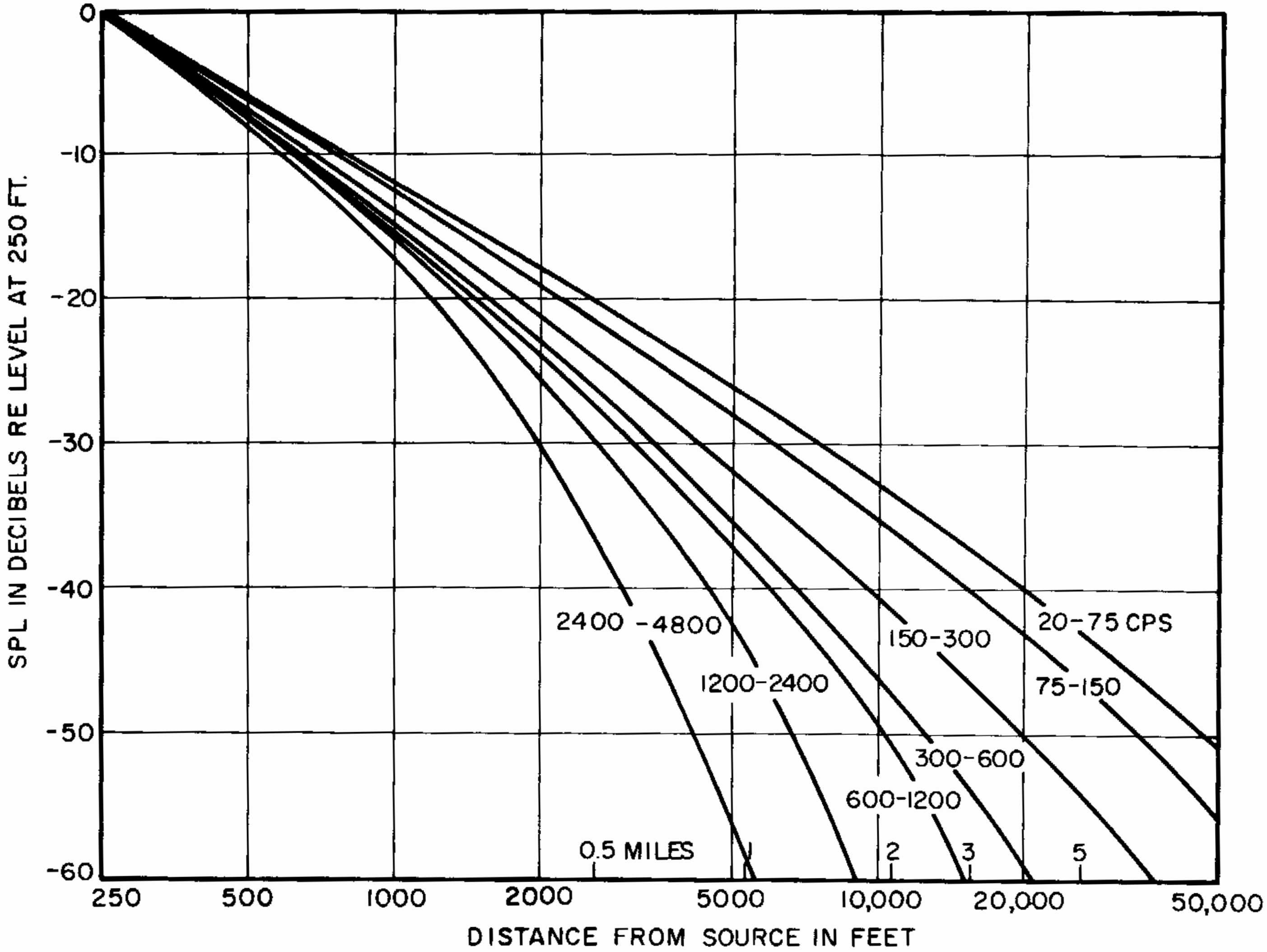


FIG.2 CONSERVATIVE VALUES OF REDUCTION OF SOUND PRESSURE LEVEL WITH DISTANCE FOR JET AIRCRAFT OPERATING ON THE GROUND TEMPERATURE GRADIENTS AND WIND SPEEDS ARE ASSUMED TO BE VERY LOW.

in which personnel associated with operation of the aircraft may be located. In addition, measurements should be made at those positions where personnel may be located while carrying out routine trimming or maintenance operations.

Insertion-loss measurements are also made in the close field of ground run-up suppressors for the purpose of providing objective data for comparing suppressors with one another. Average noise reductions similar to those defined for the distant field are also used in the close field.

For jet engine test cells, the insertion-loss method of determining general acoustical performance is of limited usefulness. Therefore, the noise-field method must also be used for comparing the close-field acoustical performance for test cells. A method of using the noise-field description for the purpose of comparing test facilities with one another is given in Section 3b below.

2. Acoustical Measurements

a. Measurement Positions. The measurement positions in control rooms of engine test cells are described in the first section below. The measurement positions near jet aircraft are described in the second section below.

Measurements in Control Rooms. Sound pressure level measurements are made at each operator's normal working position in the control room. The operator should not be at his position during the acoustical measurements.

Measurements around Ground Run-up Suppressors. Sound pressure level measurements are made at the positions indicated in Fig 3. The microphone should be held at a height of about 6 ft above the ground. If the suppressor is symmetrical about

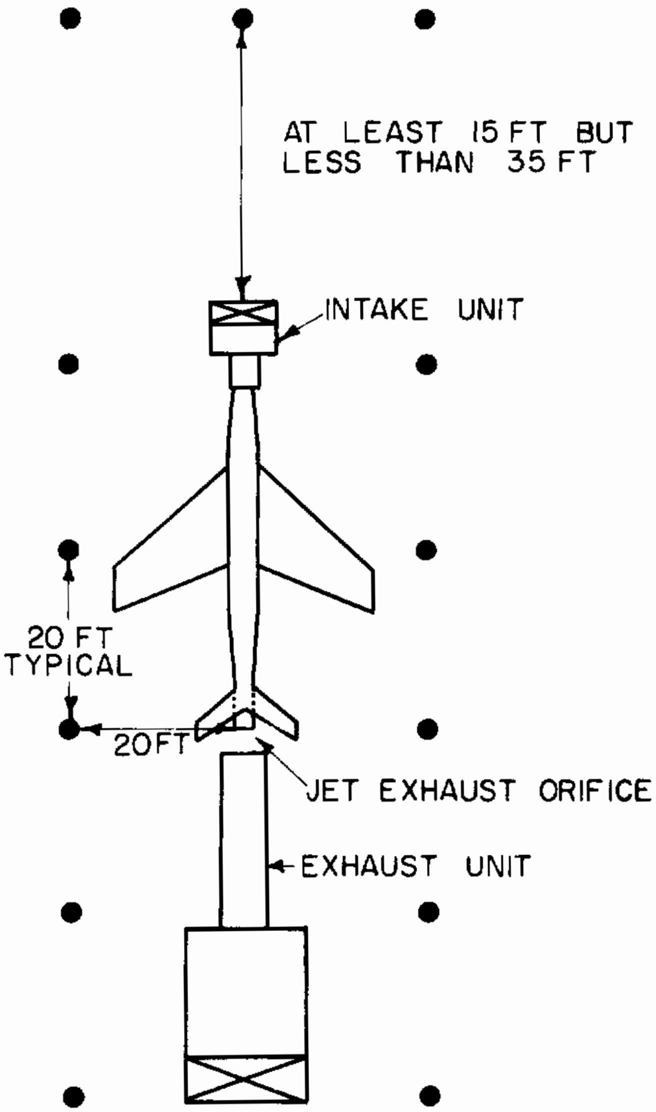


FIG. 3 CLOSE - FIELD MEASUREMENT POSITIONS.

the longitudinal axis of the suppressor and the aircraft, measurements need be made only on one side of the measurement rectangle.

b. Measurement Equipment. The measurement equipment used for the close-field measurements, both for test cells and suppressors, is identical to that needed for the distant-field measurements. The measurement equipment is discussed on page 7.

c. Data Records. Data records for the close-field measurements are the same as those for the distant-field measurements (see page 8).

d. Conditions for Acoustical Measurements. The conditions for the acoustical measurements are similar to those required for the distant-field measurements. However, there is no restriction on maximum wind velocity for the close-in measurements because sound propagation will not be influenced by the wind velocity and wind velocity gradients over the short distances involved. The influences of ambient temperature, ambient pressure, and engine operating condition are the same as those discussed for the distant-field case.

3. Analysis and Presentation of Data

a. Immediate Evaluation of Data in the Field. Before leaving the measurement site, it is helpful to plot the sound pressure levels as a function of octave bands of frequency. Such plots may aid in determining whether errors have been made in reading the measuring instruments. Errors can sometimes be detected by noting an unusual peak or dip (of the order of 10 db or more) in the octave band spectrum. If any unusual spectra occur, the measurements should be repeated before leaving the measurement site.

b. Presentation of Data. The data presentation for test cell evaluation is slightly different from those for ground run-up suppressors. Test cells are covered in the first paragraph below and ground run-up suppressors in the second.

Test Cells. The sound pressure levels in octave bands of frequency at the several engine operator's positions provide an adequate description of the acoustical conditions in the control room for the noise-field method.

If the data are to be used for classifying test cells, then the several sound pressure levels should be averaged by the method used for finding average SPL's in the distant field. The average sound pressure level by itself does not provide a useful basis for comparing facilities. The average sound pressure level depends upon the power level (PWL)* of the engine under test, as well as the noise reduction characteristics and the geometry of the test facility. If the power level of the engine** is reported along with the average sound pressure level, then average sound pressure levels can be compared by adjusting the sound pressure levels by the power level differences.

For example, suppose an average sound pressure level of 60 db exists in the control room of test cell A, in which the engine under test has a power level of 170 db re 10^{-13} watt. In test cell B, the power level of the engine is 175 db and the average sound pressure level in the control room is 55 db. If the power level of the engine in test cell B were equal to the power level of the engine in test cell A, (170 db), then the average sound pressure level in test

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* PWL = $10 \log_{10} W/10^{-13}$, where W is the acoustic power in watts.

**See Volume Two, Appendix A, for methods of calculating PWL from engine operating parameters.

cell B would be only 50 db. Therefore, test cell B is 10 db more effective than test cell A.

Ground Run-up Suppressors. The sound pressure levels in octave bands of frequency at all measurement positions on the measurement rectangle and at appropriate crew positions should be reported. These data provide basic information for determining the noise exposure of personnel in the vicinity of the aircraft.

A description of the noise field that includes all of the individual data points is unwieldy and contains somewhat redundant information as sound pressure levels in some areas are nearly equal. Therefore, it is useful to resort to averaging techniques similar to those used for the distant-field data.

The noise field can be described by an average SPL over two areas. One area includes the positions directly opposite, and to the rear of, the tailpipe (aft positions). The other area includes the two positions opposite the tailpipe, and all positions forward of the tailpipe (forward positions). The average value of SPL's in these areas is found by the same method used for averaging sound pressure levels in the distant field. The average value of sound pressure level in octave bands in these areas describes the noise field at the operator's positions.

The average insertion loss in each of these two areas can be used for the purpose of comparing the close field general acoustical performance of ground run-up suppressors. The average insertion loss is found from the difference in the average sound pressure levels with and without the suppressor attached to the aircraft.

SECTION III
PROCEDURES FOR THE MEASUREMENT AND ANALYSIS OF ACOUSTICAL BALANCE

A test facility is said to be acoustically balanced in its noise control design if all major noise sources (air inlets, exhaust gas outlets, walls, etc.) contribute equally to the total noise at the receiving points for which the noise control is required. An acoustically balanced design is usually sought after because noise reduction requirements are usually met most economically by a design which is at least approximately balanced (see Volume Two of this report).

Improvement of an existing facility is also guided by the principle of acoustical balance. An analysis of the acoustical balance of a particular facility may show, for example, that the noise from the exhaust gas outlet is 15 to 20 db above the combined noise contributions from all other noise sources. In that case, it would be possible to improve the general acoustical effectiveness by 15 db, simply by adding acoustical treatment to the exhaust gas outlet only, rather than to all the noise sources. Thus significant savings in cost could be effected by performing the measurement and analysis of acoustical balance before attempting to improve the facility.

Procedures for the measurement and analysis of distant-field acoustical balance are presented in Part A. Acoustical balance in the close field is discussed in Part B.

A. Measurement and Analysis of Distant-Field Acoustical Balance

1. Basis for Selection of Recommended Procedures

Acoustical balance could be analyzed directly if it were possible to measure the contribution from each source of noise independently, with all others turned off. This direct approach could be used to intercompare different facilities, such as adjacent test cells, by operating only the test cells one at a time. The several "secondary noise sources" (e.g., intake, exhaust and walls) of a particular facility, however, all radiate noise that originates from the engine under test in that facility. An indirect approach is therefore necessary.

The method described here is, briefly:

1. To make certain specially prescribed measurements near each secondary source;
2. To obtain, using the results of these measurements, an approximate determination of the noise power of each secondary source;
3. To calculate, using these power determinations, the expected average SPL's on a circle surrounding the test facility;
4. To sum the average SPL's from each secondary source to obtain the total average SPL;
5. To measure the average SPL's that exist on the circle surrounding the test facility.

Neither this method nor any other practical method can, in principle, yield an absolutely unambiguous result, because of interactions between the noise sources, as discussed below. In practice, however, this recommended procedure has been shown to give adequately accurate results; and it is the most straightforward and reliable procedure that has been found for this type of acoustical balance analysis.

The above outlined procedure involves the energy flow system shown in Fig 4. The separate paths (1, 2, 3) and

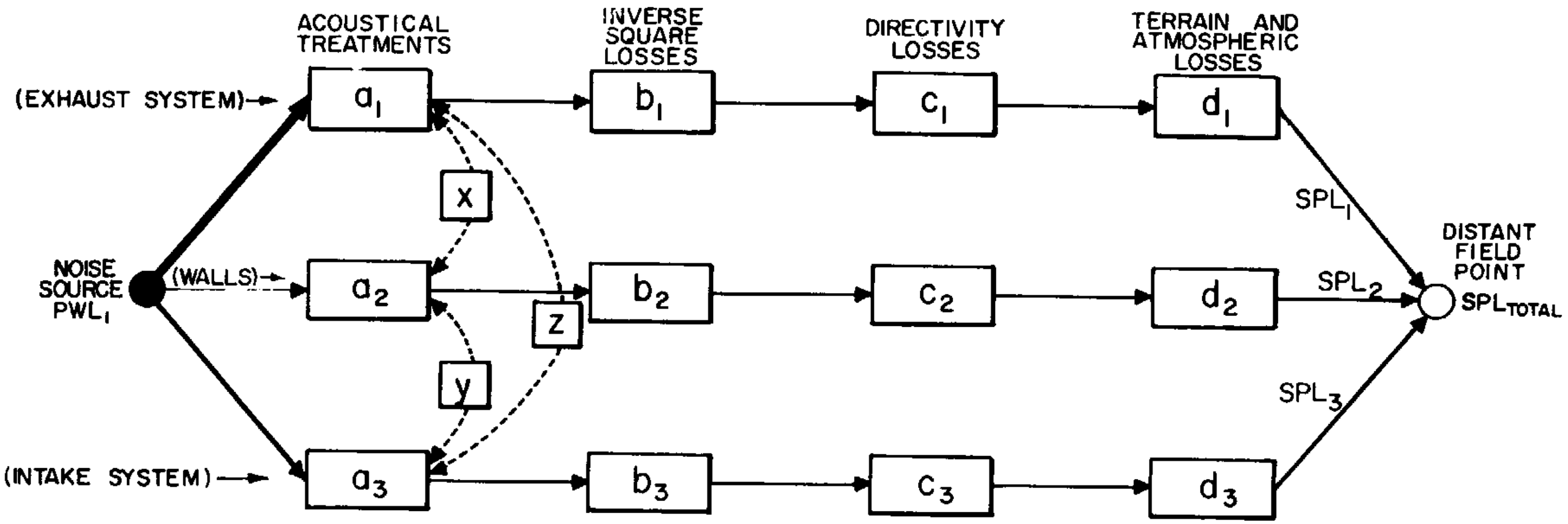

FIG. 4 A SIMPLIFIED DIAGRAM OF NOISE ENERGY FLOW OVER SEVERAL PATHS BETWEEN A NOISE SOURCE AND AN OBSERVER.

noise reduction elements (a_1, a_2, a_3) correspond to the separate secondary sources of noise. The elements designated x, y and z represent the noise reduction on some of the interaction paths for transmission of noise from one source to another. Along these paths the sound pressure levels may be reduced by such effects as inverse-square loss, directivity and shielding.

In terms of Fig 4, the purpose of the acoustical balance study is to determine the distant-field contributions SPL_1, SPL_2, SPL_3, etc. of the several secondary sources. Only the sum of these contributions, SPL_{total}, can be measured directly. The nth contribution must be obtained from the formula:

$$SPL_n = PWL_n - b_n - c_n - d_n, \qquad (1)$$

in which PWL_n is the power level of the nth source, b_n is the inverse square loss over the nth path, c_n is the directivity loss over the nth path, and d_n is the loss attributable to terrain and atmosphere.

An important feature of the recommended procedure is the selection of a standardized distance from the primary noise source (the engine under test) to the distant-field points. A distance of 250 ft has been chosen. At this distance the values of d_n are negligible, and the values of b_n are substantially the same (about 56 db) for all sources (see Volume Three, Section VI).

If the distance were much greater than 250 ft, the atmosphere and terrain losses d_n would need to be included in Eq 1. Since these losses vary with weather conditions and with topography, their inclusion considerably complicates the analysis. If the distance were much less than 250 ft, the inverse square losses b_n would be significantly different for the different sources of a given facility. In fact, different parts of any one source (a wall, for example) might lie at substantially different distances from the field points, in which case the inverse square loss must be calculated by more complicated methods.

The single-value simplification for b_n is valid only if no part of any noise source is more than about 75 ft (in plain view) from the engine. For distances between 75 and 125 ft, the procedure may be used with caution. If any source is more than 125 ft from the engine, the procedure described here should not be used.

The power level of each secondary source is found from measurements of SPL over each source and from Eq 2 below:

$$PWL_n = SPL_{av_n} + 10 \log_{10} A_n \qquad (2)$$

where SPL_{av_n} is the average sound pressure level* over the nth source and A_n is the area of the nth source in sq ft. This formula is applicable only under certain conditions, all of which will not be fulfilled during the measurements. Nevertheless, the relationship will be adequate for our purposes if, at least, it can be assured that the SPL measured at the nth source is radiated from the nth source and not from some other source. That is, the terms x, y, and z, must be great enough so that the measured SPL at a source is due to noise radiation from that source only.

When the conditions outlined above are satisfied, the average sound pressure level on the 250 ft circle caused by

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* See pages 12-14.

the nth source, SPL_n, is:

$$SPL_n = SPL_{av_n} + 10 \log A_n - b_n - c_n \qquad (3)$$

Thus, the analysis of design balance consists of measuring the average SPL over each source, SPL_{av_n}, and the area of each source, A_n, and calculating the inverse square loss, b_n, and the directivity index for the source, c_n.

The total value of average sound pressure level on the 250 ft circle is found by summing the SPL_n's by use of Fig 1. The sum of the contributions of the n sources should equal the average value of SPL measured on the 250 ft circle.

Measurements are made to determine the average SPL at 250 ft from the test facility. These measurements are described in Section II, page 7. If the analysis is correct, the sum of the contributions from each of the sources at 250 ft will equal the measured SPL. However, the equality of the measured and calculated SPL's does not guarantee that the analysis is correct. The possibility of compensating errors, which may cause an equality, cannot be excluded. In the language of the mathematician, equality is a necessary, but not sufficient, condition for an accurate determination of the contributions from the various sources.

2. Acoustical Measurements

a. Measurement Positions.

At Air Inlets. A test facility has one or more air inlets. In some facilities a single air inlet is used for both the primary, or combustion air, and the secondary, or cooling air. In other facilities, there are separate air inlets for the primary and secondary air. The acoustical measurement problems associated with the various air inlets are the same and no distinction need be made between them.

