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DDC TECHNICAL REPORT 58-202 (2)

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

Volume 2: Design and Planning for Noise Control

**NORMAN DOELLING
RICHARD H. BOLT**

**AND
THE STAFF OF BOLT BERANZ AND NEWMAN INC.**

NOVEMBER 1961

PROJECT No. 33(61-0)-35
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AERONAUTICAL ENGINEERING LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

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<p>Aeronautical Systems Division Aerospace Medical Laboratory Wright-Patterson AFB, Ohio, Rpt. No. WADC-TR-58-202 (2). NOISE CONTROL FOR AIR-CRAFT ENGINE TEST CELLS AND GROUND RUN-UP SUPPRESSORS. Vol. 2. Design and Planning for Noise Control. Final report, Nov. 1961, xiii + 192 pp, incl. illus., tables, 22 refs. This is part 2 of 3 parts. Unclassified report</p> <p>This volume is the second in a series of three volumes on the physical aspects of noise control in aircraft engine test cells and ground run-up suppressors. This volume provides methods for planning and designing engine test cell facilities. Procedures are presented for determining noise reduction requirements of an aircraft engine test cell from the noise source characteristics, the acoustic criteria and the location. The reference test cell concept is used. Procedures for designing a facility to meet these noise reduction requirements are presented. The analysis and design of ground run-up noise suppressors are similarly treated, but in less detail.</p>	<p>UNCLASSIFIED</p> <p>1. Acoustics 2. Jet Engine Noise 3. Damping 4. Ground Support Equipment I. ARDC Project 7210 Task 71708 II. Biomedical Laboratory Contract AF 33 (616)-3335 Contract AF 33(616)-3938 UNCLASSIFIED</p>	<p>UNCLASSIFIED</p> <p>1. Acoustics 2. Jet Engine Noise 3. Damping 4. Ground Support Equipment I. ARDC Project 7210 Task 71708 II. Biomedical Laboratory Contract AF 33 (616)-3335 Contract AF 33(616)-3938 UNCLASSIFIED</p>	<p>UNCLASSIFIED</p> <p>1. Acoustics 2. Jet Engine Noise 3. Damping 4. Ground Support Equipment I. ARDC Project 7210 Task 71708 II. Biomedical Laboratory Contract AF 33 (616)-3335 Contract AF 33(616)-3938 UNCLASSIFIED</p>
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Project 7210

Task 71708

**BIOMEDICAL LABORATORY
AEROSPACE MEDICAL LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

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 Wright Air Development Center under 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, Bioacoustics Branch, Aerospace Medical Laboratory, Aeronautical Systems Division,* Wright-Patterson Air Force Base, Ohio.

This is the second of three volumes concerning physical effects of noise control in aircraft engine test cells. Volume 1 presents recommended procedures for measuring noise control effectiveness and Volume 3 presents a technical justification for many of the procedures described herein and in Volume 1, 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 the preparation of this report.

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.

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

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ABSTRACT

This volume is the second in a series of three volumes on the physical aspects of noise control in aircraft engine test cells and ground run-up suppressors. This volume provides methods for planning and designing engine test cell facilities. Procedures are presented for determining noise reduction requirements of an aircraft engine test cell from the noise source characteristics, the acoustic criteria and the location. The reference test cell concept is used. Procedures for designing a facility to meet these noise reduction requirements are presented. The analysis and design of ground run-up noise suppressors are similarly treated, but in less detail.

PUBLICATION REVIEW

This report has been reviewed and approved.

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Colonel, USAF, MC
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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^{22/}
2. Design and Planning for Noise Control
3. An Engineering Analysis of Measurement Procedures and of Design Data.^{23/}

These three volumes deal only with the physical aspects of noise control. The present volume explains how to design a test facility to meet a criterion for noise control but it does not deal with the establishment of criteria. Information concerning the psychological and physiological problems of criteria for noise control is contained in other Air Force reports^{1-6/}.

The acoustical design of an aircraft engine test facility involves two steps; determination of noise reduction requirements and the attainment of these requirements. In the beginning of this report a systematic procedure is presented for finding the noise reduction requirements for an engine test facility. These requirements can be determined simply from a consideration of the acoustical criteria and certain engine performance parameters (thrust, mass flow, etc., for a jet engine and horsepower, blade tip speed, etc., for a propeller

engine) which are correlated with the noise characteristics of the engine.

The attainment of the required noise reduction is discussed in subsequent sections. Emphasis is placed on control of noise by planning rather than by the use of massive double wall structures and large amounts of acoustical treatment for air passages.

The aerodynamic aspects of design are considered insofar as they influence acoustical design. A subsequent report^{7/} considers the aerodynamic aspects in detail.

A series of appendices which contain technical data is incorporated to minimize reference to other reports. With the exception of information on criteria, these appendices contain essentially all of the engineering data that are required for design purposes. The methods presented in the report and the use of the data in the appendices are illustrated by examples throughout the text.

SECTION II

ANALYSIS OF NOISE REDUCTION REQUIREMENTS

This section presents a systematic procedure for determining noise reduction requirements. The procedure set forth here is general, in that the outline of the procedure can be used for all noise control problems. The steps in the procedure are developed in terms of noise reduction requirements for aircraft test facilities. In the broad aspects, the procedure is equally applicable to engine test cells and ground run-up suppressors. However, certain specific portions of the procedure are developed here with an emphasis on jet engine test cell design. Alternate procedures are suggested in the Appendices and in Section V, for those situations in which the specific methods or data would be markedly different from those used in the present chapter.

A. General Discussion of Procedures

1. The Noise Flow Diagram Method of Analysis

Noise control design for aircraft test facilities involves many inter-related steps that can be broken down to three parts:

1. A source of noise, such as a jet engine;
2. A path, over which the noise is transmitted; and
3. A receiver, such as a test cell operator or a resident in a nearby community.