Several measurement positions must be used over an air inlet in order to obtain a useful approximation (within 2 to 3 db) of the average SPL over the opening. The number of measurement positions will depend upon the area of the inlet, which may vary from about 10 sq ft for an aircraft without a combustion air inlet muffler to 600 sq ft for a large test cell. Two measurement positions are recommended for areas up to 10 sq ft, 4 measurement positions for areas from 11 to 400 sq ft and 6 measurement positions for areas larger than 400 sq ft. The location of these measurement positions is not critical. In general, a symmetrical pattern of measurement positions should be avoided, but at the same time the measurement positions should not be crowded into one particular area.

If there is acoustical treatment located in the plane of the intake openings, measurements should be made in a plane about 2 ft away from the acoustical treatment. When the microphone is held 2 ft away from the acoustical treatment, wind noise (see Section 3 below) at the microphone is lower than when the microphone is close to the treatment.

When the microphone is held 2 ft away from the treatment, the radiating area of the source (used in the PWL computations) is taken to be the entire cross section of the air inlet and not just the open area between the acoustical treatments.

<u>At Exhaust Gas Outlets</u>. Acoustical measurements in the plane of an exhaust gas outlet are complicated by the high temperature (250° F to 600° F) and high velocity (150 to 400 ft/sec) of the exhaust gases. Measurements can be made

directly in the exit plane of an exhaust gas outlet only with very special equipment designed for this purpose. If such equipment is available*, then the measurements are similar to those described above. They are different only in that measurements should be made directly between the acoustical treatments rather than 2 ft away. At the exhaust, the wind noise at the microphone will be lower if the microphone is located just inside of the acoustical treatment.

If special measurement equipment is not available, it is necessary to make the acoustical measurements outside of the hot gas stream and to estimate from these measurements, the power level at the exhaust exit plane. The Aircraft Manufacturers Association's EN-1 positions[15] can be used as measurement locations outside of the exhaust gas stream. For jet-engine test cells, these positions are defined as follows: "The microphone should be located in a plane perpendicular to the axis of the sound-proofing exit (referred to as the emitter) at a distance of one emitter diameter from the emitter plane and at a radius of one emitter diameter from the emitter center line. Measurements should not be made at a distance less than 14 ft or more than 50 ft from the center of the emitter. (The emitter diameter of an eliptical (sic) or rectangular opening shall be the minor dimension.)"

The definition describes a locus of points on a circle around the exhaust outlet. Several measurement positions on this circle are necessary to determine the average SPL because the noise field around a rectangular opening is generally not uniform. It is recommended that at least two

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*To the author's knowledge, no high temperature measurement equipment is commercially available. A condensor microphone can be used if its preamplifier and cables are thermally insulated.

measurement positions be used to determine the average SPL on the "EN-1 circle". The measurement positions should not be immediately adjacent to one another, nor 180° apart. If two measurement positions are used, they should be about 90° apart. If three positions are used, they should be about 120° apart.

At Walls. The recommended measurement positions at walls of test cells are shown in Fig 5. Three measurement positions are located on the side of the test section and three measurement positions are located on the side of the exhaust section. The test section and the exhaust section will usually be separated by a wall, but if no wall exists, the dividing line between exhaust and test section may be taken to be the middle of the eductor tube. The measurements should be made at a height of about 4 to 6 ft above the ground and at a distance of no more than 1 ft from the test cell wall. It is desirable to have the measurement positions near the wall so that the test cell structure will provide acoustical shielding of the measurement position from the intake and exhaust gas openings.

The measurement positions should be located at approximately equal intervals over the test section and exhaust section. If, however, there are minor acoustical leaks, such as poorly sealed expansion joints, then care should be taken to avoid measurement positions near the leaks. The close-field SPL may be quite high at the leak, but the contribution from the leak in the distant field will almost always be negligible.

Three measurement positions should be located behind the exhaust stack as shown in Fig 5. One position should be about 6 ft above the ground, one about 6 ft below the exhaust gas outlet and one approximately midway between the other two.

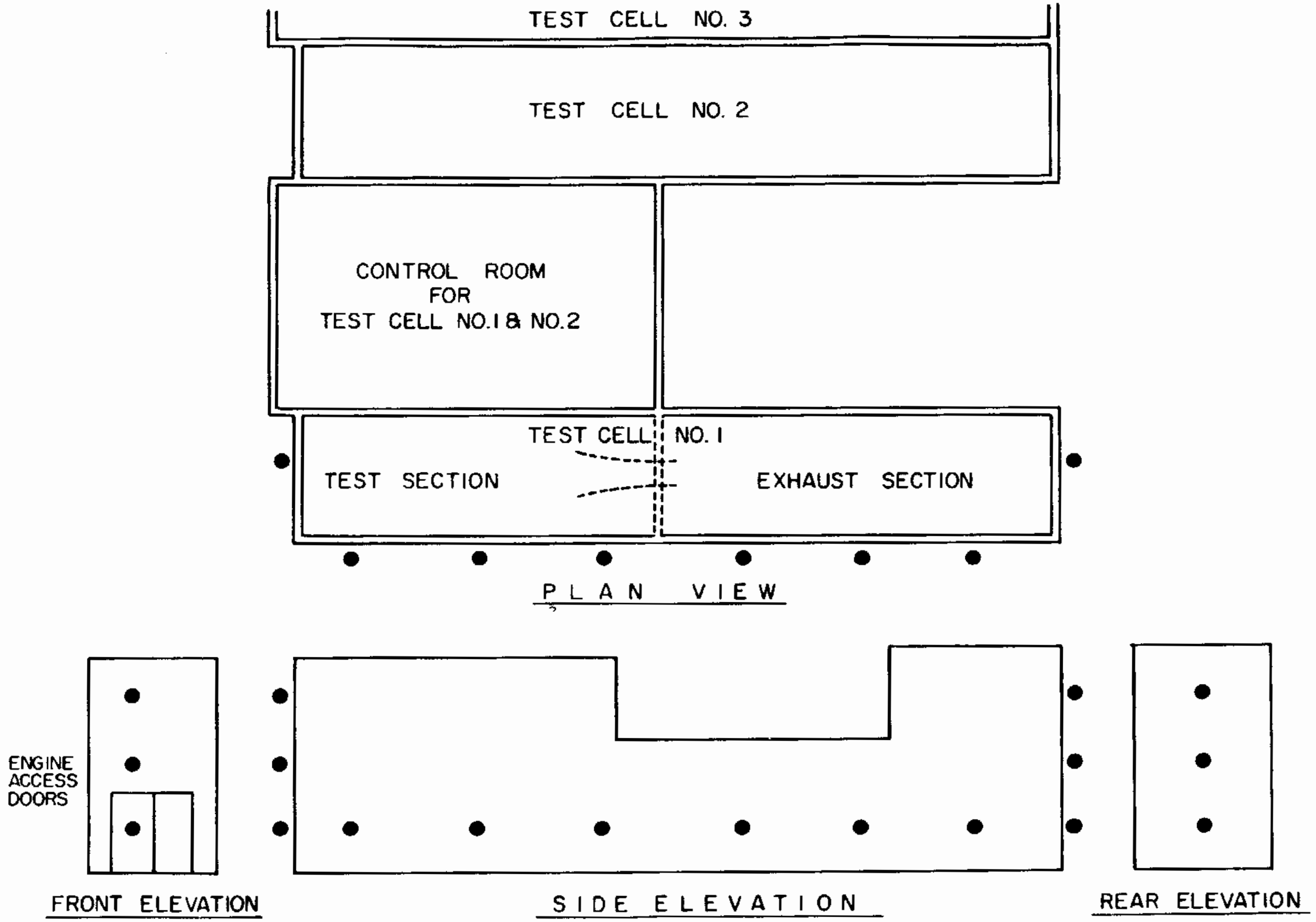

FIG. 5 MEASUREMENT POSITIONS NEAR WALLS OF A TEST CELL.

If the exhaust stack is more than 40 ft high, four measurement positions should be used. The upper and lower positions should be as previously described and the other two should be equally spaced between the upper and lower positions. All measurements should be made within 1 ft of the exhaust stack.

The measurements over the front wall of the test cell should be made in the manner prescribed for the measurements made at the rear of the exhaust. If there appear to be leaks near the engine access doors (which are usually located at the front of the test section) then the measurement positions should be about 2 ft from the doors and should not be located directly in front of meeting stiles. (See front elevation in Fig 5.)

Measurement positions near walls of ground run-up suppressors should be the same as those for test cells, except the measurements near the test section (i.e., fuselage or engine pod) are omitted. If there is no suppressor on the air intake then the front measurements are also omitted.

On a 250 Ft Semicircle. Measurements of SPL should be made on a 250 ft circle centered at the exhaust orifice of the engine. The measurement positions and procedures are completely described in Section II (pages 7 to 10). The measurements are made only on the side of the test facility that faces an open area and not on the side that faces the other test facilities.

b. Measurement Equipment. Acoustical balance studies can be conducted with a sound level meter and an octave band filter* set. However, a tape recorder is very useful, not

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*See Section II, paragraph A2-b (page 8) for some comments relative to the use of the sound level meter and octave band filter.

only because measurements can be made rapidly, but also because averaging SPL over an area is easily accomplished. Data obtained by moving the microphone slowly across the radiating area can be played back into a graphic level recorder (GLR) and the average SPL can be obtained from the GLR record. As mentioned in Section II, a tape recorder should never be used unless it has been specifically designed and modified for use as an acoustical measurement instrument.

A microphone windscreen which reduces aerodynamically induced noise at the microphone must be used for measurements over the intake and exhaust openings. Because windscreens are essential for reliable measurements and because they are not commercially available, plans are included in Appendix B for a simple windscreen. It is not be be inferred that the design presented in Appendix B is the best possible design for this application. Its primary merits are simplicity of construction with readily available materials, and relatively small size.

Use of a windscreen does not guarantee that data obtained in moving air streams are not due to wind noise. However, a simple test can be made to determine if the noise is caused by wind noise or by acoustic signals from the secondary source. A sound pressure level measurement (in octave bands of frequency) is made at a position in the air stream with and without the windscreen. If the noise level is the same with and without the windscreen, the measured SPL's are definitely not wind noise. If the noise level drops more than 15 db*, the measured SPL's both with and without the windscreen are probably wind noise. Any drop in level of less than 15 db indicates

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* The 15 db value is appropriate only for the windscreen shown in Appendix B and for air velocities in the ranges from about 50 to 100 ft/sec.

that wind noise was measured without the windscreen, but that the addition of the windscreen has lowered the wind noise level below the level of the noise radiated from the source.

c. Data Records. To facilitate analysis and evaluation of data, the information listed in paragraph A2-c on page 8 should be recorded in a log book. In addition, a plan, section, and elevation of the test facility that show measurement positions should also be included.

d. Conditions for Measurements.

Ambient Temperature and Pressure. The change in PWL of an engine with ambient temperature and pressure is small compared with the probable errors involved in the acoustical balance study, and may be neglected.

Engine Operating Condition. Acoustical balance varies with engine operating condition. Measurements should be made at or above 95% of maximum compressor revolution rate (e.g., near military power) as the balance at or near military power is usually of primary interest.

Frequently, it is desirable to know the acoustical balance at afterburner condition, but measurements may not be possible at afterburner condition because of limited engine operating time. The approximate changes in levels at the exhaust and intake areas which may occur in going from military power to afterburner condition are presented in Table I. The acoustical balance study may be carried out at military power and the approximate levels at afterburner can be obtained by adding the value shown in Table I to the military power results to obtain the approximate contributions at afterburner.

TABLE I

RELATIVE CHANGE IN NOISE LEVELS AT SECONDARY SOURCES IN GOING FROM MILITARY POWER TO AFTERBURNER

Frequency Band in cps	TEST CELL		GROUND RUN-UP SUPPRESSOR		
	Intake(s)	Exhaust	Intake		Exhaust
			Primary	Secondary	
20-75	0	3	0	5	8
75-150	0	2	0	4	6
150-300	0	1	0	4	5
300-600	0	0	0	4	5
600-1200	0	0	0	4	5
1200-2400	0	0	0	4	5
2400-4800	0	0	0	4	5
4800-10,000	0	0	0	4	5

The numbers given in Table I are estimates based on limited measurements. More accurate results can be obtained by measurements at afterburner condition. If at all possible, the prescribed measurements should be carried out at afterburner condition as well as at military power.

Choice of Test Facility. Usually several test facilities of the same type are located at one place. In order that useful measurements at walls and at 250 ft can be obtained, an"end" test cell or suppressor must be used. Interpretation of measurements near walls is difficult even for an end test cell and is nearly impossible if measurements are made over walls which form one side of a corridor between test cells, as is the usual geometry (see plan in Fig 5).

3. Evaluation and Analysis of Data

a. Immediate Evaluation of Data in the Field. Before leaving the measurement site, it is worthwhile to inspect as much of the measured data as possible. If the SPL's from the several measurement positions over a source opening are plotted on one graph, errors arising from incorrect octave band analyzer readings may be readily apparent. If, in one octave band of frequency, the relative levels at two adjacent positions are very different from the relative levels in the other octave bands of frequency, an error in reading the octave band analyzer has probably been made.

A more serious, and less easily resolved problem is that of determining if the SPL at one source is due to radiation from that source or from an adjacent source. One method of partially resolving this problem is discussed below using primary and secondary air inlets as an illustrative example. The method may also be applied to other pairs of sources. Basically the method consists of measuring SPL's near the boundary of a measurement grid before and after insertion of a barrier and interpreting the resulting changes in SPL.

The measurement positions and the location of the barrier are shown in Fig 6. The barrier should be about 4 ft by 8 ft and should weigh roughly 1 lb/sq ft (a 1/2 in. sheet of plywood will suffice). If the SPL's do not change or if the SPL's increase* slightly when the barrier is inserted, then the SPL's measured over the primary and secondary air inlets result from radiation from those sources respectively. If the SPL on one side of the barrier decreases when the barrier is inserted (SPL_{21} is less than SPL_{20} in Fig 6), and the SPL on the other side increases or does not change (SPL_{11} is equal to or greater than SPL_{10}), then the SPL over one source is probably due to radiation from the other source. In such

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*The SPL's at Positions 1 and 2 may increase when the barrier is inserted because of reflection of sound from the barrier and the resulting constructive interference of the direct and reflected sound waves. Destructive interference is seldom significant.

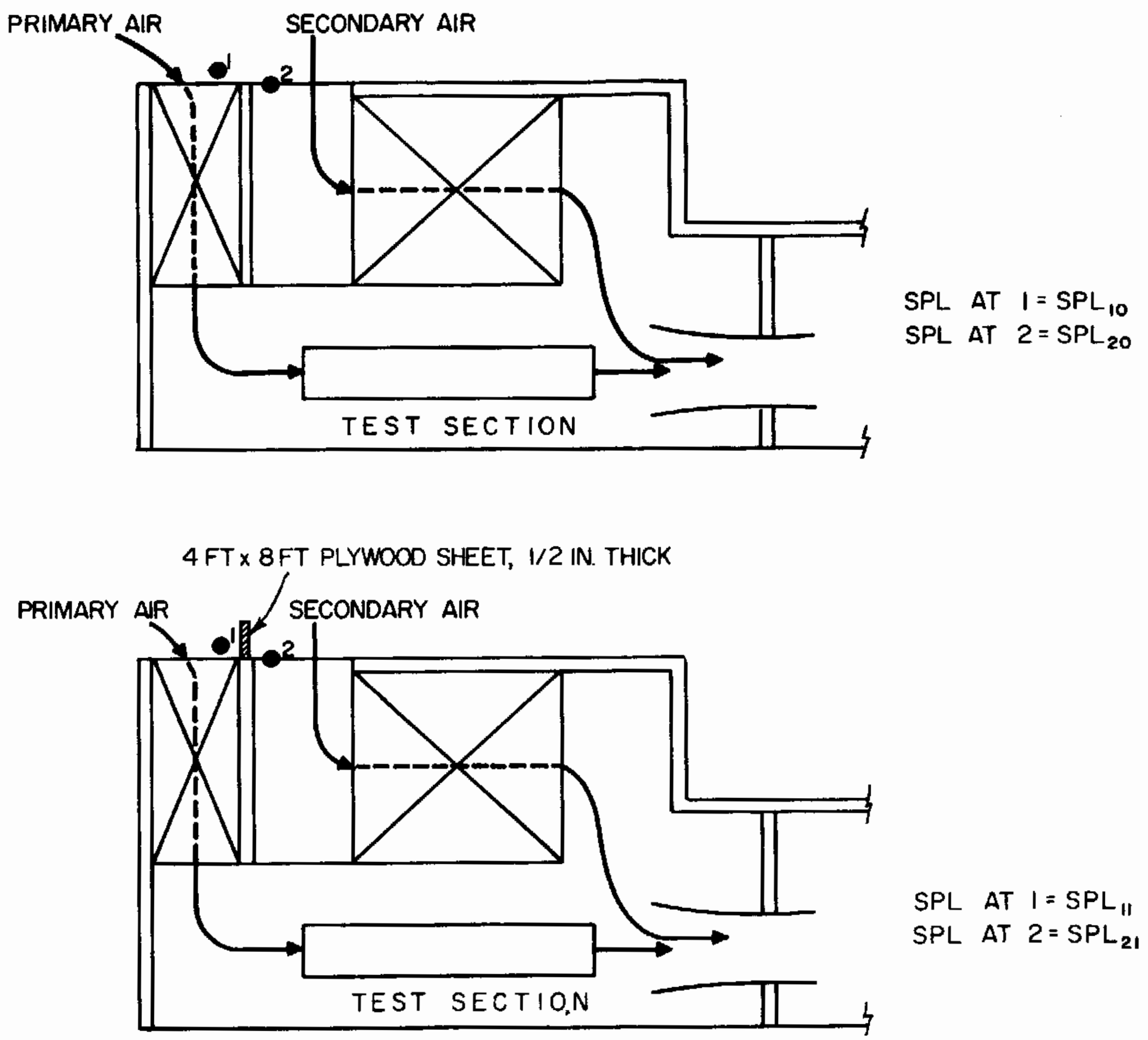


FIG. 6 AN EXAMPLE OF MEASUREMENT POSITIONS USED FOR EVALUATION OF DATA NEAR AIR INTAKE OPENINGS.

case, it is necessary to correct the average SPL over one source. In the specific example referred to in the parentheses, the average SPL over the secondary air inlet would be decreased by an amount (SPL_{20} - SPL_{21}).

The average SPL resulting from radiation from the secondary air inlet may be even lower than this corrected average SPL because it cannot be assured that the SPL measured with the barrier in place, SPL_{21}, results entirely from radiation from the secondary air inlet. Transmission through and around the barrier from the primary air intake may still be greater than the levels radiated from the secondary air inlet. However, if the corrected average SPL is used in the calculations, the design balance study will at least show that the secondary air is a smaller contributor than the primary air, although it cannot be quantitatively determined how much smaller the secondary air contribution is.

b. Evaluation of Data Measured at Test Cell Walls. Identification of those measurements of SPL at walls which are attributable only to radiation from the wall and not from the air inlet or exhaust gas outlet is difficult. In this Section some methods are presented for eliminating some of the grosser errors which might arise from indiscriminate use of the measured data.

One property of concrete walls that is important in the evaluation of the measured data is a low dissipation factor for bending waves. If a noise field excites the wall at some point, noise will be radiated from all parts of the wall because the noise-induced wall excitation propagates freely in all directions with very little dissipation.

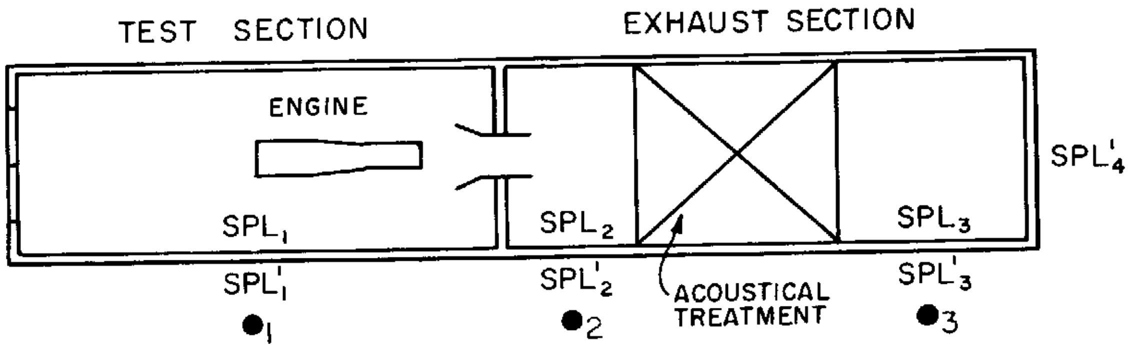


FIG. 7 RELEVANT TO THE EVALUATION OF DATA MEASURED AT TEST CELL WALLS.