Each part can be analyzed quantitatively in engineering terms. The source-path-receiver relations, shown diagrammatically in Fig 1, are very helpful in reducing the noise control problem to an orderly sequence of steps.

As indicated in Fig 1, this three-part division is complicated in that each part may contain a multiplicity of components. Multiple sources, for example, are found in a single jet engine; some noise is radiated from the intake, some from the jet stream to the rear of the engine and some from the combustors. Furthermore, the noise at the receiver may originate from several test cells, ground run-up operations, and aircraft fly-overs.

Multiple paths may include walls, doors, windows, and air intake and exhaust passages. Multiple receivers may include residents in surrounding communities, personnel in adjacent buildings, and personnel in work spaces associated with the operation of the test facility.

Constructing a noise flow diagram is the first step in any noise control problem. The noise flow diagram shown in Fig 1 represents a typical test cell. The noise source, S, radiates a certain acoustic power into the test section. This acoustic power creates certain sound pressure levels* (SPL's) at positions B-1, B-2, etc., near the engine. The sound pressure levels are diminished as they progress along the several paths, such as the air intake and exhaust and the building structure, so that lower sound pressure levels are found at the output of these paths, C-1, C-2, etc. The intake, the exhaust, and the building structure radiate sound energy towards the several receiver locations. The sound pressure levels at locations D-1, D-2, and R-1, R-2, etc. are lower than the sound pressure levels at C-1, C-2, etc., because of spreading of sound energy and atmospheric effects.

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

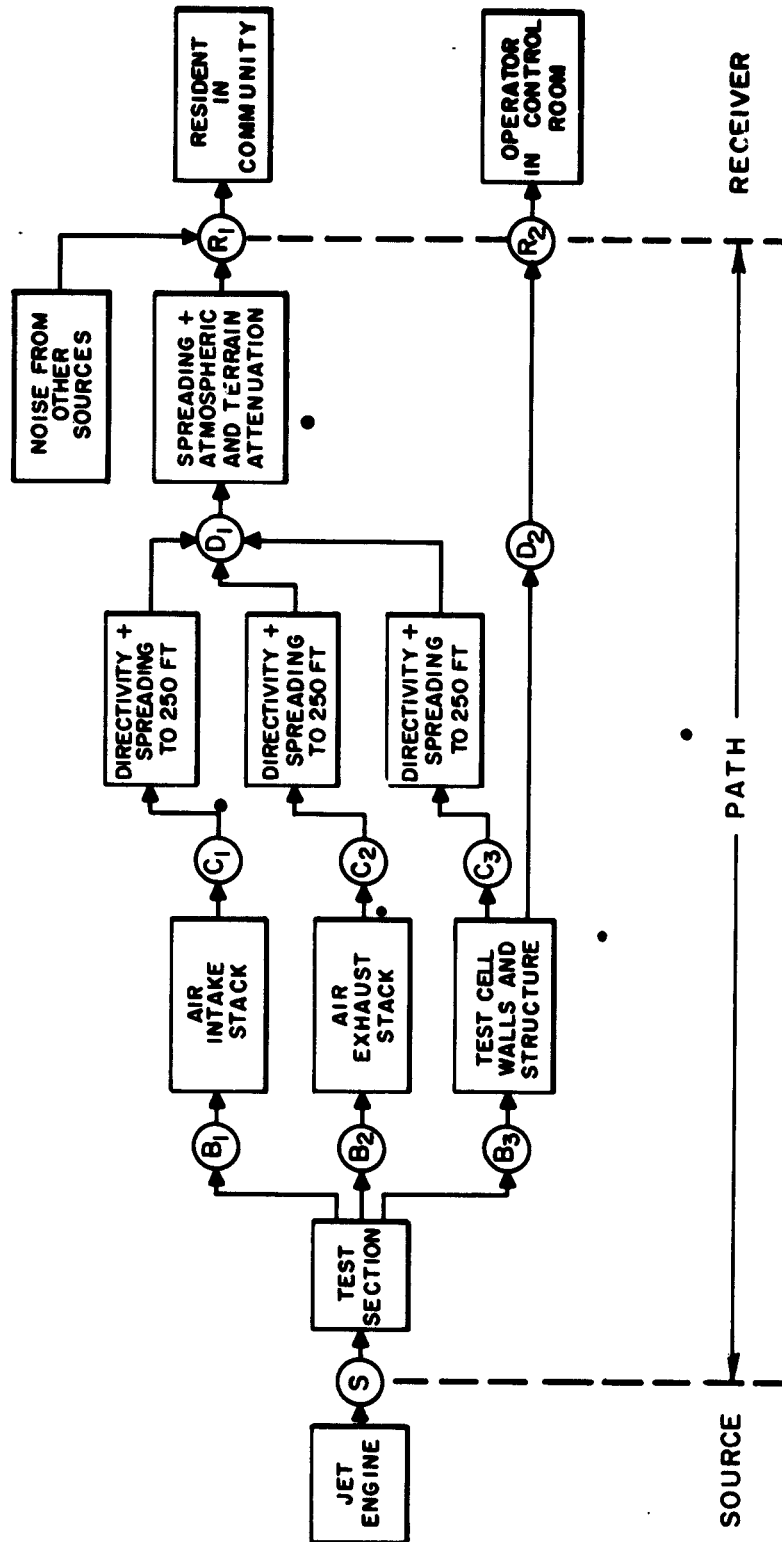


FIG. 1 A NOISE FLOW DIAGRAM

The analysis and design of noise control is a system problem. The total system, as described above, contains sources, paths, and receivers. The noise flow diagram is an engineering representation of the relevant components, their connections, their inter-relations and their effects on the noise fields. Any noise control problem, as presented to the engineer, can at once be depicted in a noise flow diagram, but one that does not, as yet, contain noise control measures. During the successive steps in design, the noise flow diagram can be modified to incorporate the proposed noise control components. Noise flow diagrams thus provide a convenient framework within which noise control problems can be analyzed systematically.

The noise flow diagram in Fig 1 suggests the basic method underlying solutions to all noise control problems. Briefly, one evaluates all "losses" of sound intensity (S to B to C to R in Fig 1) between source and receiver with the test facility present and compares the resulting sound pressure level at the receiver with the criterion or required sound pressure levels at the receiver. The difference between these two sound pressure levels is just the net or total noise reduction which must be obtained to accomplish a satisfactory noise control design.

In principle the procedure is simple; in practice complex. For example, the directivity losses depend on the dimensions and geometry of the final design. But, in turn, the dimensions depend on the aerodynamic requirements, such as static pressure drop limitations for the intake, treatment and velocity limitations for all acoustical treatments. But these aerodynamic requirements are influenced by the acoustical treatments that will be necessary to

satisfy the noise reduction requirements which cannot be found until the exact value of the directivity is known.

Obviously, the design procedure is circuitous and the solution must be obtained by an iterative procedure. One way to start this procedure is to make certain arbitrary assumptions regarding the geometry, the dimensions, and the aerodynamic requirements. Extensive experience with problems of this type has led to the concept of a reference test cell which gives an arbitrary but realistic starting point for an iterative design procedure.

2. The Reference Test Cell Concept

A reference test cell is a guess at the final design; a guess based on experience, but none-the-less a guess to start the iterative procedure. From experience one can make quite accurate predictions of the probable geometry, dimensions and aerodynamic limitations of the final design. From this first guess, or reference test cell, one can evaluate the directivity losses, spreading losses and losses at "bends" in air passages. Knowing the noise source levels which can be determined from engine parameters, and the total losses, one finds the sound pressure levels at the various receivers. A close estimate of the required noise reduction is then given by the difference between the sound pressure levels found at the receivers for the reference condition and the required sound pressure levels.

A reference noise concept can be, and generally is, applied to all forms of noise control problems. The more closely the reference situation resembles the final situation, the more useful the reference concept becomes. The concept is most useful, therefore, for classes of problems in which

considerable engineering experience has already been gained. Aircraft engine test facilities constitute such a class.

The reference cell must provide a realistic estimate for the design of a suitable environment for engine testing and for incorporation of noise reducing components. The reference test cell may include special features of geometry and construction that contribute to noise control, or that will be needed to accommodate noise attenuating treatments, but it does not include such treatments per se.

The approximate open area of the air passages can be estimated from velocity and temperature limitations of acoustical materials and from approximate intake pressure drop requirements. As acoustical treatments will occupy roughly one half of the cross section of an air passage, the total cross section of the air passage is about twice the open area requirement.

In the next section, the concept of a reference condition is illustrated for a jet engine test cell. In later sections, the steps necessary in determining the noise reduction requirements are detailed. Where the procedures outlined below are fundamentally different for other noise control problems, such as jet engine ground run-up mufflers or test cells for reciprocating engines and turboprops, specific procedures are discussed in other portions of the text. (See especially Appendix A for noise source characteristics of other engines and Section V for a discussion of noise reduction requirements for ground run-up suppressors).

3. Assumptions for the Design of the Reference Test Cell

The assumptions made for determining the geometry and dimensions of the reference test cell are listed below. The limitations imposed on acoustical materials by gas velocity and temperature are based on typical conditions required in many contemporary facilities. The designer may want to vary the numerical values given in items 4 and 6 below to fit special conditions. The assumptions and limitations are as follows:

1. The test cell has a "U" shape, with a vertical intake stack and a vertical exhaust stack at opposite ends of a horizontal test section, as sketched in Fig 2.
2. The intake stack, the exhaust stack, and the test section all have the same cross-sectional area.
3. The intake and exhaust stacks are treated with acoustical material that blocks 1/2 of the cross-sectional area.
4. The maximum allowable air velocity in the intake is 50 ft/sec*. This velocity is typical of that for standard lengths of noise reducing treatments and is set by the allowable pressure drop.
5. Only air is used for cooling the exhaust gases.
6. The maximum allowable temperature in the exhaust is 450°F. With this temperature, the exhaust velocity will be about double the intake velocity, which is below the point of erosion for standard noise reducing treatments.

4. Determination of the Required Cross-Sectional Area for the Reference Test Facility

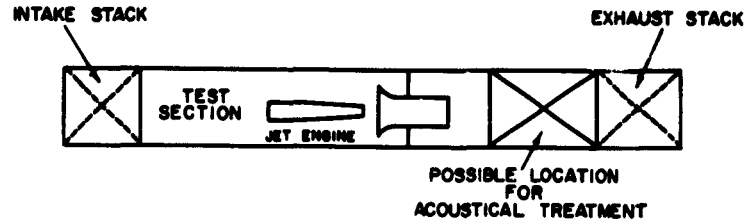
The previous list of assumptions and limitations can be

*In a more general case, one might independently specify linear velocity in both the intake and exhaust stacks. However, if the area of the intake and exhaust stacks are considered equal, and, in addition, if only air is used to cool the jet exhaust gases, then limitations on the exhaust gas temperature and intake air velocity completely specify the required cross-sectional area of the reference test facility.

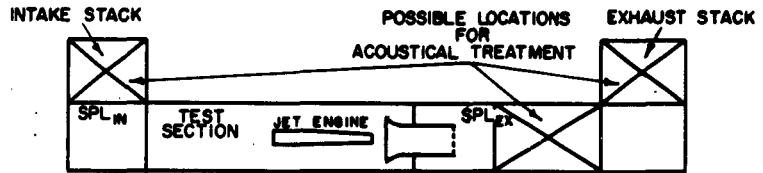
combined to determine the required cross-sectional area in terms of the air weight flow through the jet engine for which the test cell is designed. For the particular velocity and temperature values given in items 4 and 6 above, one finds that the required area is 1.5 sq ft for each pound per second of weight flow through the engine. For a typical J-57, the weight flow of air is about 170 lbs/sec. The required cross-sectional area of the test facility is therefore about 255 sq ft. The square root of the area which is used in determining the directivity index (see Appendix B) is therefore approximately 16 ft.