Consider, for example, the exhaust section of the test cell, shown in Fig 7. SPL_2 may be very much greater than SPL_3 because of the intervening acoustical treatment. It might be expected then that SPL'_2 would also be very much greater than SPL'_3. Such, however, is not the case. Because the dissipation is low, the vibration amplitude of the wall (which determines the SPL outside the wall) will be nearly the same at Position 3 as at Position 2, hence, SPL'_3 will be very nearly equal to SPL'_2. In the absence of other sources of noise, the SPL over the exhaust section will be nearly uniform. If the noise field varies along the exhaust wall, (or the test section wall), the noise probably results from some source other than the wall.

Therefore, only the lowest of the three SPL's measured over each wall section is used. The procedure does not assure that the SPL that is used is due to radiation from the wall, but any level higher than the lowest is almost certainly the result of radiation from some other source.

A further aid in finding the SPL owing to radiation from the wall only is knowledge of the fact that the loss in vibration energy (and hence sound radiation) is about 3 db at a 90° corner. It is possible to find which level, that at the side exhaust wall or that at the end exhaust wall, is more probably caused by radiation from a wall. For example, suppose the lowest SPL's at the end and side exhaust walls are 90 db and 100 db, respectively. Since the SPL "loss" around the corner should only be 3 db, the SPL radiated from the side exhaust wall can be no more than 93 db. Thus, in this case, the SPL at the side exhaust wall due to radiation from the wall is about 93 db and the SPL at the end exhaust wall is 90 db. If the lowest measured SPL's are reversed (e.g., 100 db at the end and 90 db at the side), the SPL radiated from the side exhaust wall is 90 db and from the end wall, about 87 db.

This scheme presumes that there is acoustical treatment between Position 2 and 3 and that SPL_2 is the primary source of radiation from the walls. If there is no acoustical treatment, then, $SPL_2 = SPL_3$ and $SPL'_2 = SPL'_3 = SPL'_4$. Hence, the lower of the SPL's at the side and end is to be used in the other PWL calculations.

There are also some restrictions on the difference in SPL radiated from the test section walls and the SPL radiated from the side exhaust walls. If there is no wall dividing the test section from the exhaust section, then, $SPL'_1 \doteq SPL'_2$, and the lowest SPL over the entire wall is taken as the SPL radiated from the wall (after first testing the side exhaust wall levels against the rear exhaust wall levels as per above). If there is a wall of thickness comparable to the exterior wall, dividing the test section from the exhaust section, then SPL'_1 is not equal to SPL'_2 in general. If SPL_2 is very much greater (15 to 20 db) than SPL'_1, then SPL'_1 will be 8 db less than SPL'_2. However, if SPL_1 is only a few db less than SPL_2, then SPL'_1 will be only a few db less than SPL'_2. SPL'_1 is estimated to be about 5 db less than SPL'_2 in most test cells.

Thus, for example, if the minimum SPL at the test section is 80 db and the SPL at the exhaust is only 75 db, we would estimate the radiation from the test section wall to be about 70 db (75-5). If, on the other hand, the minimum SPL at the test section were 90 db and the SPL at the exhaust wall were 105 db, we would estimate the levels at the exhaust wall to be only 95 db (90 + 5) instead of 105.

In summary, to find the SPL radiated by the walls, the lowest SPL at each wall section is selected. The SPL's at the rear exhaust wall and the end exhaust wall are compared. Assuming SPL_2 is the major source of noise, the SPL at the side exhaust wall must be about 3 db higher than the SPL at the end exhaust wall. From this comparison, the SPL's at the side and end exhaust walls are found. A comparison is then made of the SPL at the test section and the SPL at the side exhaust wall to see which of these SPL's yields the lower SPL radiated from the walls.

As a summary example, assume the following SPL's have been measured in the 300-600 cps octave band:

Measurement Positions	Measured SPL in db
Test Section	81, 82, 83
Side Exhaust Wall	80, 83, 89
End Exhaust Wall	79, 77, 75

The lowest value on the end wall (75 db) implies that the SPL at the side wall can be no more than 75 + 3 = 78 db. For an SPL of 78 db at the side exhaust wall, the SPL at the test section caused by wall radiation is only 78 - 5 = 73 db. Therefore, take the average SPL as 73 db for the test section wall, 78 db for the side exhaust wall, and 75 db for the end exhaust wall.

c. Evaluation of Data Measured at Suppressor Walls. The evaluation of data measured at suppressor walls is more difficult than evaluation of data at test cell walls for two reasons. First, other secondary sources are usually located closer to all parts of the walls and, second, the propagation of vibration in the wall structures is not as well known. In general, the walls are not flat and do not form a simple geometry. More frequently steel walls that are combinations of cylinders and rectangles are found. Because of the more complex geometry and because of certain vibrational properties of steel walls, we cannot impose as many boundary conditions on the SPL's radiated from the walls as was the case for test cells.

Frequently by observing a decrease in SPL with distance from a source other than the wall, one can at least determine that the levels near the other source probably result from radiation from that source and not from the wall. The lowest SPL at each of the three measurement areas (at the rear of the exhaust, at the exhaust side walls, and in front of the intake) should be used as the average SPL over each of the respective areas.

d. Data Analysis

Calculation of Average Sound Pressure Levels on the 250 ft Measurement Circle. The average sound pressure levels on the 250 ft measurement circle are found by use of Eq 3, which can be written as:

$$SPL_n = SPL_{av_n} + 10 \log_{10} A_n - 56 - DI \qquad (4)$$

where SPL_n is the average SPL on the 250 ft circle due to the nth secondary source,

SPL_{av_n} is the average SPL over the nth secondary source,

A_n is the area of the nth secondary source in square feet,

DI is a directivity index (DI) of the nth source.

The average sound pressure level over each secondary noise source is found by summing the sound pressure levels at each microphone position by use of Fig 1. The average sound pressure level is then found by subtracting 10 $\log_{10} n$, where n is the number of microphone positions.

If measurements are made at EN-1 exhaust positions, the average SPL at the EN-1 positions must be converted to the average SPL at the exhaust gas outlet. The average SPL's at the exhaust gas outlet are found by adding to the SPL's at the EN-1 position 11 db in the octave bands between 20 and 1200 cps, 10 db in the 1200-2400 cps octave band, 9 db in the 2400-4800 cps octave band, and 7 db in the 4800-10,000 cps octave band (see Section 6, Volume Three).

The "average" SPL's at the test section wall, and at the side and end walls are found from the lowest estimated values of SPL as determined from the procedures outlined in Section b above.

At air inlet openings, the area of the radiating surface is taken to be the total cross-sectional area if measurements were made 2 ft above the acoustical treatment. If measurements were made at the exhaust gas outlet just inside of the acoustical treatment, the radiating area is taken to be the total open area between the acoustical treatments. The radiating area shall be taken to be the total area of the exhaust gas outlet if the average SPL there is derived from EN-1 measurements.

The value of the directivity index, DI, will generally be different for each secondary source. The directivity indices for vertical intake and exhaust stacks are given in Figs 8 and 9 respectively. If the test facility has a

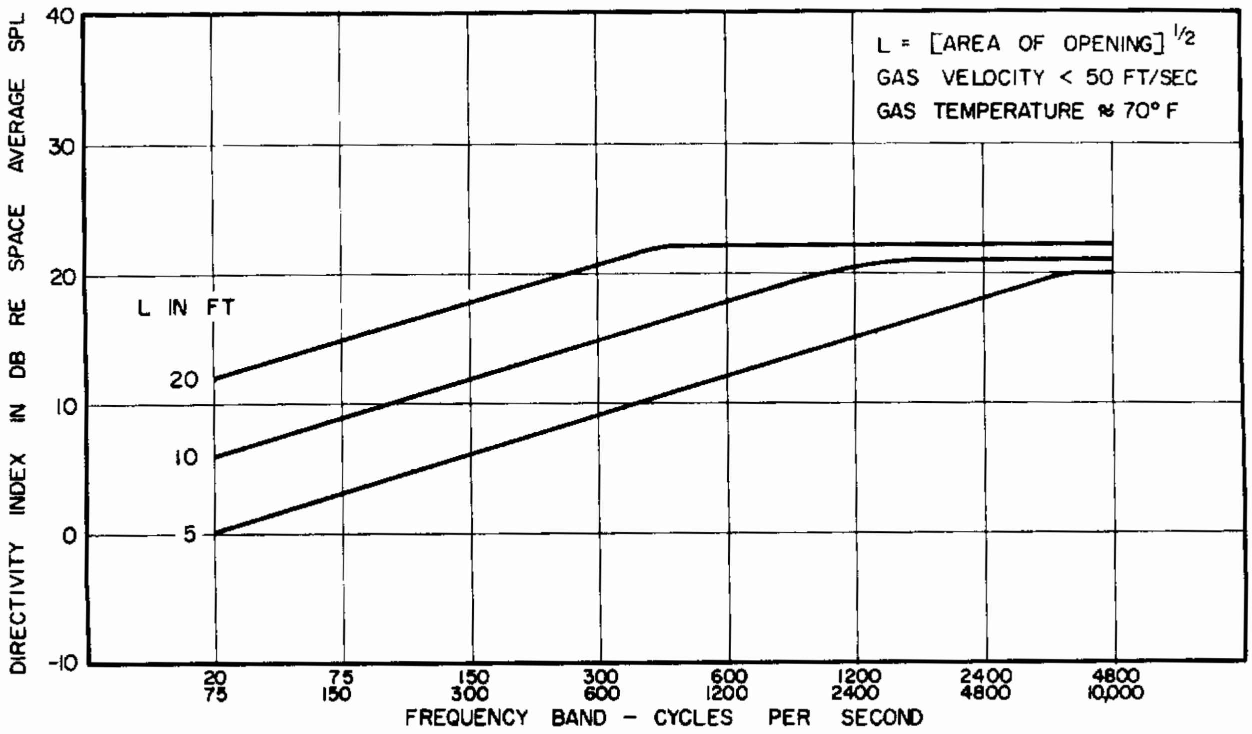


FIG. 8 DIRECTIVITY INDEX IN THE PLANE OF AN AIR INTAKE OPENING.

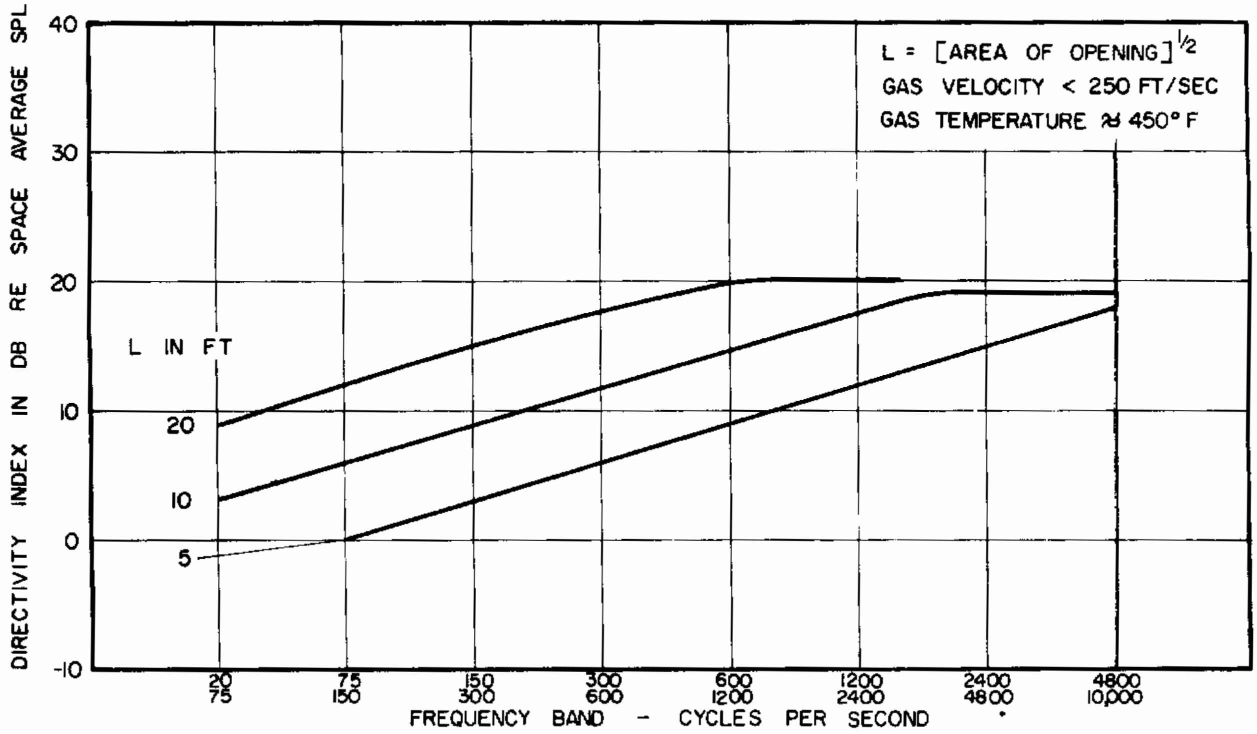


FIG. 9 DIRECTIVITY INDEX IN THE PLANE OF AN EXHAUST GAS OUTLET.

horizontal intake or exhaust, (i.e., the intake or exhaust plane is normal to the ground), then the average directivity index on the 250 ft circle will be zero.

The directivity index for walls is generally zero, but since the walls radiate only toward one side of the cell, a -3 db directivity index should be used.

Comparison of Measured and Calculated Sound Pressure Levels. After the contributions from each source are obtained, the individual contributions should be summed (by use of Fig 1) to obtain the total average SPL on the 250 ft measurement semicircle. This sum is compared with the average SPL obtained from measurements on the 250 ft semicircle. If the various assumptions inherent in the method are correct, the sum of the individual contributions should equal the average SPL obtained from the 250 ft measurements.

Generally, the two sums will not be equal. A 5 db difference is considered reasonable and anything less than a 3 db difference is fortuitous. If the difference between the measured SPL at 250 ft and the sum of the individual contributions is greater than 5 db, then the results cannot be considered a reliable estimate of the various contributions. One may hope that the relative levels of the various contributors is approximately correct, although the absolute levels are not.

If the wall contributions are greater than measured SPL's, they should be disregarded, as they are probably the least reliable of all of the calculated SPL's.

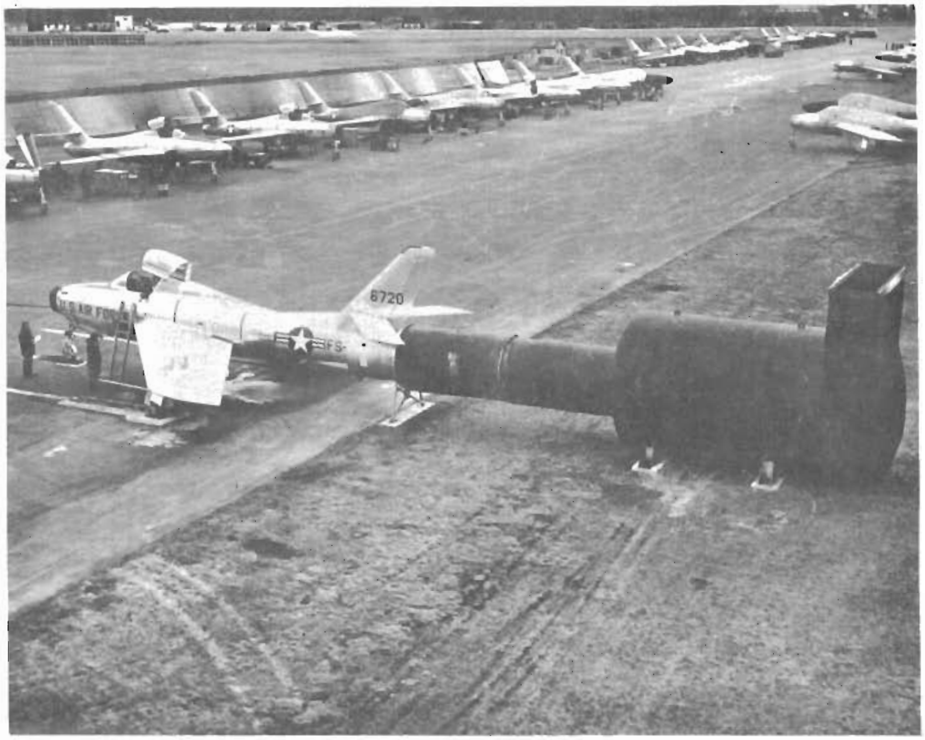
4. Interpretation of the Results of an Acoustical Balance Study

An acoustical balance study will usually be carried out to determine the most economical manner by which a test facility can be improved. Interpretation of the results of the study for this purpose are discussed below. Acoustical balance studies may also be carried out prior to construction of additional test facilities in order to determine if the new facilities could be constructed in a more economical manner. Application of the design balance principles to the design of new facilities are discussed in Section III of Volume Two of this series.

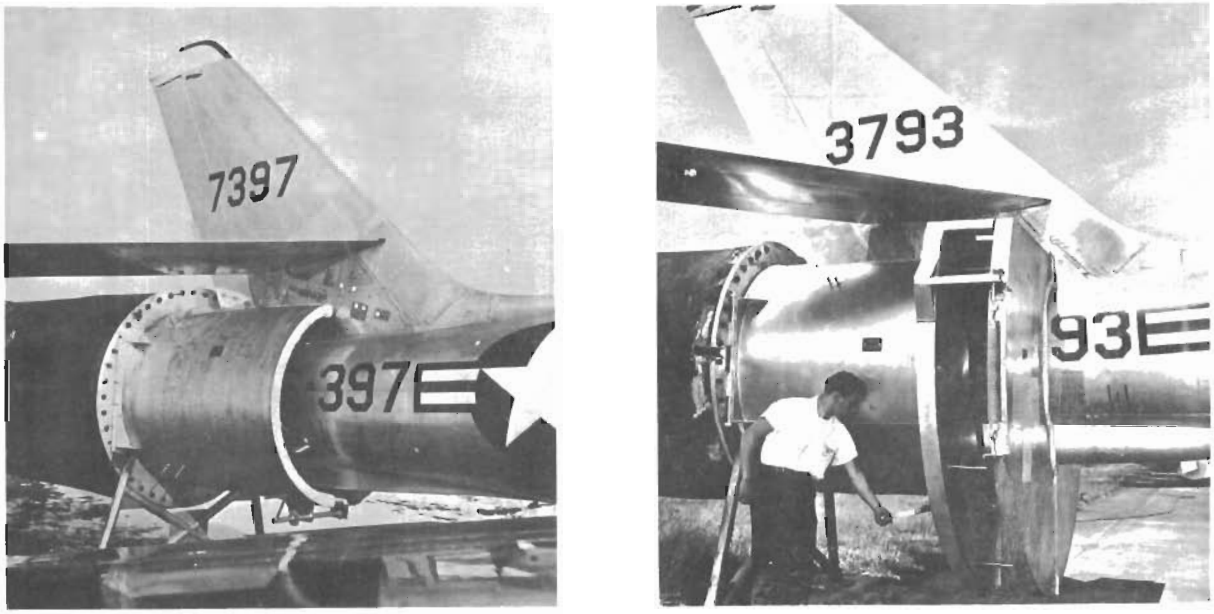
The interpretation of results for improving an existing design can best be presented by an example. The example selected shows not only how the data were analyzed and interpreted, but also how the subsequent modification of the test facility yielded results which were predicted from the original design balance study.

Measurements of general acoustical effectiveness and measurements and analysis of acoustical balance were carried out on a ground run-up suppressor used by the Republic Aircraft Corporation for F84F and RF-84F aircraft. The ground run-up suppressor consists only of an exhaust suppressor containing Durastack acoustical treatment designed by the Industrial Acoustics Company. The prototype model of the muffler is shown in Fig 10a. The coupling section and secondary air inlets of both the prototype and production version are shown in Figs 10b and 10c respectively.