The derivation of the relation between the required area and weight flow is given in Appendix F. In addition to the assumptions about the reference test facility, certain assumptions have been made about the engine and atmospheric conditions. The exhaust gas temperature is assumed to be about 1150° F, a typical value for a jet engine operating at military power without afterburner. The ambient atmospheric conditions are those for a standard sea level NACA day. The methods for finding the relation between mass flow and area are given in a general form so that the designer may modify these assumptions, if, for example, afterburner operation is required or if the test facility is to be located at a high altitude in an extreme climate.

Having assumed the "U" shape, and having found the cross-sectional area of the reference test facility, one can now estimate the losses of sound intensity from the engine to the criteria locations. The next steps in finding the noise reduction requirements are to find the acoustic power level of the source and the sound pressure levels at the various locations B-1, B-2, C-1, C-2, etc., in the noise flow diagram.



PLAN



ELEVATION

FIG. 2 A REFERENCE TEST CELL.

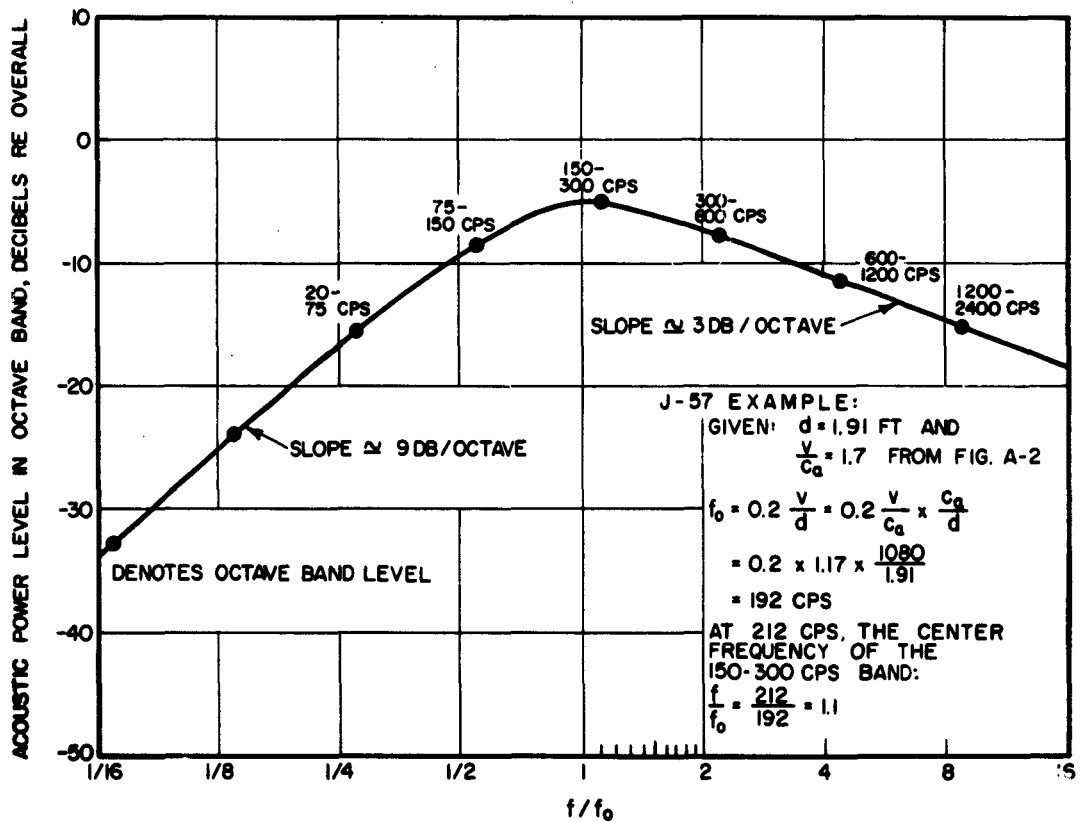


FIG. 3 A NON DIMENSIONAL JET SPECTRUM.

B. Noise Source Characteristics

1. Acoustic Power Levels

The acoustic power level* (PWL) of the engine in the reference test cell is found from relevant engine performance parameters. The equations and procedures used to calculate the overall acoustic power level are given in Appendix A. A summary of the information required and the procedures for finding the overall power level are given in Table I. The overall power level of the J-57 used in this reference test facility is found to be 174 db.

The octave band power levels are found from the overall power level by use of Eq A-6 and Fig A-4. The method for obtaining the power level spectrum from the engine parameters is illustrated in Fig 3** for the same typical J-57 engine which is used as an illustration in Table I. One finds from this figure that the power level in the 150-300 cps band, for example, is 5 db less than the overall power level, or 169 db.

The procedure outlined above for finding octave band power levels is applicable only for jet engines that do not have jet stream modifiers. For noise control problems, the jet stream modifier can be characterized by the noise reduction

*PWL = $10 \log_{10}(W) + 130$ db, where W is the acoustic power in watts.

**Note that the center frequency of the 20-75 cps band is taken to be one-half that of the 75-150 cps band. This is pedagogically simpler, though erroneous. The error involved is negligible (less than 1 db). The difficulties arise from the use of a 20-75 cps band, which is not an octave, rather than a 37.5-75 band which is an octave. Criteria have been developed through experience derived from 20-75 cps band data and it is, therefore, desirable to use the 20-75 cps band.

TABLE I
 PROCEDURE FOR FINDING THE OVERALL ACOUSTIC POWER LEVEL OF JET ENGINES

Step	Parameter	Dimensions	Source	Example (Typical J-57)
1. Locate	(a) Thrust, f (b) Weight flow of air, m (c) Tailpipe Temperature, T (d) Tailpipe Diameter	lbs/sec of ft	Engine Mfg. " " " "	10,000 170 - - 1.91
2. Find	Kinetic power of jet stream	watts	FIG A-1	13×10^6
3. Find	Jet velocity/ambient speed of sound, v/c_a	none	FIG A-2	1.7
4. Find	Conversion efficiency, η	none	FIG A-3	1.9×10^{-3}
5. Calculate	Acoustic power, W	watts	Item 2 } Item 4 }	2.5×10^4
6. Calculate	Acoustic power level, PWL	db re 10^{-13} watt	Item 5 } Eq (A-4) }	174 db

it affords. A jet stream modifier may be considered as a noise reduction element inserted between the noise source and the points B_1 , B_2 , and B_3 in Fig 1. The noise reduction characteristics of some jet stream modifiers are given in Appendix E. Generally, one will have to evaluate the power level reduction characteristics of such devices by field measurements. The change in acoustic power level (as a function of octave bands of frequency) afforded by the jet stream modifier can be added, algebraically, to the sound pressure levels at positions B_1 , B_2 , and B_3 , which are found by the methods of paragraph 2 below. The remainder of the analysis is then carried out as without an exhaust diffuser.

2. Sound Pressure Levels in the Reference Test Cells

The sound pressure levels at the "input" to the exhaust and intake acoustical treatments (see Fig 2) can be found from the acoustic power levels and the cross-sectional area of the test section. The relations between the octave band sound pressure levels and the octave band power levels are calculated from the equations A-7, and A-8 in Appendix A. For the J-57 engine used in the previous examples and for the reference test facility dimensions found in paragraph A above, the 150-300 cps octave band sound pressure level at the exhaust acoustical treatment is, from Equation A-7:

$$\begin{aligned}
 \text{SPL}_{\text{ex}} &= \text{PWL} - 10 \log_{10} A_{\text{ex}} \\
 &= 169 - 10 \log_{10} (255) \\
 &= 145 \text{ db} \qquad (1)
 \end{aligned}$$

From Eq A-8 and Fig A-5, the 150 - 300 cps octave band sound pressure level at the input to the intake acoustical treatment is:

$$\begin{aligned}
\text{SPL}_{in} &= \text{PWL} - 10 \log_{10} A_t + C & (1a) \\
&= 169 - 24 - 10 \\
&= 135
\end{aligned}$$

and the 150-300 cps octave band sound pressure level in the reverberant field of the test cell is:

$$\begin{aligned}
\text{SPL} &= \text{PWL} - 10 \log_{10} A_t + C & (2) \\
&= 169 - 24 - 6 \\
&= 139 \text{ db}
\end{aligned}$$

3. Sound Pressure Levels Outside of the Reference Test Cell

The sound pressure levels outside of the reference test cell are found by subtracting from the sound pressure levels at the input to the acoustical treatments the losses of bends, the directivity losses and the inverse square or spreading losses at a distance r from the reference test cell. The sound pressure level at a distance r caused by the sound pressure level at the exhaust is:

$$\text{SPL}_r = \text{SPL}_{ex} - B + 10 \log_{10} A_{ex} - 10 \log_{10} (2\pi r^2) - DI \quad (3)$$

in which SPL_r is the sound pressure level at a distance r from the reference test facility,

SPL_{ex} is the sound pressure level at the input to the exhaust acoustical treatment,

B is the loss around an unlined bend in the exhaust passage (4 db in all bands - see Appendix C).

A_{ex} is the area of the exhaust gas passage, and
DI is the directivity index of the exhaust
acoustical treatment (see Fig B-1, Appendix B).

The sum of the third and fourth terms are the net loss of sound pressure level due to spreading, or spherical divergence.

A similar equation could be written for the sound pressure level at a distance r which results from the sound pressure level at the input to the intake acoustical treatment. The subscript, ex, would be replaced by the subscript, in. The term, B, would be zero because the sound pressure level at the intake which has already been determined is beyond the bend in the intake (see Fig 2).

Throughout the design procedure, one continually uses equations of the form of Eq (3). Rather than evaluating Eq (3) at each of the criteria distances, r_1 , r_2 , r_3 , etc., it is generally more convenient to evaluate the sound pressure level at one fixed distance from the test facility. A convenient value for r has been found to be 250 ft (see Volume One or Volume Three of this series).

The criteria at the several distances must then also be translated to 250 ft for comparing the criteria with the sound pressure levels from the reference test cell. The method for the translation of criteria is given in a following paragraph. In Table II below, the method for finding the sound pressure levels at 250 ft which result from the sound pressure levels at the input to the exhaust and intake treatments is illustrated for the engine and reference test facility used in the previous examples.

TABLE II
 CALCULATION OF SOUND PRESSURE LEVELS AT 250 FT
 FROM THE REFERENCE TEST CELL
 (150-300 cps Band Only)

<u>STEP</u>	<u>INTAKE</u>	<u>EXHAUST</u>	<u>SOURCE OF DATA</u>
1. SPL at input to acoustical treatment, db	135	145	Eqs 3 and 4
2. Loss of SPL around 90° Bend db	—	4	Appendix C
3. Spreading Loss to 250' = $10 \log_{10} 2\pi(250)^2 - 10 \log 255$	32	32	Area of Ref. cell cross-section and area of 250' hemisphere
4. Directivity Loss, db	15	12	Area of Ref. cell and Figs B-1, B-2
5. Total Losses to 250', db	47	48	Sum of Items 2, 3, and 4
6. SPL at 250', db	88	97	Item 1 - Item 5

4. Summary

At this point, the noise levels at a given distance from the test facility have been found. This has been accomplished by assuming a reasonable geometry for the test cell and by assuming certain values for flow conditions in the test cell. These assumptions lead to a rough estimate of a cross section of the cell (approximately 16' x 16'), and permit a reasonable determination of the directivity indices.