The secondary sources at which acoustical measurements were made are: 1) the primary air inlet in the nose of the F84F, 2) the secondary air inlet, and 3) the exhaust gas outlet. The average measured SPL's for the prototype and the calculations involved in the balance study are given in Table II below for one representative octave band (300-600 cps).



(a) COMPLETE SUPPRESSOR



(b) COUPLING AND SECONDARY AIR INTAKE - PROTOTYPE

(c) COUPLING AND SECONDARY AIR INTAKE-PRODUCTION MODEL

PHOTOGRAPHS COURTESY OF REPUBLIC AVIATION CORP.

FIG. 10 DURASTACK GROUND RUN-UP SUPPRESSOR

TABLE II

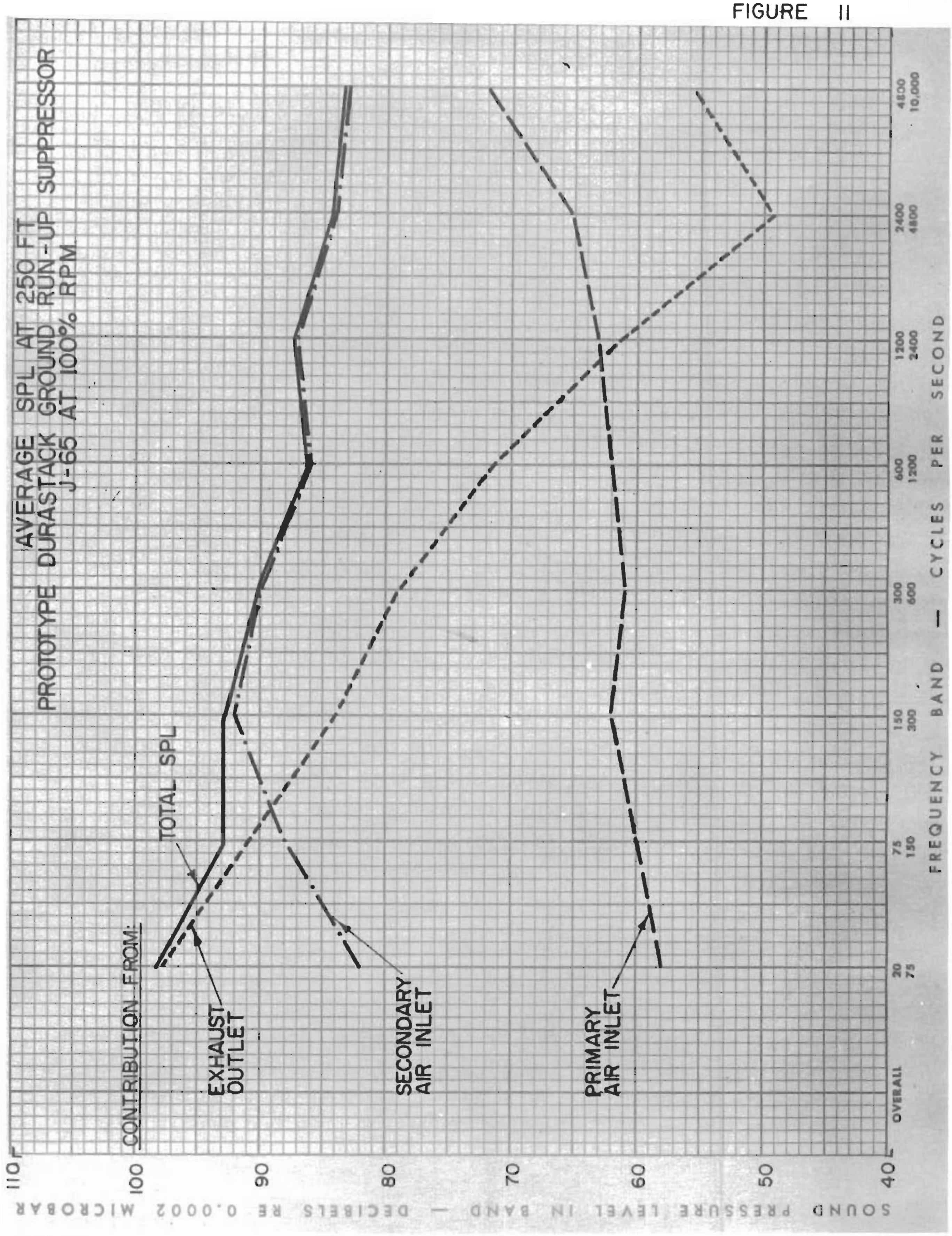
CALCULATION OF AVERAGE SPL'S AT 250 FT

	Primary Air Inlet	Secondary Air Inlet	Exhaust Gas Outlet
1. Measured Average SPL in 300-600 cps band	112 db	135 db	126 db
2. Area of Emitter (A) in sq ft	3	12	32
3. 10 $\log_{10}$ (A) db	5 db	11 db	15 db
4. PWL = SPL + 10 $\log_{10}A$ db	117 db	146 db	141 db
5. Inverse Square Loss = 10 $\log_{10} 2\pi\ (250)^2$	56 db	56 db	56 db
6. Directivity Loss	0 db	0 db	6 db
7. Total Losses (5 + 6)	56 db	56 db	62 db
8. SPL at 250 ft = PWL - total loss	61 db	90 db	79 db

Calculated Total Average SPL at 250 ft = 61 + 90 + 79 = 90 db

Measured Average SPL at 250 ft = 90 db

FIGURE 11

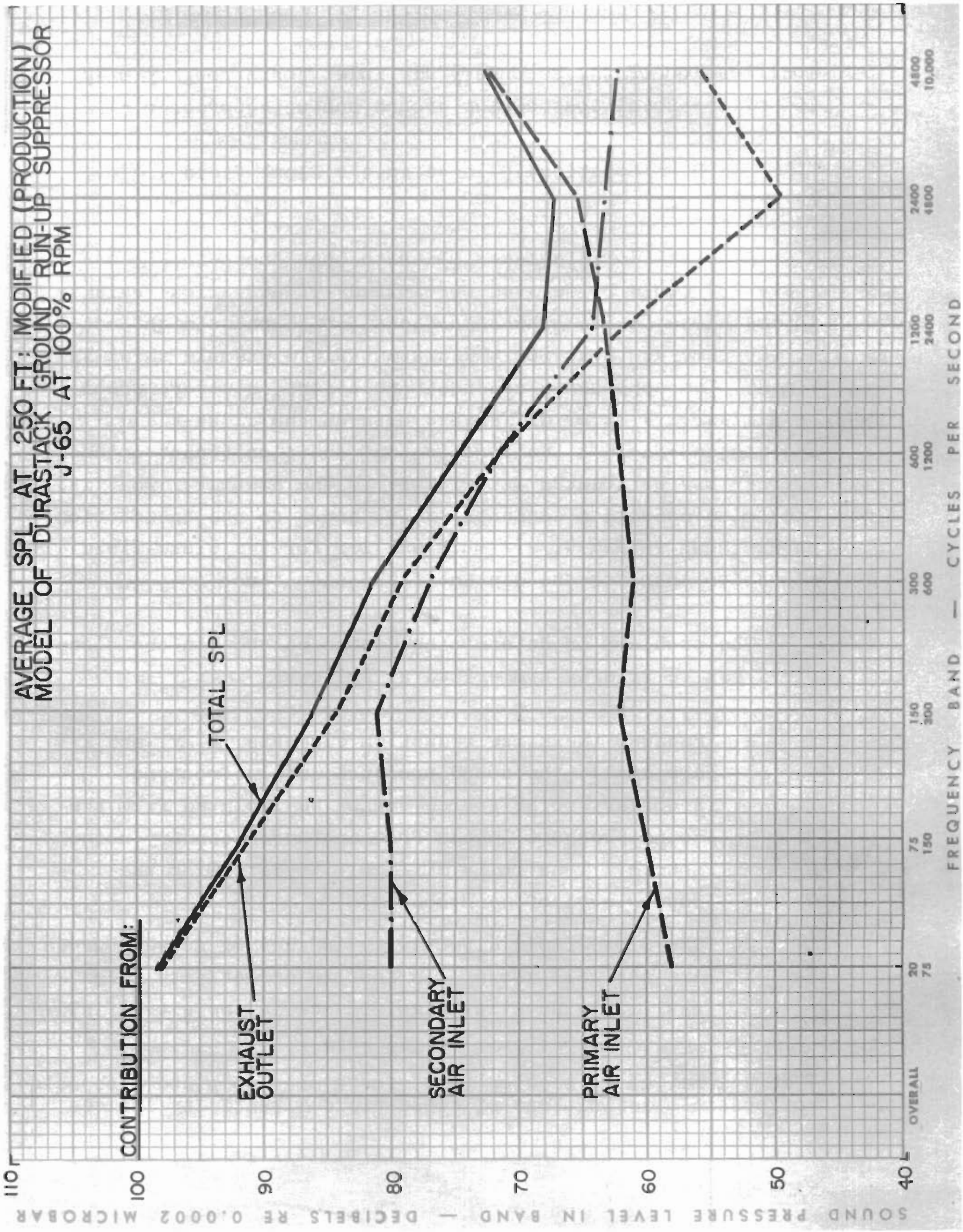

AVERAGE SPL AT 250 FT
PROTOTYPE DURASTACK GROUND RUN-UP SUPPRESSOR
J-65 AT 100% RPM
CONTRIBUTION FROM:
TOTAL SPL
EXHAUST OUTLET
SECONDARY AIR INLET
PRIMARY AIR INLET
SOUND PRESSURE LEVEL IN BAND — DECIBELS RE 0.0002 MICROBAR
110
100
90
80
70
60
50
40
FREQUENCY BAND — CYCLES PER SECOND
OVERALL
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10,000

To find the average SPL over the entire circle at 250 ft, the PWL of each source is first found by adding 10 $\log_{10}$ A to the average SPL (Steps 1 to 4). The directivity and inverse square losses are then calculated (Steps 5 and 6) and subtracted from the PWL to obtain the average SPL at 250 ft. The sum of the SPL's from the three sources (obtained by use of Fig 1) is roughly 90 db which compares fortuitously well with the measured value of 90 db.

The results of the design balance study, shown in Fig 11 for eight octave bands, indicate that the noise reduction in the high frequencies could be increased significantly (from 5 to 20 db) by modifying only the secondary air inlet. Subsequent to the first set of measurements, the secondary air inlet was modified by Industrial Acoustics Company. In the production model of the suppressor, an acoustically lined bend was added as an additional noise reduction element. The results of the design balance study of the production model are shown in Fig 12. The new secondary air inlet radiates much less noise compared with the original secondary air inlet. In the range from 150-2400 cps, the design balance is greatly improved. This design study shows that further additional noise reduction over a wide frequency range can be achieved only by simultaneously modifying the exhaust suppressor system and the secondary air inlet. Furthermore, to obtain greater noise reduction for frequencies above 1200 cps, an intake suppressor must be added.

Note that more elaborate modification of the secondary air inlet than was carried out would have been fruitless because the exhaust contributions would prevent further reduction in the total average SPL. As a final comment, it is pointed out that the additional noise reduction obtained from the

FIGURE 12


AVERAGE SPL AT 250 FT: MODIFIED (PRODUCTION) MODEL OF DURASTACK GROUND RUN-UP SUPPRESSOR J-65 AT 100% RPM

modification of the secondary air inlet costs roughly only 10% of the total cost of the ground run-up suppressor.

B. Acoustical Balance in the Close Field

1. Discussion

A noise flow diagram similar to that shown in Fig 4 (page 25) could be derived for a study of acoustical balance in the close field. The significant noise paths might not be the same as those for the distant field example shown in Fig 4. The components and their relations, however, would be similar. A major difference between the close-field and distant-field situations is that the significant noise sources may be located quite close to one another. That is, the noise reduction elements, x, y, and z on the interaction paths shown in Fig 4, are much smaller for the close-field situation than for the distant-field situation.

The problems of determining design balance in the close field can be briefly summarized as follows:

1. Because the noise reduction elements, x, y, and z are small, the sound pressure levels from one secondary noise source cannot be isolated from the sound pressure levels from another secondary noise source. Thus it is difficult to determine the power level of each source;
2. The close-field directivity indices of noise sources are not well known. In fact, a directivity index has little physical significance in the close field.*

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*See Volume Three, Section VI-C, for a more complete discussion of possible definitions of close-field directivity indices.

Even if the power level of the individual sources can be found, it is almost impossible to predict the contribution from each secondary source to the total close-field SPL's, because the close-field directivity indices are not known. It is necessary to rely upon the human ear as well as acoustical measuring instruments for estimating, at least in a qualitative manner, the acoustical balance characteristics in the close field.

2. Acoustical Balance of Control Room Structures

In control rooms, the major noise paths are the walls between the control room and the test section, and windows and doors in those walls. In addition, poorly sealed wall penetrations for instrumentation control wiring and even the ground below the control room may be significant noise paths. If noise paths between the control room and the test section are significantly unbalanced, the major noise sources can usually be identified by ear. If the design is well balanced, it will probably not be possible to identify the major noise source by ear. Acoustical measurements could be made to estimate the PWL of the various sources, such as doors, windows, walls and control wire penetrations, but these measurements are usually fruitless, owing to the proximity of the various sources to one another.

In summary, if there is poor balance, the major noise source can easily be identified by ear. One cannot determine, however, how much the total SPL will be reduced by a decrease in the noise radiated from that source, since the contribution of other sources to the total SPL is not known. If the major noise source cannot be identified by ear, the control room is probably reasonably well balanced and improvement of the control room must be obtained by improving the noise transmission characteristics of all components.

3. Acoustical Balance in the Close Field of Ground Run-up Suppressors

In the close field of ground run-up suppressors, problems of determining acoustical balance are similar to those in a control room. The various noise sources, however, are usually located somewhat farther apart, and SPL measurements to determine PWL of the various sources can sometimes be made. However, the close-field directivity characteristics of the various sources are usually not well known. Aural detection of leaks will be useful if the acoustical balance is poor.

In addition to aural techniques, it is suggested that the measurements outlined in Section II-B-2 be carried out. These measurements will sometimes provide useful information about the major contributors to the close-field noise levels. Sometimes they can help in the prediction of how much the total noise level will be decreased if a given amount of noise reduction is added.

Consider, for example, Fig 13 in which the close-field SPL's measured around the Durastack ground run-up suppressor at Republic Aviation Corporation are shown. The SPL's in two octave bands are plotted as a function of position on the measurement rectangle. The abscissa of the graphs corresponds to the numbered measurement positions shown in the insert diagram. It is obvious that the prototype secondary air inlet was a primary source of noise at all measurement positions forward of positions 3 and 9. With the prototype data only, one cannot determine whether the levels aft of positions 3 and 9 result primarily from the exhaust gas outlet or the secondary air intake. By comparing the data from the prototype with the data from the modified

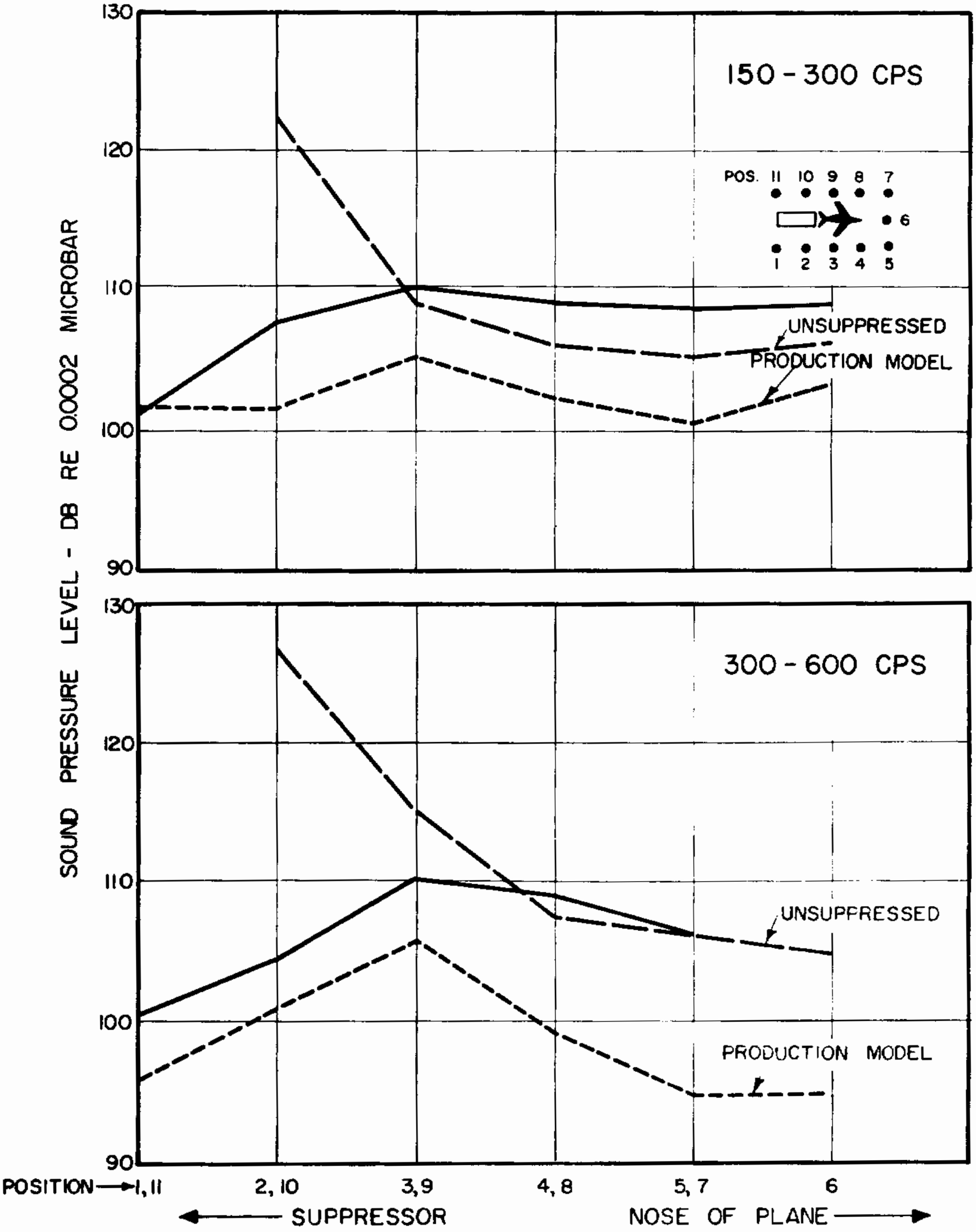


FIG. 13 CLOSE-FIELD SPL'S AROUND A DURASTACK GROUND RUN-UP SUPPRESSOR.

suppressor, one can see that the noise to the rear of positions 3 and 9 was at least partially due to the prototype secondary air intake.

Inspection of the data from the modified suppressor suggests that the high SPL's at positions 3 and 9 result from the secondary air inlet which is between these positions. One cannot determine accurately from the data how much the SPL at positions 3 and 9 could be reduced by adding more noise reduction to the secondary air intake.

By studying the data in the 150-300 cps band, it can be seen that the noise levels at positions 1 and 2, and at positions 4 and 5 are about 3 to 4 db less than the SPL at position 3. It would appear reasonable then to assume that, if more noise reduction were added to the secondary air inlet, the SPL at that position might drop 3 to 4 db. In the 300-600 cps band, the peak at position 3 is more pronounced, being about 10 db above the SPL in the front of the plane. One might estimate that an increase of about 10 db in noise reduction could be obtained by adding treatment to the secondary air inlet.

In summary, a combination of aural techniques and acoustical measurements will aid in the identification of the major noise contributors. The techniques, however, do not tell what the contributions of the less important sources are to the total noise, and hence one cannot predict accurately how much the close-field noise levels will decrease, if noise reduction is added to the major noise source.

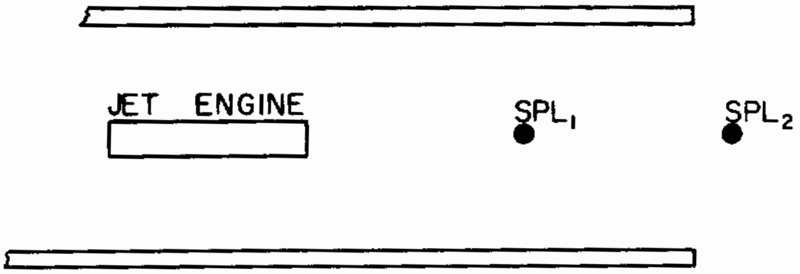
SECTION IV

PROCEDURES FOR THE MEASUREMENT OF ACOUSTICAL PERFORMANCE OF NOISE CONTROL COMPONENTS

The acoustical performance of noise control components can be defined in many ways. Each definition may require different measurement procedures and equipment. A useful definition must therefore be based on a measurement procedure which can readily be carried out with standard measurement equipment. Some possible definitions are first discussed and then, the limitations and merits of various noise sources, microphones, frequency analyzers, etc. are treated. Finally, some examples are presented to illustrate how slightly different measurement procedures might be applied with different measurement equipment.

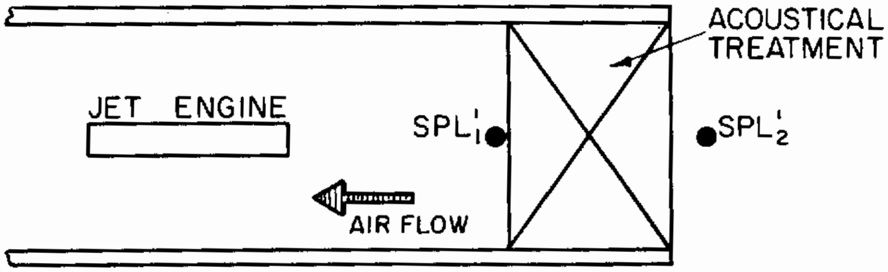
A. The Definitions of Acoustical Effectiveness

In the literature of acoustics, the acoustical effectiveness of a noise control component is defined in numerous ways. However, all of the various definitions can be reduced to two classes in terms of the measurement procedures that are used to determine acoustical effectiveness. The two classes are insertion-loss noise reduction and SPL-difference noise reduction. An insertion-loss measurement is made at one point prior to, and after a noise control component is inserted between the noise source and the observation point. In Fig 14, for example, the insertion-loss noise reduction of the acoustical treatment (noise control component) would be $SPL_2 - SPL_2'$. An SPL-difference measurement is made at two positions; one on the side of the noise source and one on the side away from the noise source. In Fig 14, the SPL-difference noise reduction of the acoustical treatment would be $SPL_1' - SPL_2'$.



TEST CELL WITHOUT ACOUSTICAL TREATMENT.

(a.)



TEST CELL WITH ACOUSTICAL TREATMENT.

(b.)

FIG. 14 RELEVANT TO THE DEFINITION OF ACOUSTICAL EFFECTIVENESS.

Neither the insertion loss nor the SPL difference is an intrinsic property of a noise control component, anymore than the power or voltage reduction of a resistor in an electrical circuit is an intrinsic characteristic of the resistor. In the example shown, SPL_2 and SPL_2' (and, hence, either noise reduction quantity) may be influenced by other components beyond the acoustical treatment; or even by other remote influences, such as a large building which reflects sound back towards the measurement positions. In fact, the noise control component itself can modify the noise radiated by the source, thereby changing the SPL at the input to the acoustical treatment (e.g., SPL_1 is not necessarily equal to SPL_1').

These introductory remarks are offered so that the reader will be aware that measurements of the acoustical effectiveness of noise control components made in a given facility do not uniquely describe the acoustical effectiveness of the component when used in other locations. If a component is to be used in the design of another test facility, the reader should consult Appendix C of Volume Two of this report which explains how noise reduction of treatments vary with respect to various environmental conditions.

Insertion-loss measurements are more directly useful than SPL-difference measurements in noise control problems associated with aircraft engine test facilities. Unfortunately, removal and insertion of the massive noise control components usually found in test facilities is, in a practical sense, impossible. Therefore, one must resort to SPL-difference measurements. The measurement procedures in this Section are outlined in terms of SPL-difference measurements, but they are directly applicable to insertion-loss measurements.

For noise control components with air flow passages, the SPL-difference noise reduction (L_{nr}) is defined, in this report as,

$$L_{nr} = (SPL_{1_{av}} + 10 \log_{10} A_1) - (SPL_{2_{av}} + 10 \log_{10} A_2) \qquad (5)$$

where $SPL_{1_{av}}$ and $SPL_{2_{av}}$ are the average SPL's over the input and output respectively, (see page 12).

A_1 and A_2 are the areas of the input and output planes respectively.

The areas of the input and output planes are generally equal so that the noise reduction, L_{nr}, is approximately equal to the difference in average SPL's.

For impervious noise control components, noise reduction (NR) is used as a definition of acoustical effectiveness;

$$NR = SPL_1 - SPL_2 \qquad (6)$$

where SPL_1 is the average SPL in the reverberant field on the source side of the impervious barrier

SPL_2 is the average SPL measured over the barrier on the receiver side.

The noise reduction, NR, can be related to the more familiar quantity, transmission loss, (TL)* under certain

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$$*TL = 10 \log_{10} \frac{W_1}{W_2} \text{ db}$$

where W_1 = the acoustic power in watts incident on the wall.
W_2 = acoustic power in watts transmitted through the wall into a perfectly absorbing space.

particular conditions (see Reference 15, Part XXV).

B. Measurement Positions

The location and number of microphone positions used in the measurement of acoustical effectiveness are discussed in this Section. Two measurement techniques, both of which are the SPL-difference type, are presented; the grid technique and the EN-1 technique.

1. Grid Technique

A grid is an array of microphones located in a plane normal to the air flow though an acoustical treatment. The average SPL's in grids located on the "input" and "output" sides of an acoustical treatment are used in the calculation of L_{nr} from Eq 5. Because of "wind-noise" considerations, one grid is usually located about 2 to 4 ft "upstream" (see Fig 14) of the acoustical treatment where the air flow is slower and less turbulent than at the plane of the treatment. The other grid is usually located very near (less than 1 ft) the "downstream" end of the acoustical treatment because the air flow beyond the treatment may be quite turbulent, and wind noise may be quite high.*

The selection of an appropriate number of microphone positions in a grid is dependent primarily upon the time and equipment available for the measurements (see Section C below). If time is not limited, the primary consideration will be the accuracy required of the measurements. The SPL in a grid can be accurately described only by making measurements at many

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*A microphone windscreen should be used if measurements are made with an engine as a noise source. See Appendix B and page 34 in Section II for a more complete discussion of windscreens and techniques for using them.

positions in a grid, from which an average SPL is obtained.

In view of the other sources of "error" in the measurement and data reduction systems (of the order of 2 db*), 4 to 6 microphone positions in each grid are recommended. If more microphone positions are used, no great increase in accuracy is gained, because the errors in the data reduction system remain. If fewer positions are used, the probability of approximating the space average SPL within a few db becomes very small.

The location of microphones in the grid is not critical. In general they are placed in a somewhat random fashion. If the acoustical treatment is symmetrical about some axis, and the noise source is symmetrical about the same axis, it may be convenient to make measurements in only one symmetrical area. (An example showing a situation in which symmetry can be used is given in Paragraph D below.)

2. The EN-1 Technique

Measurements of acoustical effectiveness of exhaust acoustical treatments are complicated by the high exhaust gas temperature (typically from 250° F to 600° F) and the high exhaust gas velocity (typically from 100 ft/sec to 250 ft/sec). If high-temperature measurement equipment is not available, the measurements may be made either with an "artificial noise source" (e.g., a loudspeaker or impulsive noise source) or by means of the EN-1 technique ** with the engine as a noise source.

The EN-1 difference measure of acoustical effectiveness is defined as the difference between the SPL at the engine

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*See Volume Three, Section III.

** See ref. 7, pages 13-26.

EN-1 microphone and that at the exhaust EN-1 microphone.

The engine EN-1 microphone is located as follows[*] :

> "The microphone should be located in a plane perpendicular to the engine axis and at a distance of two nozzle exit diameters aft from the rear of the engine and radially two nozzle exit diameters from the engine centerline. No measurement should be made at a distance of less than 3 ft from the nozzle center."

The exhaust EN-1 microphone position is located as follows[*] :

> "The microphone should be located in a plane perpendicular to the axis of the soundproofing exit (referred to as the emitter) at a distance of one emitter diameter from the emitter plane and at a radius of one emitter diameter from the emitter centerline. Measurements should not be made at a distance less than 14 ft or more than 50 ft from the center of the emitter. (The 'emitter diameter' of an elliptical or rectangular opening shall be the minor dimension.)"

Data obtained from the EN-1 technique are not directly comparable to data obtained by an SPL-difference technique. The SPL-difference technique essentially relates the total acoustical energy at the input of a treatment to the total acoustical energy at the output of the treatment. On the other hand, the EN-1 difference relates an SPL near the jet engine exhaust orifice (which may or may not be near the input to a treatment) to an SPL which is located a certain distance away from the output of the acoustical treatment.

On the basis of measurements in many test cells, a relationship has been derived, in a semi-empirical manner, between the measured "EN-1 difference" and the SPL-difference noise reduction, L_{nr}, as follows:

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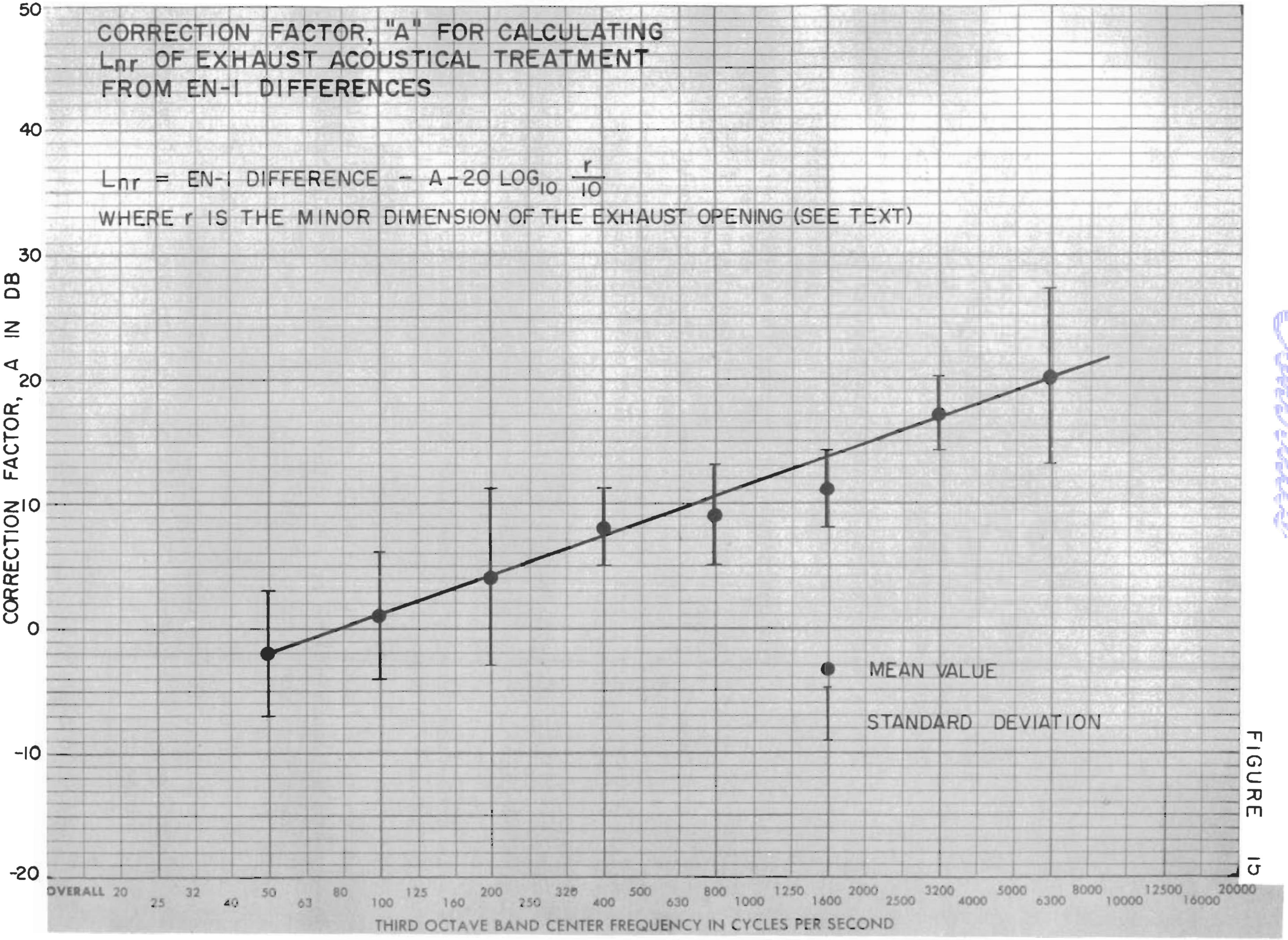
[*] See ref. 7, pages 13-26.

FIGURE 15



CORRECTION FACTOR, "A" FOR CALCULATING L_{nr} OF EXHAUST ACOUSTICAL TREATMENT FROM EN-I DIFFERENCES

$$L_{nr} = \text{EN-I DIFFERENCE} - A - 20 \log_{10} \frac{r}{10}$$

WHERE r IS THE MINOR DIMENSION OF THE EXHAUST OPENING (SEE TEXT)

$$L_{nr} = \text{"EN-1 difference"} - A - 10 \log_{10} \left(\frac{r}{10}\right) \qquad (7)$$

where r is the minor dimension of the exhaust (emitter diameter) in feet, and A is given in Fig 15. The large standard deviation shown in Fig 15 indicates that although this relation may be useful "on the average", the difference between measured L_{nr} and the EN-1 differences for any given test cell may be significantly different from that shown.

The relation between L_{nr} and EN-1 differences was derived on the basis of SPL differences measured without air flow through the exhaust acoustical treatments. However, on the basis of a limited amount of data, (see Section V of Volume Three of this series) it appears that the influence of air flow is small and that the noise reduction without air flow provides a close approximation to noise reduction with air flow.

C. Instrumentation for Acoustical Measurements

As stated in the Introduction, the selection of a measurement technique is governed by the measurement equipment and the engine operating time available to a measurement crew. If a large amount of equipment is available, many measurements can be made in a short time. If, on the other hand, only a small amount of measurement equipment is available, then the number of measurement positions that can be used will be limited by the amount of engine operating time that is available. In turn, the number of measurement positions that can be used will determine the accuracy* of the measurements.

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*By accuracy is meant the difference between the noise reduction measured in a given experiment and the noise reduction that would be obtained using an infinite number of measurement positions in the grids.

The instrumentation for acoustical measurements can be divided into four parts for discussion purposes: (1) a noise source which may be the aircraft engine in the test facility, or a loudspeaker, or an impulsive noise source; (2) a microphone (or microphones); (3) a tape recorder which may be used to store data for subsequent analysis; and (4) a frequency analyzer.

In the paragraphs below, the several parts of the instrumentation are discussed, along with various combinations that can be used for component evaluation.

1. Noise Sources

a. Aircraft Engine. An aircraft engine is the most desirable noise source from an acoustical viewpoint. By using an engine, one makes the measurements under the acoustical environment in which the noise control component is used. Thus, problems associated with the variation of L_{nr} with noise source or with air flow, need not be considered.

There are, however, two disadvantages to using the engine as a noise source. First, the engine is a very expensive noise source, not only in terms of fuel comsumption, but also in terms of man-hours required to operate the engine. Second, measurements in exhaust acoustical treatments may be impossible with conventional instrumentation, because of the high velocity and temperature of the exhaust gases.

b. Substitute Noise Sources.

Loudspeakers. There are several advantages to the use of a loudspeaker system. First, no engine operating time is required. Second, conventional instrumentation, such as a sound level meter and octave band analyzer system, can be used in conjunction with the loudspeaker. Third, very narrow-band frequency analysis can be accomplished (if desired) by using a pure-tone oscillator as an input to the power amplifiers which drive the loudspeaker. The primary disadvantage of loudspeaker systems is that the acoustic power output is usually limited to a few hundred watts. Since the test facility may have a noise reduction of 40 to 60 db, the noise from a loudspeaker at the output of an acoustical treatment will very frequently be below ambient noise levels. Ambient noise levels are usually highest in the low frequency range in which the acoustical power output of a loudspeaker system is low. Therefore, low frequency measurements are particularly difficult to obtain.

Impulsive Noise Source. The primary advantage of an impulsive noise source is that a large acoustic output can be obtained from a small, easily handled device.* Thus, impulsive sources can be readily used for field measurements. The primary disadvantage of an impulsive noise source is that a tape recorder and a special data reduction system 16/ are required because the duration of the noise impulse is short. If many measurements are to be made, the savings resulting from the use of an explosive noise source justifies the elaborate data reduction system.

In Section V of Volume Three of this series, noise reductions measured with an impulsive noise source are compared with noise reductions measured with a jet engine

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*A 10 gauge cannon used to start yacht races has been employed in the Air Force program. The PWL of the source is about 170 db when averaged over 150 milliseconds. (See Ref 17 and Volume Three, Section III, for a more complete discussion of the characteristics of the impulsive noise source.)

as a source. The noise reduction is found to be very nearly independent of the source, provided the noise source location with respect to the acoustical treatment is held constant. Although the source of noise from a jet engine is distributed in space, the source can be approximated by a localized, substitute source placed at the forward end of the eductor or augmentor tube.

If the distance from the jet exhaust nozzle to the exhaust acoustical treatment is less than 15 jet exhaust nozzle diameters, part of the noise of the jet engine will be generated in the acoustical treatment. In such a case, the noise reduction measured in the exhaust acoustical treatment closest to the engine with a substitute noise source cannot be related to the noise reduction which would be measured with the jet engine as a source. Fortunately, aerothermodynamic considerations in test cell design usually require that the distance from the jet nozzle to the exhaust acoustical treatment be greater than 15 nozzle diameters.

If a jet stream modifier (exhaust diffuser) is used as a noise reduction element in the test facility, then the above considerations do not apply. The location of the apparent source of jet engine noise will be much closer to the exhaust nozzle, perhaps within about 2 to 5 nozzle diameters.

2. Microphones

Several types of microphones have been used in the measurement program. The relative merits of each are discussed briefly in the paragraphs below. A more comprehensive discussion of microphone characteristics is given in Ref 16.

a. Rochelle Salt Microphones. The main advantages of a Rochelle Salt microphone are economy and the relative simplicity of associated equipment. The usefulness of these microphones is limited because 1) the transducer element deteriorates rapidly at a relatively low temperature (130° F), 2) the sensitivity and output impedance vary with temperature, 3) the frequency response above 2500 cps is irregular, 4) mechanical destruction of the transducer element occurs near 140 db SPL, 5) long cables cannot be used because the output impedance is high.

b. Barium Titanate Microphones. Barium Titanate microphones have properties similar to the Rochelle Salt microphones. They are useful at slightly higher temperatures than the Rochelle Salt, but the high frequency response is more irregular than the Rochelle Salt.

c. Condensor Microphones. The condensor microphone, while being more expensive and having more complex associated equipment, has been found to be most desirable for many reasons. The frequency response is flat over a very wide range; it is adaptable for measurements over a wide range of SPL; the sensitivity is very stable over long periods of time and is relatively independent of temperature; and the maximum useful temperature is very high (being established only by the preamplifier and associated wiring). A major disadvantage is that the wind noise of these microphones is high and a windscreen may be required (see Appendix B).

d. High Temperature Microphones. High temperature microphone systems usually have condensor microphones as sensing elements, and have all of the acoustical characteristics of condensor microphones. Condensor microphones have been used at 600° F for short periods of time by use of a Teflon water jacket around the preamplifier, and Teflon cables.

3. Tape Recorder

In general, data is obtained by using a tape recorder and carrying out the frequency analysis at a later date. If an engine or a loudspeaker is used, a tape recorder is not essential. It is, however, an effective means of reducing engine operating time.

If an impulsive noise source is used, a tape recorder is essential, since a sound level meter does not respond fast enough. Perhaps a peak reading meter could be used in lieu of a recorder, but there has been no need for such a system. An obvious disadvantage to the use of a peak meter is that the impulsive source must be fired at least once for each frequency band of interest. For an octave band analysis, at least eight (8) shots per measuring position would be required. For a 1/3 octave band analysis, twenty-four (24) shots would be required for each position.