From engine parameters, the acoustic power level of the engine is found. The sound pressure levels at 250 ft from the cell have in turn been obtained.

The values of the criteria sound pressure level at 250 ft must now be found.

C. Acoustical Criteria

1. Discussion

The selection of acoustical criteria at locations on and around air bases is a complex problem which has been treated at length in References 1 through 6. In this Volume, it is assumed that the acoustical criteria at various locations in and around the test facility have been established. These criteria may include the maximum allowable noise levels in communities surrounding the air base, in office buildings, living spaces, hospitals, and recreation areas on the base^{2/}. The criteria may also include maximum allowable noise levels in the control room and adjacent work spaces associated with the test cell or ground run-up suppressor or both (see especially Section IV of Ref. 2).

The establishment of criteria for permissible noise

levels from a single engine test cell requires information concerning the anticipated operating schedule of the test cell in question as well as all other adjacent test cells. Furthermore, one must know, or assume, the detailed location, orientation, and scheduling of other noise sources, such as aircraft ground run-up and take-off activities, noises from nearby manufacturing operations, etc. Several significant factors of aircraft flight operations, including the runway utilization and the flight profiles for each type of aircraft, must also be known⁶. Similarly, the selection of a criterion for minimization of damage risk to personnel must include a consideration of not only their exposure to noise from the test facility but also their exposure to noises from other sources³.

The end result of a criteria analysis is most usefully expressed as a set of octave band noise levels which are not to be exceeded when an engine is operating at some specified condition in a single test cell. The allowable noise levels from a single cell must be determined by considering the operating schedules of all test cells and all other noise activities in the surrounding area.

2. Translation of Criteria to Reference Locations

The criteria at the several positions around the test facility are to be compared with the noise levels from the reference cell for an initial estimate of the noise reduction requirements. This comparison could be obtained by calculating the SPL's from the test cell at each of the criterion locations. It is usually better to transform the criterion levels back to the reference distance from the cell by adding the appropriate inverse square and ground and air losses to the criterion. There are two reasons for following the latter course. First, translating the criteria

to a standard distance facilitates the comparison of the several different criterion requirements that may be imposed in a particular problem. The final design must satisfy the most stringent of these requirements in each frequency band. Second, the iterative nature of the design procedure may require comparison of the criteria with the noise levels from the cell several times.

The allowable sound pressure levels at a distance of 250 ft from the engine can be found by adding the propagation losses given in Fig 4 to the criterion levels.

A list should be compiled which shows the acoustical criterion at each location around the engine test cells. This list should include the criterion location, the criterion sound pressure levels in octave bands, the distance from each criterion location to the jet engine, the corrections to be added to the criterion to obtain the criterion values at 250 ft, and finally the criterion sound pressure levels on the 250 ft circle.

A sample worksheet for one octave band (150-300 cps) is shown in Table III below. Only a few representative criteria locations are indicated. Generally, there would be many more.