4. Frequency Analyzers

The most common frequency analyzers have a bandwidth of 1 octave, 1/2 octave or 1/3 octave. Narrow (i.e., 2%, 4 cps, etc.) band analyzers are generally not used for measuring acoustical effectiveness of noise control components in test facilities.

It can be shown that the measured noise reduction in octave bands of frequency depend not only upon the noise reduction spectrum (i.e., the noise reduction vs. frequency characteristics) of the component, but also upon slope of the spectrum of the noise input to the component.

The extent of the dependence of noise reduction on the slope of the input spectrum has been calculated for inputs with constant slope (see Volume Three, Section III). It is found that for 1/3 octave bands, the dependence is small and may be considered negligible for the range of noise reduction spectra and input spectra encountered in test cell design. The variation of octave band noise reduction with the slope of the input spectrum may be significant. Thus, the noise reduction of a component measured in one situation may not be obtained in another situation, if the input spectrum slopes are not identical.

The variation of octave band noise reduction with the slope of the input spectrum has been calculated for a wide range of input slopes* and noise reduction slopes. These calculations are summarized by Fig 16.

For example, suppose the noise reduction of an acoustical treatment has been measured with an input having a slope of 15 db/octave and that the noise reduction spectrum has a slope of 20 db/octave. The noise reduction is found to be 50 db in one octave band. It is desired to know the noise reduction of the same treatment for an input spectrum having a slope of -9 db/octave. Entering the graph on the abscissa of 20 db/octave and going up to an input spectrum slope of 15 db/octave one reads a relative noise reduction of about +2 db. Going down from the abscissa to -9 db/octave one finds a relative attenuation of -3 db. The attenuation for a -9 db/octave slope is therefore 5 db lower than the attenuation for a +15 db/octave slope or 50-5 = 45 db.

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*The slopes given in Fig 16 are those which would be obtained from a plot of octave band SPL's versus log frequency. These slopes are 3 db greater than the slopes obtained from a "per-cycle" SPL (spectrum level) vs. frequency presentation.

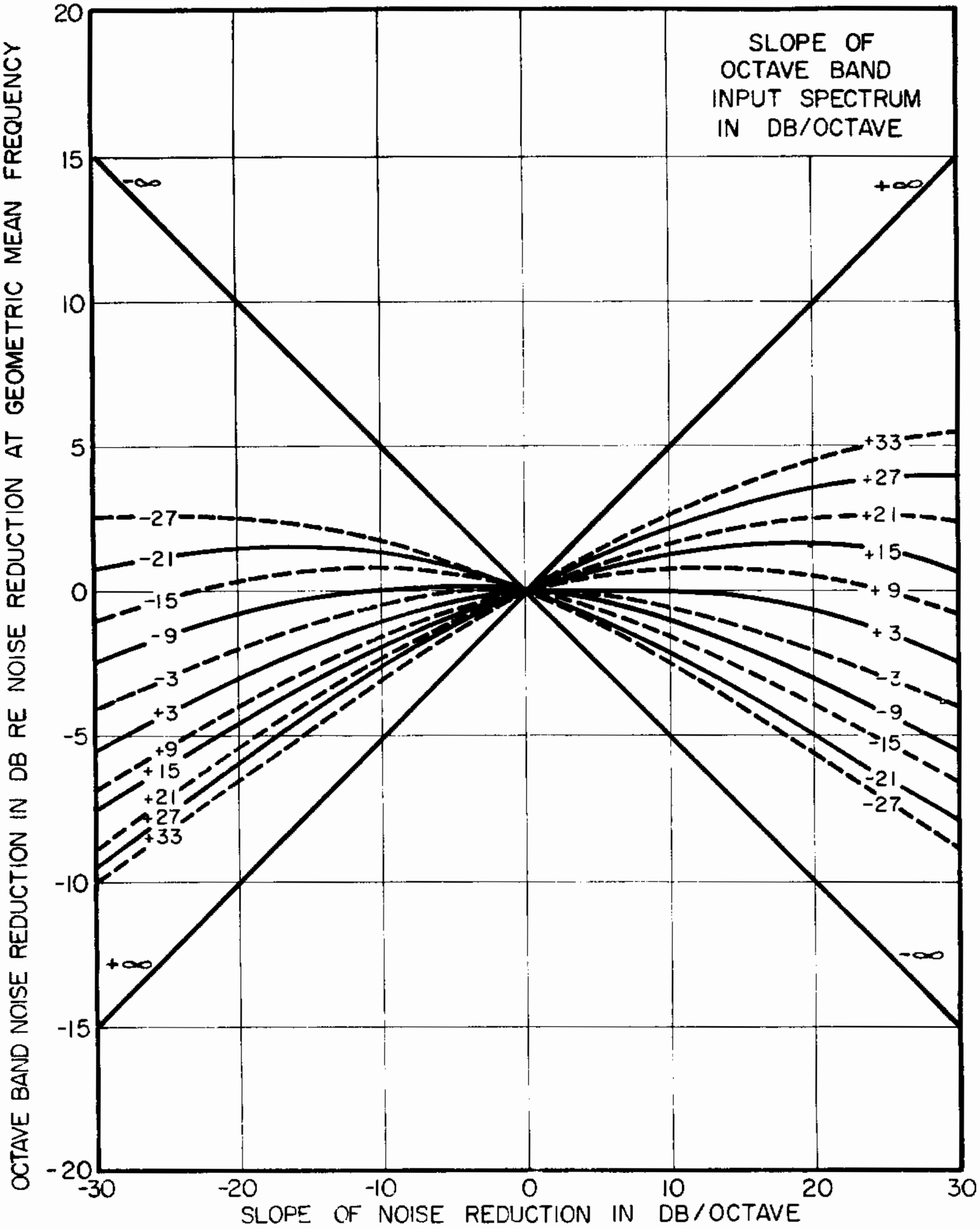

FIG. 16 OCTAVE BAND NOISE REDUCTION AS A FUNCTION OF THE SLOPE OF THE NOISE REDUCTION AND INPUT SPECTRA

It is assumed in the derivation of this graph that both the input and the noise reduction spectra are continuous (no "pure tones"). In addition, the slope must be relatively constant in an octave band. If the slope is not constant, the average slope on either side of the octave band in question may be used as a first approximation.

5. Evaluation Systems

Evaluation systems are made of combinations of noise sources, microphones, frequency analyzers and, in some cases, tape recorders. Some possible evaluation systems are presented in diagrammatic form in Table III. Microphones have not been considered since the various types previously mentioned may be used with any of the evaluation systems. The comments noted in Table III are applicable to measurement systems which may be used for component evaluations. These comments do not necessarily hold for other types of evaluation, such as the measurement of gross acoustical effectiveness.

The comments in the table may be summarized briefly as follows: One-third octave band analyzers are more useful than octave band analyzers for measurements because the influence of input spectra on noise reduction is less for the former than the latter. However, one-third octave band measurements require too much time in the field to be practical without a tape recorder. Thus systems 4, 8 and 12 are the most desirable.

D. Examples

1. The Measurement of Acoustical Effectiveness of Noise Control Components in Air Flow Passages

In this Section, measurements of the acoustical effectiveness of the intake and exhaust treatments of a typical jet

TABLE III

SOME POSSIBLE EVALUATION SYSTEMS

NOISE SOURCE	TAPE RECORDER	FREQUENCY ANALYZER	MEASUREMENT SYSTEM NO.
Engine	No	OBA	1
		TOBA*	2
	Yes	OBA	3
		TOBA	4
Loudspeaker	No	OBA	5
		TOBA	6
	Yes	OBA	7
		TOBA	8
Impulsive Noise Source	No	OBA	9
		TOBA	10
	Yes	OBA	11
		TOBA	12

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*One-third octave band analyzer.

TABLE III (CONT'D.)

	Engine Operating Time	Field Measurement Time	Data Reduction Time	Frequency Resolution	Additional Comments
1.	Long	Long	Nil	Poor	Acceptable if only a few measurements are required.
2.	Very long	Very long	Nil	Good	Seldom useful owing to long field time.
3.	Short	Short	Long	Poor	Acceptable
4.	Short	Short	Very long	Good	Excellent system.
5.	None	Long	Nil	Poor	Better than 1 if many measurements must be made.
6.	None	Very long	Nil	Good	Seldom useful owing to long field time.
7.	None	Short	Long	Poor	Acceptable.
8.	None	Short	Very long	Good	Excellent system.
9.	--	--	--	--	OBA alone cannot be used with impulsive source.
10.	--	--	--	--	TOBA alone cannot be used with impulsive source.
11.	None	Short	Long	Poor	Data reduction system is complex
12.	None	Short	Very long	Good	See 11, but otherwise an excellent system.

engine test cell are presented to illustrate the material presented in the previous Sections.

a. Measurements in an Air Intake. A plan and section of a typical test cell are shown in Fig 17. Both the primary and secondary air enter the intake and pass successively through a 90° lined bend, thick parallel baffles and thin parallel baffles, and enter the test section passing through a 90° unlined bend. The measurements of SPL in the intake treatment were made in grids A and B.

In Fig 18, the average SPL for the 5 microphone positions in each grid during engine (J-65) operation at 100% of maximum compressor revolution rate is shown as a function of one-third octave bands of frequency. In the 400 cps band, the SPL's at the five measurement positions in each grid are also shown.

The SPL-difference noise reduction, L_{nr}, of the intake acoustical treatment is obtained directly by subtracting the average SPL in Grid A from the average SPL in Grid B, since the area of Grid A was approximately equal to the area of Grid B.

The L_{nr} obtained from these data and two other engine operating conditions (70% and 55% of maximum compressor revolution rate) is given by the shaded curve in Fig 19. The L_{nr} measured with the explosive noise source is given by the solid curve in Fig 19. As can be seen, the range of measured data is quite small, being in general less than 3 db except in the first three one-third octave bands. In these bands the data measured using the explosive noise source is about 5 to 10 db below the engine data.

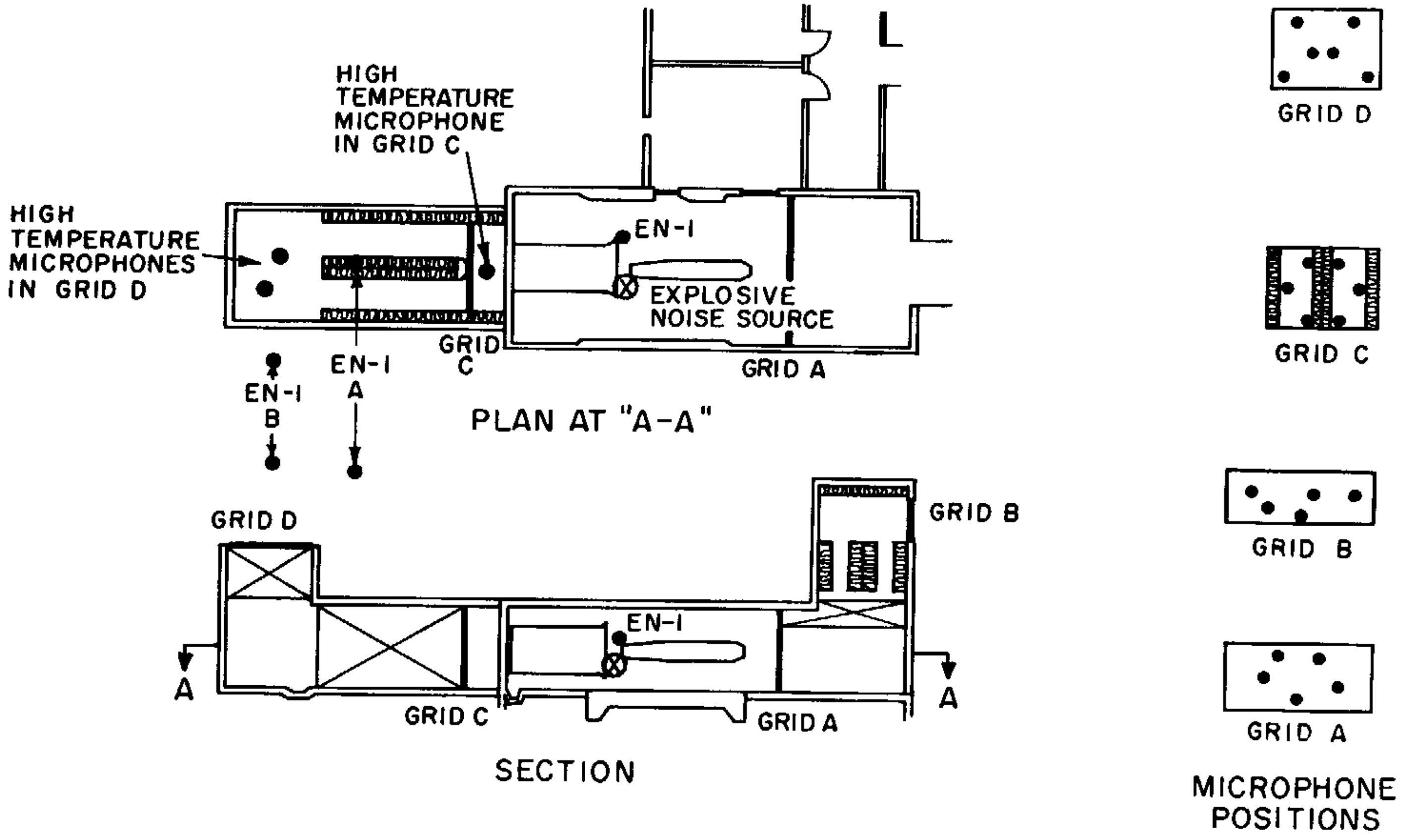
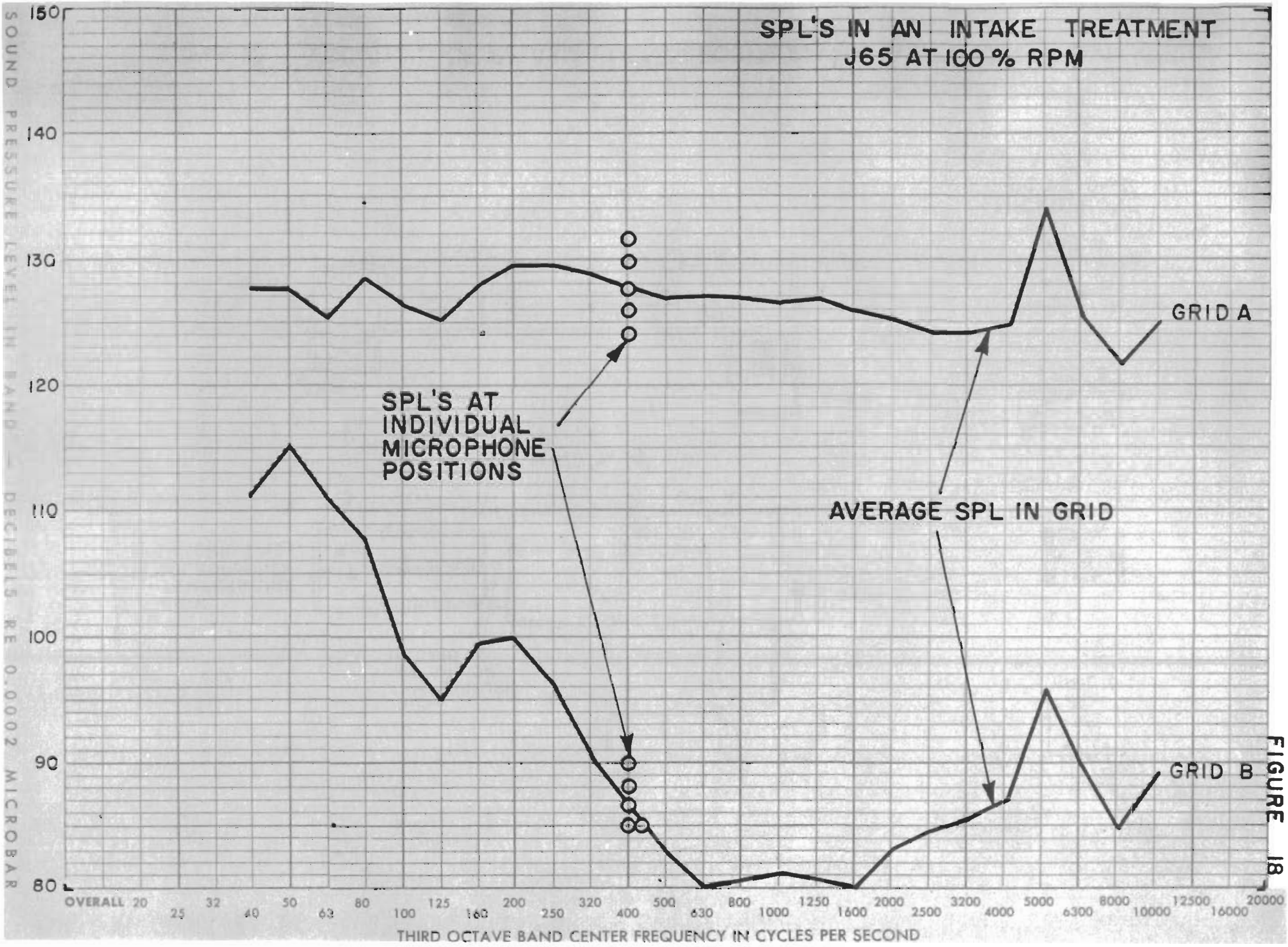


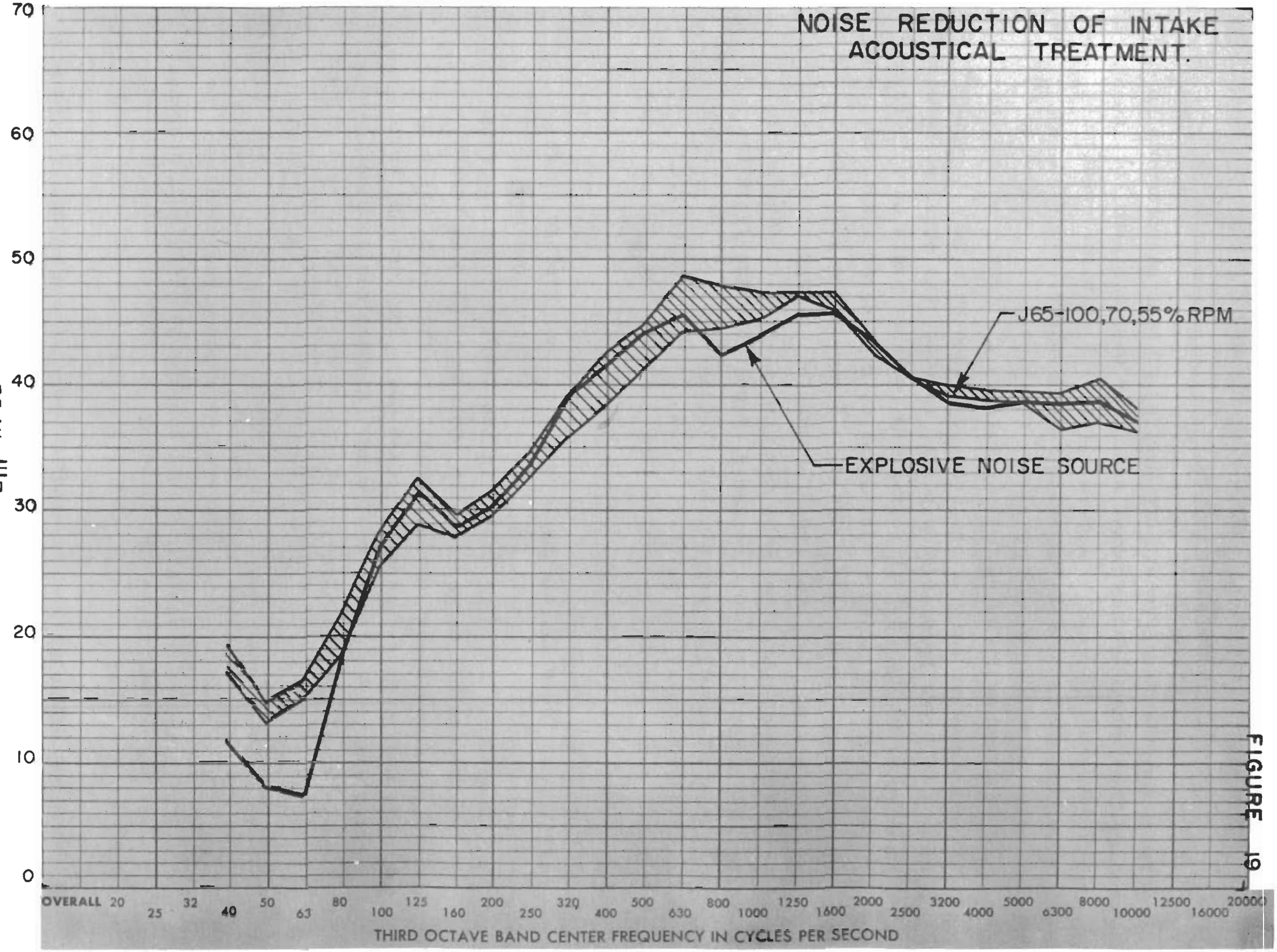
FIG. 17 LOCATION OF MEASUREMENT POSITIONS IN A TYPICAL TEST CELL.

FIGURE 18



SPL'S IN AN INTAKE TREATMENT
J65 AT 100 % RPM

FIGURE 19



NOISE REDUCTION OF INTAKE ACOUSTICAL TREATMENT.

These measurements are typical of most measurements in intake acoustical treatments. It is usually found that noise reduction does not vary significantly with engine operating condition, and that the noise reduction measured with the explosive source usually agrees quite well with the noise reduction measured with the engine as a source.

One may well inquire of the results that would be obtained if only a few of these microphone positions were used in each grid. To investigate such results, consider the data presented at 400 cps in Fig 18. If a single microphone position in Grid A were used, the measured SPL might be any one of the values shown, ranging from 132 to 124 db. If any two measurement positions were used, the range of possible average SPL's lies between 131 db to 125 db [the average value of the two highest and two lowest SPL's, respectively, found by using Fig 5 for the summation and by subtracting 3 db ($10 \log_{10} 2$) from the sum].

In Table IV, the maximum and minimum average SPL's and the possible range in SPL for 1 to 4 microphone positions are tabulated. From the table, we see that the possible range of average SPL decreases with the number of measurement positions that are used to obtain the average SPL in a grid. Not only does the range decrease, but, for example, the average values found for the several possible combinations of two microphones tend to cluster* nearer the average value of SPL found from five microphones. Similar comments, of course, apply to the data in Grid B.

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*The standard deviation of the average SPL in a grid decreases as $1/\sqrt{N}$, where N is the number of microphone positions.

TABLE IV

RANGE OF AVERAGE SPL'S IN GRID A

Number of Microphone Positions used to Obtain Average SPL	Highest Average SPL	Lowest Average SPL	Range in Average SPL
1	132	124	8
2	131	125	6
3	130	126	4
4	130	127	3

The range in L_{nr} will be the sum of the range of SPL's in Grid A and Grid B. Thus, the importance of using more than one microphone position, and, preferably four or more, is easily seen.

b. Measurements in the Exhaust Acoustical Treatment. With the engine as a noise source, the L_{nr} of the exhaust acoustical treatment can be measured directly only with special high temperature microphones and cables. Without such equipment it is necessary to use either an artificial noise source or the EN-1 technique. The noise reduction of the exhaust acoustical treatment of the test cell shown in Fig 17 was measured by three methods. The L_{nr} was measured both with the engine as a source and with the explosive noise source. In addition, the EN-1 difference was measured. The measurement grids were located in the planes C and D shown in the plan and section in Fig 17. The location of the microphones in those grids during the explosive noise source measurements is given in the insert in Fig 17*. During engine operation, only one high temperature microphone was used at Grid C and only two high temperature microphones were used at Grid D. The location of these microphones is shown in the plan in Fig 17.

The L_{nr}'s measured with the explosive noise source and with the jet engine are shown in Fig 20. As can be seen, agreement between the two sets of data is quite good up to 400 cps and also above 2500 cps. The large discrepancy in the mid-frequency range was probably caused by wind noise which resulted from the high exhaust gas velocity at Grid D. The good agreement between the two sets of data in the low frequency range is, perhaps, fortuitous, as only a single microphone position at Grid C was used during the high temperature measurements.

As previously noted, the definitions of EN-1 positions do not define a point but, instead, define a locus of points which form a circle. At the EN-1 engine position the noise field around the engine is probably symmetrical about the longitudinal axis of the engine and hence the SPL is probably constant on the EN-1 circle. The SPL's at all positions on the EN-1 circle at a square or rectangular exhaust gas outlet of a test cell is not necessarily equal. One must expect, therefore, that the EN-1 differences will depend on the position selected at the exhaust gas outlet.

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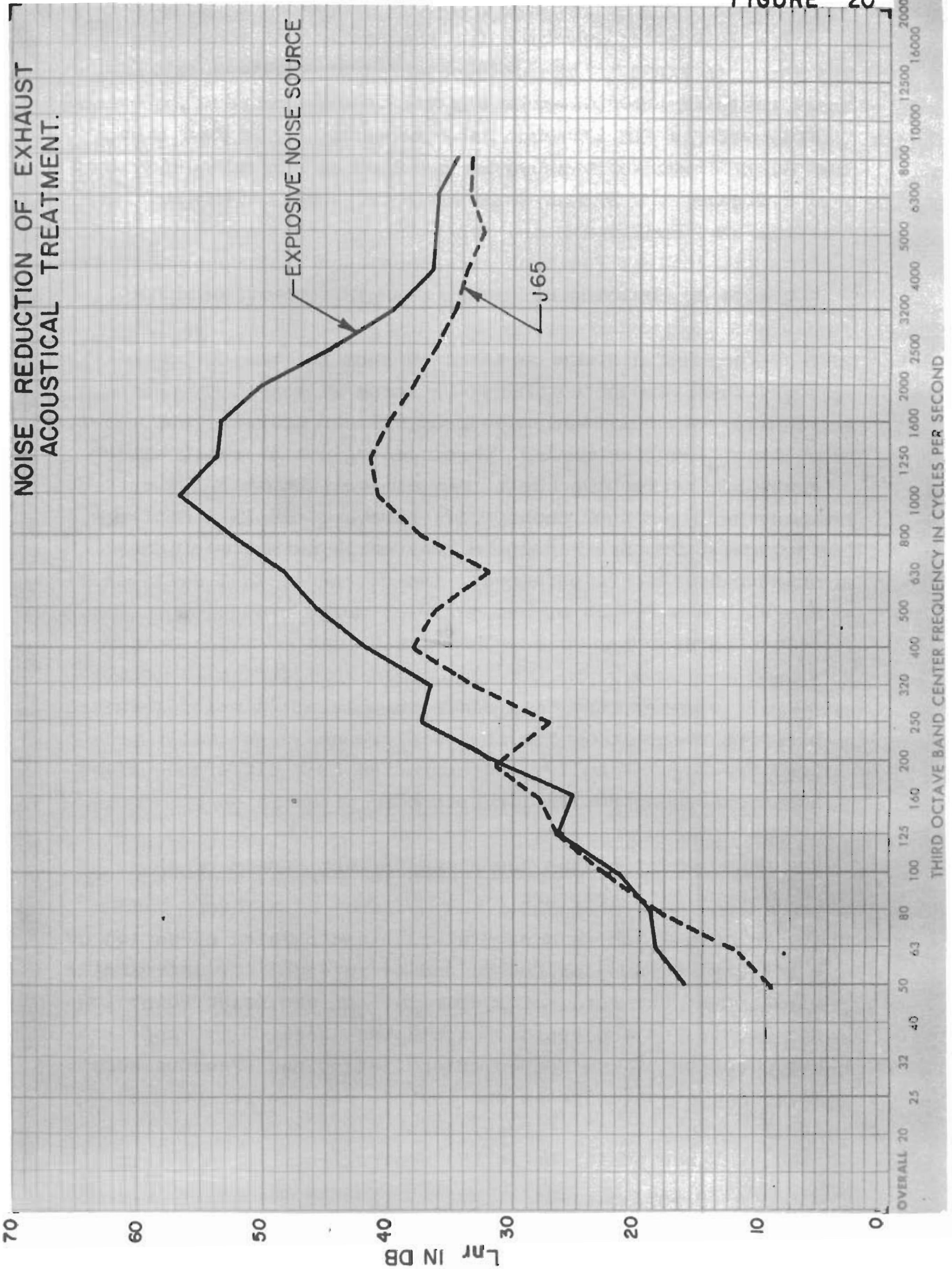
*Generally, six microphone positions are not used in such a small cross-sectional area. Six microphones were used as an experiment to determine if the symmetry assumption discussed in Section B was reasonable. (The results, not shown, were very gratifying; the difference between the average SPL's in each symmetrical area was less than 3 db over the entire frequency range. In other words, the average SPL in each symmetrical area was within 1.5 db of the space average over the entire area.)

FIGURE 20



NOISE REDUCTION OF EXHAUST ACOUSTICAL TREATMENT.

The EN-1 positions used for the acoustical measurements are shown in Fig 17. The data measured at the EN-1 exhaust stack positions are shown in Fig 21. As can be seen from the figure, the SPL at Position A is generally higher than the SPL at Position B and hence the EN-1 difference determined from the data at Position A is less than that determined from the data at Position B.

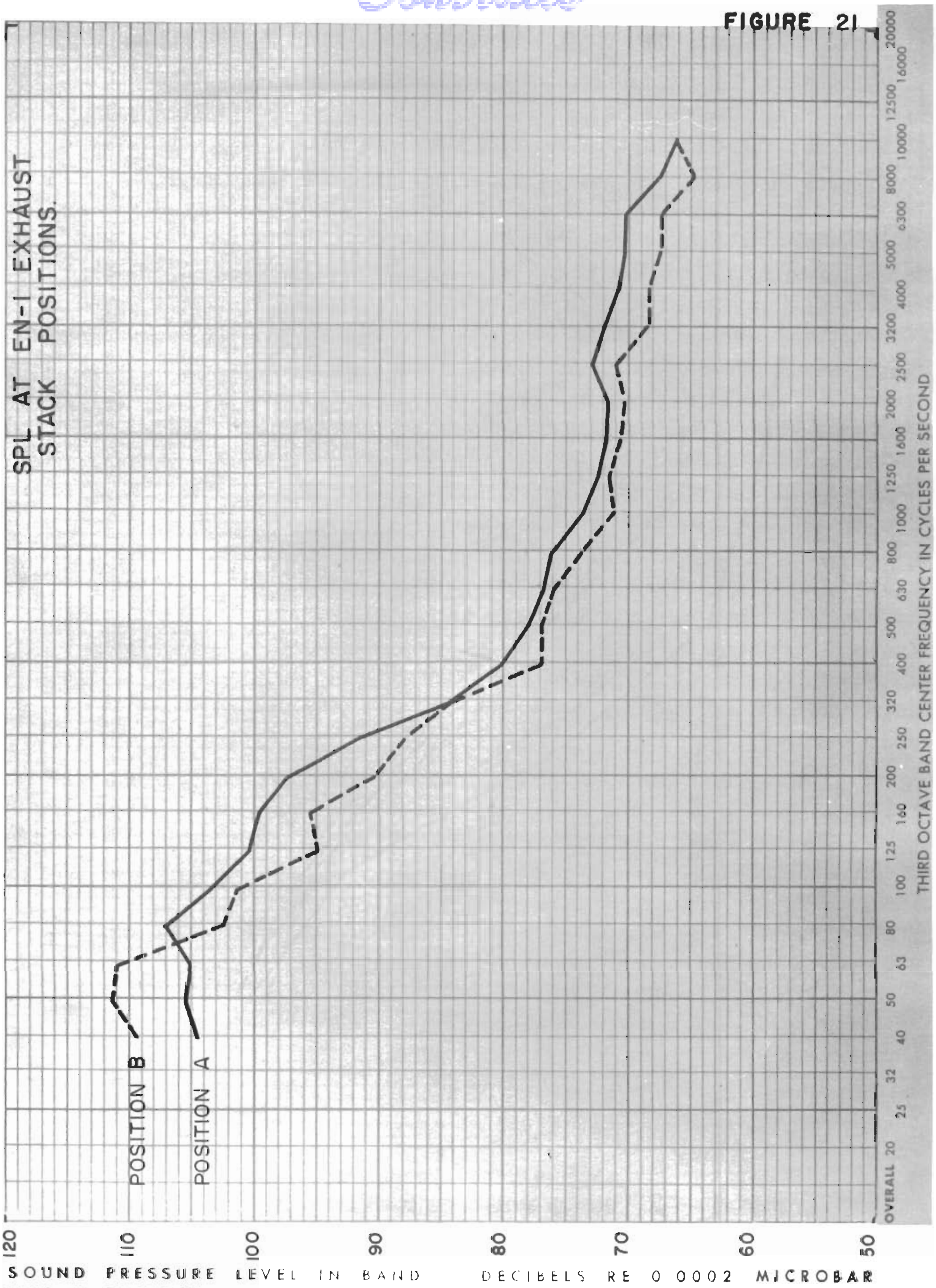
The EN-1 difference obtained from the measurements at Position A is plotted in Fig 22 along with the L_{nr} measured with the explosive noise source. As can be seen, the results obtained from the EN-1 differences suggest a much greater acoustical effectiveness of the exhaust acoustical treatments than the L_{nr} method shows. If, however, the EN-1 difference is corrected using Fig 15, a reasonable estimate of the noise reduction is obtained. The corrected EN-1 differences lie within a few db of the measured noise reduction in most octave bands.

In summary, the EN-1 difference is not a unique measure of noise reduction. The EN-1 difference is generally greater than the L_{nr}. Finally, the corrected EN-1 difference gives a reasonable approximation to the L_{nr}.

2. Measurement of the Acoustical Effectiveness of an Impervious Structure

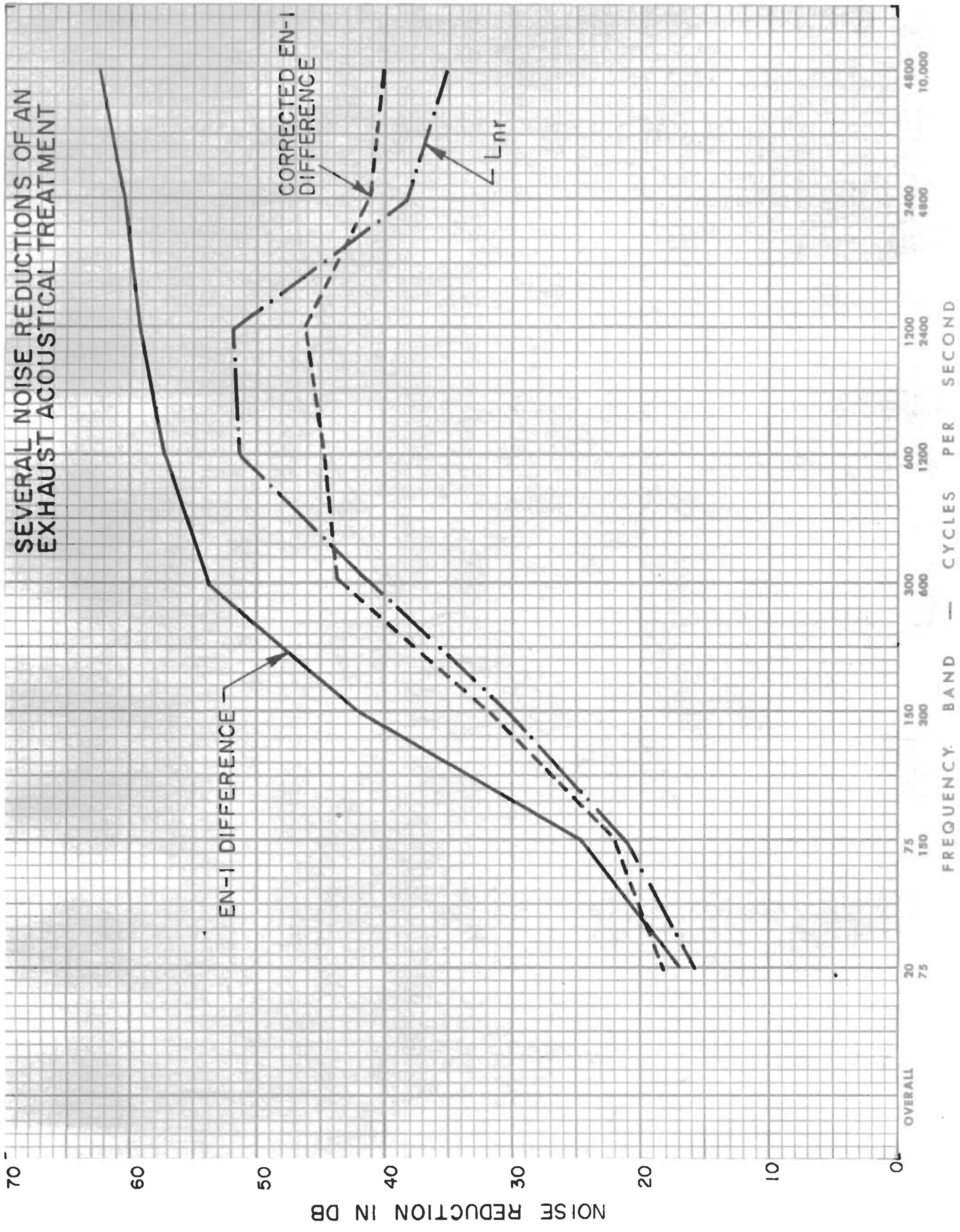
Figure 23 shows a partial plan and partial elevation of a jet engine test cell owned and operated by Aircraft Engine Division of the Ford Motor Company. An explosive noise source was located at the position indicated in Fig 23 to approximate the location of the source of the jet noise. Measurements were made at three positions in the test section to find the average SPL in the reverberant field. Measurements were made at three positions in the control room in an attempt to

FIGURE 21



SPL AT EN-1 EXHAUST STACK POSITIONS.