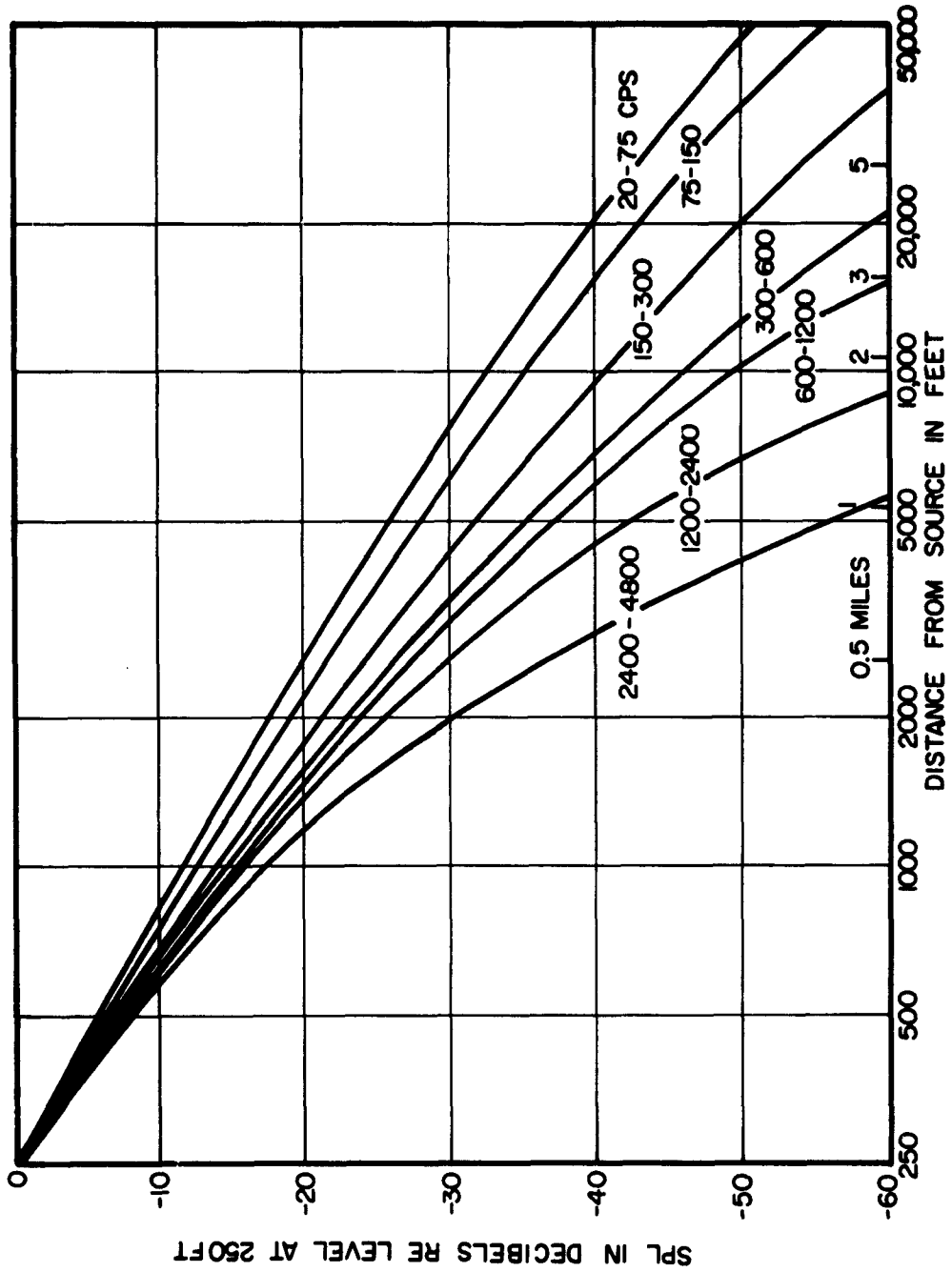


FIG. 4 CONSERVATIVE VALUES OF REDUCTION OF SOUND PRESSURE LEVEL WITH DISTANCE FOR JET AIRCRAFT OPERATING ON THE GROUND: TEMPERATURE GRADIENTS AND WIND SPEEDS ARE ASSUMED TO BE VERY LOW.

TABLE III
 SAMPLE CRITERIA WORKSHEET
 (150-300 cps BAND ONLY)

Criterion Location	Criterion* SPL	Distance from Criterion Location to Jet Engine	Correction to Criterion (from Fig 4)	Criterion SPL on 250' Ref. Circle
1. Base Operations Office	76 db	700'	11	87
2. Officers' Housing	63	1,000	14	77
3. Off-Base Residential Community	62	2,500	23	85
4. Airmen's Classroom Building	72	2,000	21	93
5. Base Hospital	60	5,000	33	93

*The criteria levels given above for offices, classrooms, and the hospital have been obtained by adding to the appropriate criterion level in each space, the noise reduction of the walls of the building.

It should not be concluded from such a table, that the location yielding the lowest criterion level in a particular band will yield the lowest values in all octave bands. The spectra of the criterion levels for communities and office spaces differ. Furthermore, losses through building structures and propagation losses, alter the spectra of the different criteria. Hence, a separate determination must be made of the lowest levels in all bands using the criterion levels from all locations of interest.

D. Noise Reduction Requirements

The establishment of a reference test cell for use with a particular engine, a J-57, was discussed in previous paragraphs of this section. The acoustic power level for the engine was calculated from the given operating characteristics. Formulas were then presented and examples worked out for determining the sound pressure levels in the test section and at 250' from the test cell. A description of how to transfer the criteria for noise in neighborhood and working areas to the reference locations was given. Enough information has now been given to permit determination of the noise reduction requirements for the reference test cell. After these requirements are known, the first steps toward the selection of acoustical treatments can be made. It is probable that modifications will then be necessary to the reference cell and the whole process will be repeated.

The noise reduction requirements for the reference noise condition are obtained by comparing the calculated sound pressure levels on the 250' circle with the criterion sound pressure levels on the 250' circle.

1. Noise Reduction Requirements on the 250 Ft Reference Circle

The total sound pressure levels on the 250 ft reference circle are obtained by adding (on an intensity basis) the contributions from the exhaust and the intake. The most stringent (lowest) criterion level (in decibels) in each octave band is subtracted from the reference noise level to obtain the noise reduction requirements for each band. The addition on an intensity basis of sound pressure levels in decibels can be carried out by use of the bar chart of Fig 5.

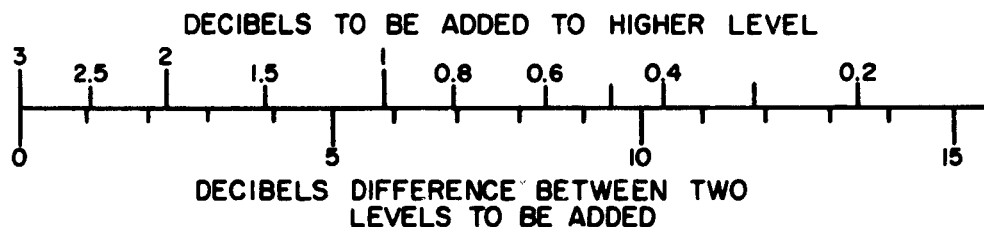


FIG.5 LINE CHART FOR THE ADDITION OF SOUND PRESSURE LEVELS ON AN INTENSITY BASIS.

The application of this bar chart can best be illustrated by example. Using the numbers from the example that was carried through in paragraph D, above, the contribution from the intake is 88 db and the contribution from the exhaust is 97 db. Fig 5 shows that for a difference in level of 9 db, the sum of the two levels is about 0.5 db greater than the larger level. In design, a quantity of less than 1.0 db is negligible. So, the total SPL on the circle is about 97 db.

After acoustical treatments are added to the test cell, the intake, the exhaust, and even the walls may contribute approximately the same noise levels to the total SPL on the 250 ft circle. If the lowest criterion SPL on the circle, 77 db, is subtracted from the contribution of the exhaust and the intake, the noise reduction requirements would seem to be 20 db and 11 db, respectively. If these noise reduction values were obtained, the combined SPL on the 250 ft circle from the exhaust, the intake and the walls (assuming 77 db for them also) would be 82 db. Obviously, the criterion would be exceeded. To meet the criterion, it is necessary that each contribution to the total SPL be less than 77 db. Specifically, if each source is made to be no more noisy than the others, the contribution from each must be,

$$SPL = SPL_c - 10 \log_{10} n \quad (4)$$

where

SPL is the sound pressure level at 250 ft
from each contributing source,

SPL_c is the criterion SPL, and

n is the number of contributing sources.