FIGURE 22



SEVERAL NOISE REDUCTIONS OF AN EXHAUST ACOUSTICAL TREATMENT

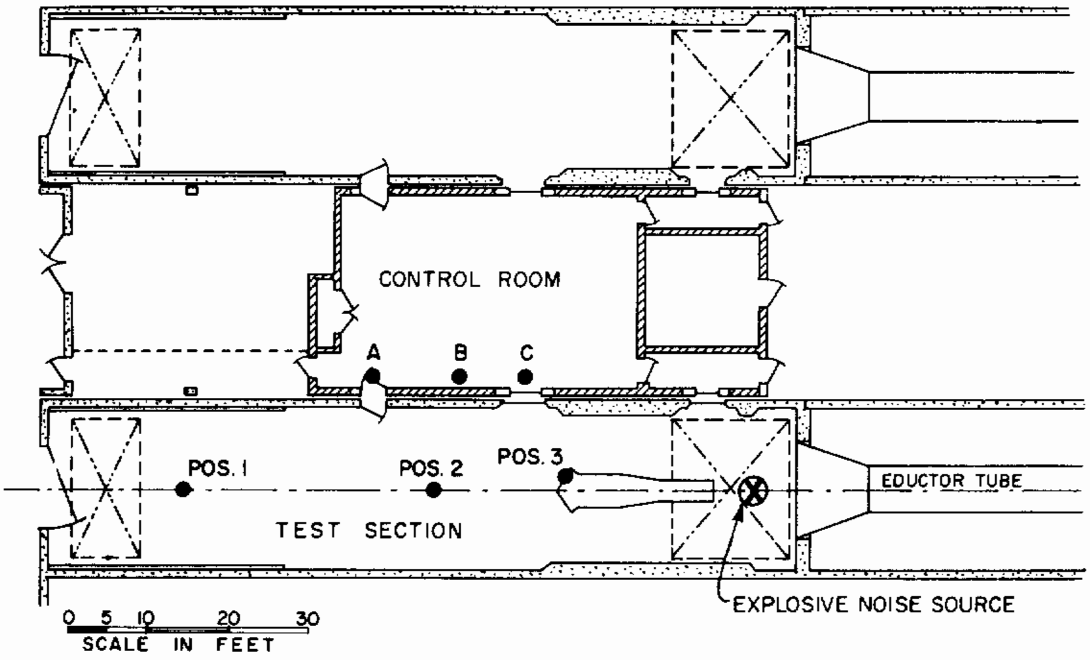


FIG. 23 PARTIAL PLAN OF FORD TEST CELL

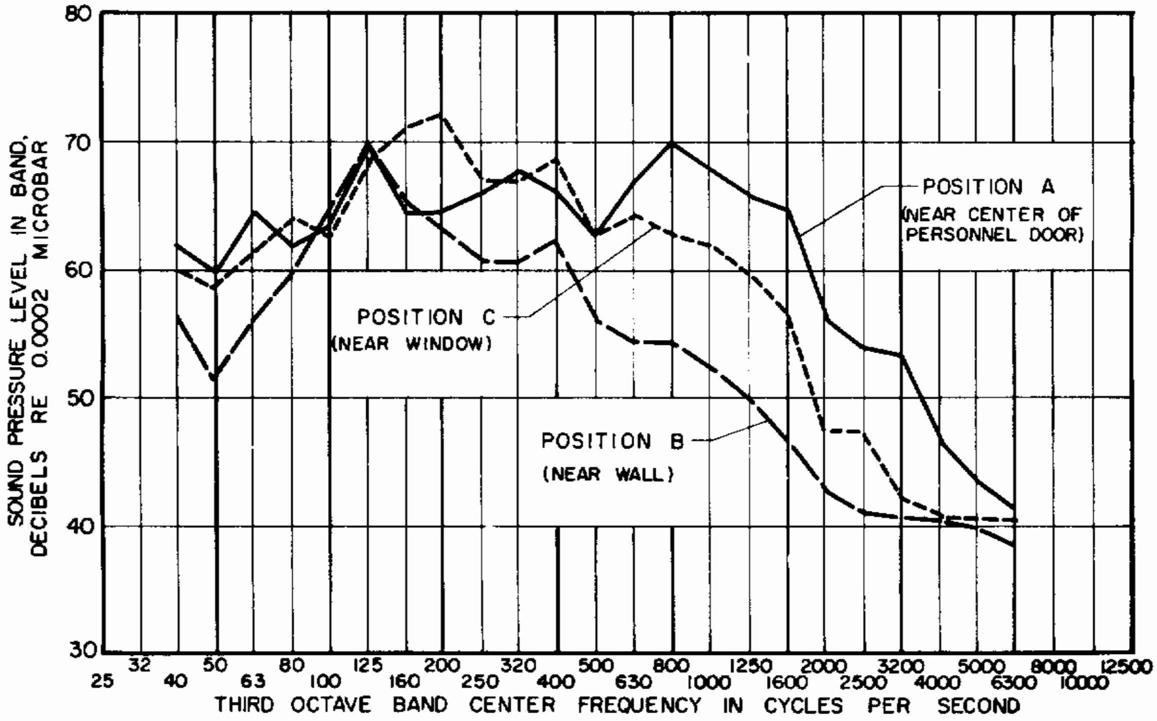


FIG. 24 SPL'S MEASURED IN CONTROL ROOM.

locate the primary "sources" of noise in the control room. The SPL's measured at the several positions in the control room are shown in Fig 24.

This example is particularly interesting because it clearly illustrates the problems involved in measuring the noise reduction of an individual component of the wall structure. As seen in Fig 24, the SPL measured near the door (Position A) is 5 to 10 db higher than the SPL's at the other two positions in the higher frequencies. It can also be seen that in the higher frequencies, the SPL near the window (Position C) is higher than the SPL near the wall (Position B). One cannot determine, however, if the SPL measured at the wall results from: 1) noise transmitted through the wall, 2) noise radiated by the window, or 3) noise radiated by the door. The noise reduction of the wall is certainly not less than the value which would be given by subtracting the SPL at the wall from the SPL in the test section, but it may be more if the SPL at the wall is due to 2) or 3) above.

It can be seen from the data, however, that the SPL near the door does not result from transmission through the wall or through the window. Similarly, the SPL near the window does not result from transmission through the door or through the wall. Thus, reliable measures of the noise reduction of the door and the window can be obtained.

REFERENCES

1. Air Force Regulation No. 160-3, "Hazardous Noise Exposure," 29 October 1956.

2. von Gierke, H. E. and A. C. Pietrasanta, *Acoustical Criteria for Work Spaces, Living Quarters, and other Areas on Air Bases, WADC Technical Note 57-248, Wright Air Development Center*, Wright-Patterson Air Force Base, Ohio, November 1957.

3. Eldred, K. M., W. J. Gannon, and H. E. von Gierke, *Criteria for Short Time Exposure of Personnel to High Intensity Jet Aircraft Noise, WADC Technical Note 55-355, Wright Air Development Center*, Wright-Patterson Air Force Base, Ohio, September 1955.

4. Rosenblith, W. A., K. N. Stevens, and the Staff of Bolt Beranek and Newman Inc., *Handbook of Acoustic Noise Control. Vol II, Noise and Man, WADC Technical Report 52-204(II), Wright Air Development* Center, Wright-Patterson Air Force Base, Ohio, June 1953.

5. Pietrasanta, A. C., and the Staff of Bolt Beranek and Newman Inc., *Guide for the Analysis and Solution of Air Base Noise Problems, WADC Technical Report 57-702, Aeronautical Systems Division*, Wright-Patterson Air Force Base, Ohio, November 1961.

6. Stevens, K. N., A. C. Pietrasanta, and the Staff of Bolt Beranek and Newman Inc., *Procedures for Estimating Noise Exposure and Resulting Community Reaction from Air Base Operation, WADC Technical Note 57-10, Wright Air Development Center*, Wright-Patterson Air Force Base, Ohio, April 1957.

7. "Uniform Practices for the Measurement of Aircraft Noise," Aircraft Industries Association, Report No. ARTC-2, pp 7 and 8, August 1952.

8. Harris, C., Editor, *Handbook of Noise Control*, McGraw-Hill Book Co., New York, 1957.

9. Peterson, A. P. G. and L. L. Beranek, *Handbook of Noise Measurement*, General Radio Co., Cambridge, Massachusetts, 1956.

10. Bolt, R. H., S. J. Lukasik, A. W. Nolle, A. D. Frost, and the Staff of Bolt Beranek and Newman Inc., Handbook of Acoustic Noise Control, Volume I - Physical Acoustics, WADC Technical Report 52-204(I), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December 1952.

11. Kamperman, G. W., "A Portable Magnetic Tape Recorder for Acoustical Measurements," Noise Control, Vol 4, 1, pp 23-27, January 1958.

12. Ingard, U., "The Physics of Outdoor Sount", Proceedings of the Fourth Annual National Noise Abatement Symposium, National Noise Abatement Council, New York, 23 and 24 October 1953.

13. Keast, D. N. and F. M. Wiener, "An Empirical Method for Estimating Wind Profiles over Open, Level Ground," Transactions, American Geophysical Union, Washington 5, D. C., March 1958.

14. Franken, P. A. and E. M. Kerwin, Jr., Methods of Flight Vehicle Noise Prediction, WADC Technical Report 58-343, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, November 1958.

15. Beranek, L. L., Acoustics, McGraw-Hill Book Co., New York, 1954.

16. Kamperman, G. W., Instrumentation for Evaluation of Engine Test Cells, WADC Technical Report 55-115, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, April 1955.

17. Galloway, W. J., B. G. Watters, and J. J. Baruch, "An Explosive Noise Source," Journal of the Acoustical Society of America, Vol 27, 2, p 220, March 1955.

18. Doelling, N., R. H. Bolt, and the Staff of Bolt Beranek and Newman Inc., Noise Control for Aircraft Engine Test Cells and Ground Run-up Suppressors. Vol 2. Design and Planning for Noise Control, WADC Technical Report 58-202[2], Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, November 1961.

19. Doelling, N. and the Staff of Bolt Beranek and Newman Inc., Noise Control for Aircraft Engine Test Cells and Ground Run-up Suppressors. Vol 3. An Engineering Analysis of Measurement Procedures and Design Data, WADC Technical Report 58-202(3), Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, November 1961.

APPENDIX A

SOME METHODS FOR ESTIMATING THE EFFECTS OF OBSTACLES UPON MEASURED SOUND PRESSURE LEVELS AT 250 FT

Sometimes it will not be possible to find a measurement site which is not obstructed by large immovable objects such as buildings, other test facilities, etc. Since the measurements should represent only the acoustical performance of the test facility, and not the acoustical shielding or reflecting properties of obstacles, all data which are influenced by obstacles must be eliminated before determining the insertion loss noise reduction of the facility. The paragraphs below suggest some ways of estimating the extent of the influence of obstacles.

If an obstacle lies between the noise source and the measurement position, data which were "optically shielded" from any portion of the test facility should be eliminated from further consideration. An example of an "optically shielded" portion of the measurement circle is shown in Fig A-1. In the example shown, all data obtained in the angular region θ should be eliminated from consideration.

SPL measurements may also be influenced by obstacles that lie beyond the measurement circle, because of reflection of sound energy back towards the measurement circle. Consider two cases, one in which the noise radiated at an angle θ is reflected back on itself, and another in which the noise radiated at an angle θ_1 is reflected back to another point on the measurement circle θ_2.

The first case is illustrated in Fig A-2(a). Noise radiated from the test facility at an angle θ is reflected from a building a distance <u>a</u> from the measurement circle. The

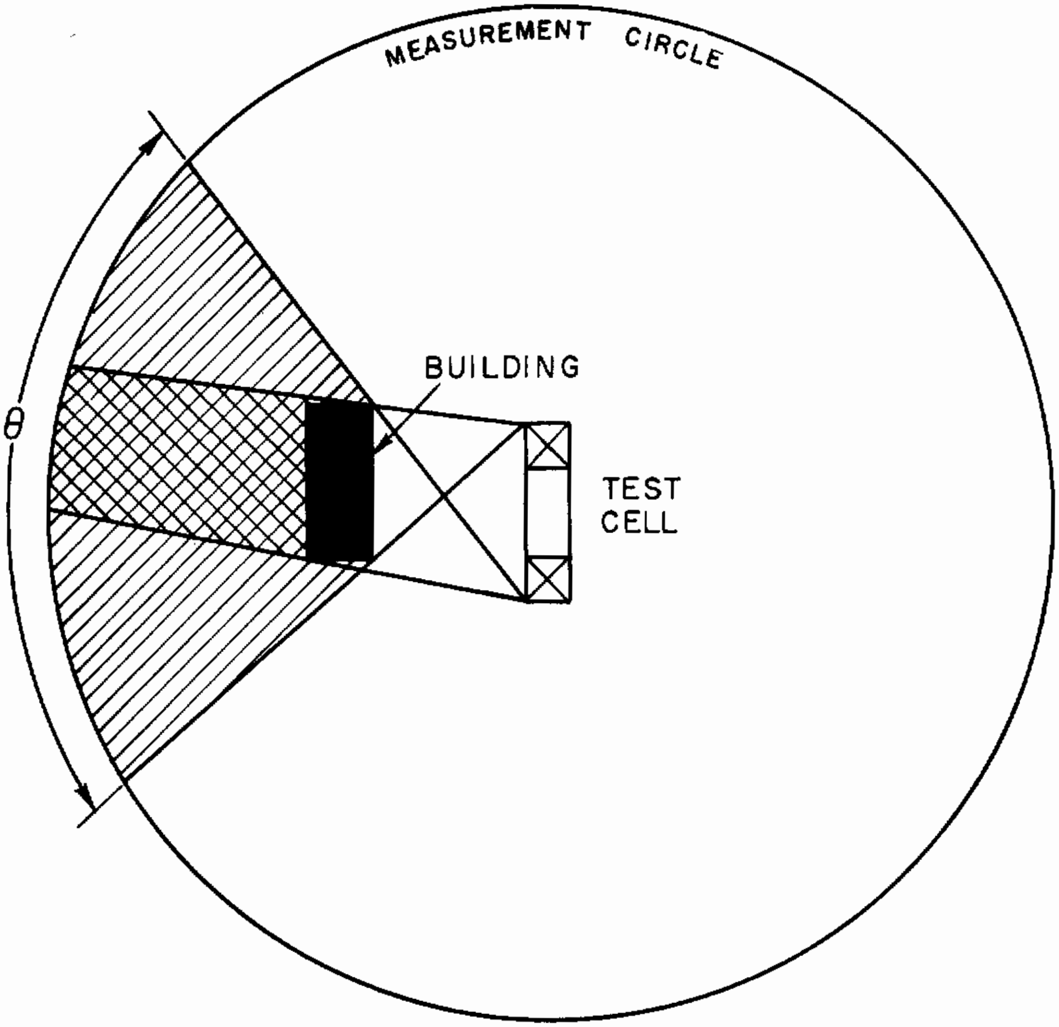
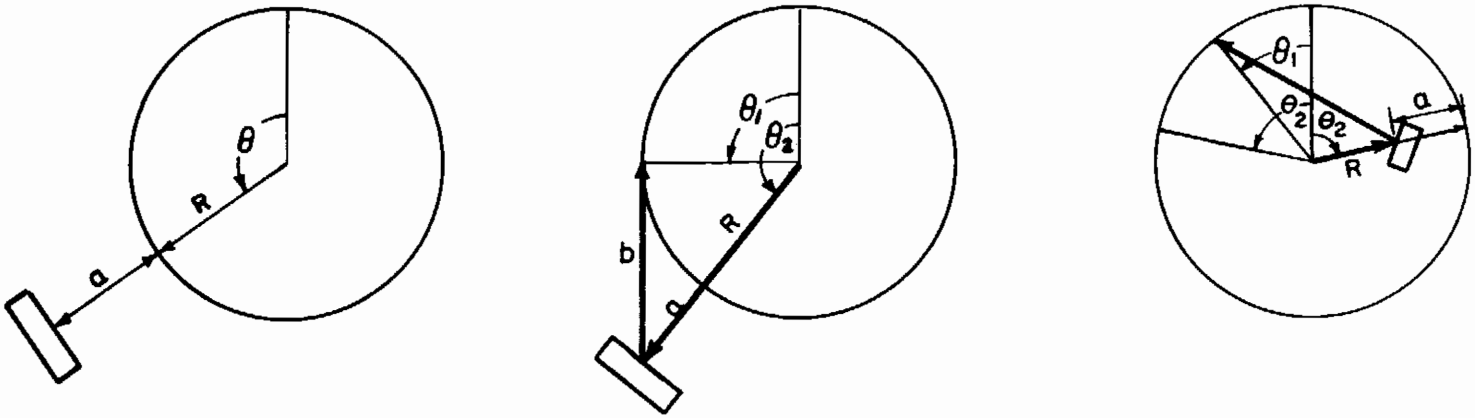


FIG.A-I AN "OPTICALLY SHIELDED" REGION ON THE MEASUREMENT CIRCLE



(a) (b) (c)

FIG. A-2 GEOMETRY USED FOR CALCULATING THE EFFECTS OF OBSTACLES magnitude of the reflected component can be calculated approximately by using simple inverse square law considerations. The direct sound has traveled a distance R from the source and the reflected sound has traveled a distance (R + 2a) from the source. The difference in level between the direct and reflected sound pressure levels is $20 \log_{10} (\frac{R + 2a}{R})$. The level of the direct noise can be calculated from the total noise level and the level of the reflected noise relative to the direct noise. Table A-1 gives the level of the direct noise relative to the measured level for R = 250 ft and several ranges of the distance a.

TABLE A-1

LEVEL OF DIRECT NOISE RELATIVE TO THE MEASURED NOISE LEVEL AT 250 FT

a in ft	SPL Measured - Direct SPL db
25-75	2
75-175	1
greater than 175	0

If a is less than 25 ft, the level of the direct sound cannot be accurately found and the measured data should be eliminated from consideration. Table A-1 may be used if a is greater than 25 ft to find the direct noise levels which are to be used in determining the insertion loss noise reduction.

The second case is illustrated in Fig A-2(b) In this case, one must inquire whether the levels measured at θ_1 on the circle are caused by direct radiation from the test facility or by noise radiated at an angle θ_2 and reflected from the obstacle to the point θ_1. Again using inverse square considerations, the SPL at θ_1, SPL_{θ_1}, due to radiation past θ_2 will be approximately:

$$SPL_{\theta_1} = SPL_{\theta_2} - 20 \log_{10} [R/(R + a + b)] \qquad (A-1)$$

If the calculated levels are more than 2 db below the measured levels, the measured levels may be considered reliable. If the levels at θ_1, calculated by the above formula, are not more than 2 db lower than the measured level at θ_1, it is very probable that the measured levels at θ_1 are due to reflections. In such cases the data at θ_1 cannot be considered reliable and should be discarded.

Another version of the second case is presented in Fig 4(c). An obstacle on one side of the measurement circle reflects noise to the other side of the circle. This problem can be solved in a manner analogous to that described for the second case by substituting (-a) for (+a) in the above expression, and assuming the SPL at θ_2 is equal to the SPL which would be measured at $(-\theta_2)$ if the building were not present.

If it is necessary to eliminate data at some positions because of obstacles, it may be possible to obtain the approximate SPL by interpolating from the data at two adjacent measurement positions. However, any data obtained by extrapolation techniques should be so noted.

APPENDIX B

A PLAN FOR A SIMPLE MICROPHONE WINDSCREEN

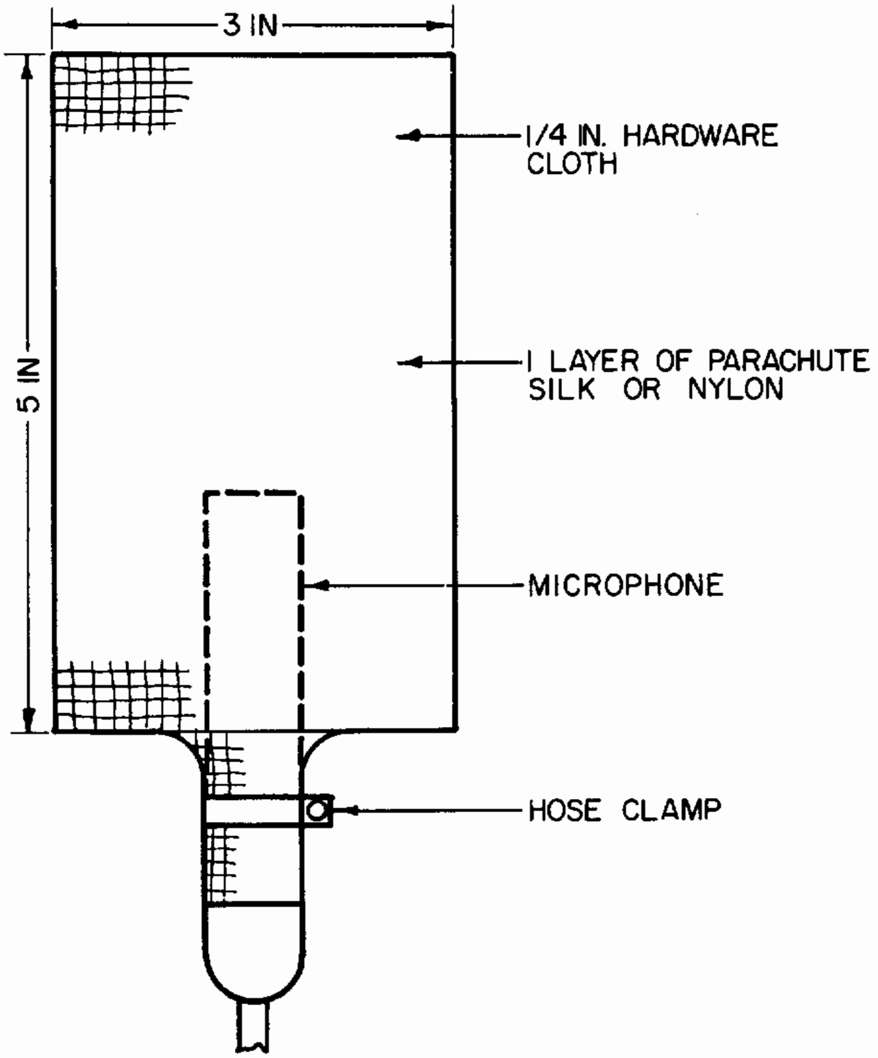


FIG. B-1 A SIMPLE MICROPHONE WINDSCREEN.