Initially, it is sufficient to assume that there are only three contributors, the intake, the exhaust, and the walls. Thus, the SPL from each on the 250' circle should be:

$$SPL = 77 - 10 \log_{10} 3 = 72 \text{ db} \quad (5)$$

2. Noise Reduction Requirements for Control Rooms and Adjacent Work Spaces

This Section has emphasized methods of determining the noise reduction requirements for areas outside of control rooms. It is also necessary, of course, to determine noise reduction requirements for control rooms and other adjacent work spaces. These noise reduction requirements can be found from the criteria sound pressure levels in the work spaces (see especially Refs 2 and 3) and the sound pressure levels in the reverberant field of the test section. The difference between these two sound pressure levels is just the noise reduction required of the walls of the test cell. The sound pressure level in the reverberant field, which is given by Eq A-8 and Fig A-5, is about 4 db greater than the sound pressure level at the input to the intake acoustical treatment.

E. Check List for Determining the Noise Reduction Requirements of an Engine Test Facility

1. Obtain the weight flow, thrust, exhaust gas temperature and the diameter of the exhaust orifice from the engine manufacturer.
2. Determine the required cross-section for the reference test cell facility from the weight flow.
3. Determine the octave band power level and the sound pressure levels in the test section and at the inputs to the intake and exhaust acoustical treatments.
4. Find the directivity indices and other losses of sound pressure level to 250 ft.
5. Determine the criteria at the various locations around the facility and translate these criteria to 250 ft from the test facility.

6. Determine the most stringent acoustical criterion in each octave band.
7. Determine the noise reduction requirements by subtracting the criterion octave band sound pressure levels from the sound pressure levels at 250 ft which result from the noise radiation from the reference test facility.

SECTION III
FUNDAMENTAL ACOUSTIC AND ENVIRONMENTAL CONSIDERATIONS
IN THE CONTROL OF NOISE IN ENGINE TEST FACILITIES

From the noise reduction requirements, one can estimate the suitability of various noise control measures which may satisfy the requirements. The noise control principles suggested in Paragraph A below are not intentionally rank ordered by noise reducing effectiveness or by economy. However, more economical and effective designs will result if the frequently neglected potentialities of noise source modification, separation of source and receiver, and directive radiation are exhausted before resorting to walls and barriers, acoustical treatments for air passages, and acoustically absorbing materials to solve noise problems.

In this section, some basic considerations pertinent to an economical solution of the noise problems associated with engine testing are given. Specific structures and techniques for satisfying the acoustic requirements in engine test cells and ground run-up noise suppressors are given in Sections IV and V, respectively.

A. Acoustic Considerations

1. Modification of the Noise Source

A logical first step in the analysis of noise reduction is to investigate the possibility of reducing the amount of acoustic power that is radiated by the noise source. The total acoustic power radiated from a jet engine can be reduced by the addition of a specially designed exhaust diffuser (jet stream modifier). As shown by the examples given in Appendix E, an exhaust diffuser can reduce the acoustic power level by the order of 10 to 15 db in the

frequency range below 1000 cps. Such reductions significantly decrease the required amount of acoustical treatment. Many aircraft noise problems may be solved completely by the use of such diffusers.

The noise source levels of propeller engines can be decreased, in some cases, by use of a dynamometer as a load for the engine rather than a propeller. In Air Training Command cells, for example, a propeller may not be required for teaching the fundamentals of engine operation. Elimination of the propeller not only reduces the acoustical requirements for the test facility, but also reduces the air flow requirements. The only air then required is that needed to cool the engine and the dynamometer. This air can be obtained very simply by use of a large fan coupled to the dynamometer. If a propeller is required, a special type that produces relatively low noise levels (see Ref 8) might be acceptable for test purposes.

2. Separation of the Source and Receiver

The analysis of the noise reduction requirements may show, in some cases, that the required reductions are prohibitively large. It might be desirable, therefore, to reconsider the site selected for the test facility. Noise reduction requirements can vary by 20 to 30 db at different possible locations on an Air Force Base. In general, one should attempt to place the facility far from locations at which low noise levels are required. By indicating the values for acoustical criteria on a map of the site, one can readily assess the relative noise reduction requirements at several possible locations.*

*Detailed noise considerations for site planning are given in Ref 5, "Noise Guide for the Analysis and Solution of Air Base Noise Problems". This reference is heartily recommended for anyone who is in a position to influence site selection.

The construction costs of a test facility may be reduced significantly by placing the source and the receiver a large distance from each other. However, such savings must be balanced against possible increases in operational expenses that may be incurred if the test facility is situated at a remote location. Continuing expenses may outweigh the savings in initial cost of the test facility or ground run-up suppressor.

Even if the site is fixed, the distance between the source and the positions of personnel can sometimes be increased. The noise levels close to a ground run-up suppressor, for example, can sometimes be reduced by moving the secondary air intake or the exhaust farther from the aircraft. Thus, the annular secondary air inlet, shown in fig 6, might be extended farther from the work area. An extension of about 10 ft might double the distance between the secondary air inlet and the personnel areas around the engine and effect a 12 db noise reduction.

In an Air Training Command test cell, where the control room also serves as a classroom, the requirements for noise reduction between the test section and the control room may be very large. In such cases, it may be more economical to separate the control room from the test cell building, and to supply a closed-circuit TV system for visual observations. The increased separation of source and receiver, in this case, not only reduces the levels outside of the control room walls, but also increases the transmission loss of the wall structures by eliminating "flanking" paths.

3. Directivity

The air intake and exhaust openings of ground run-up suppressors and test cells generally lie in a plane above

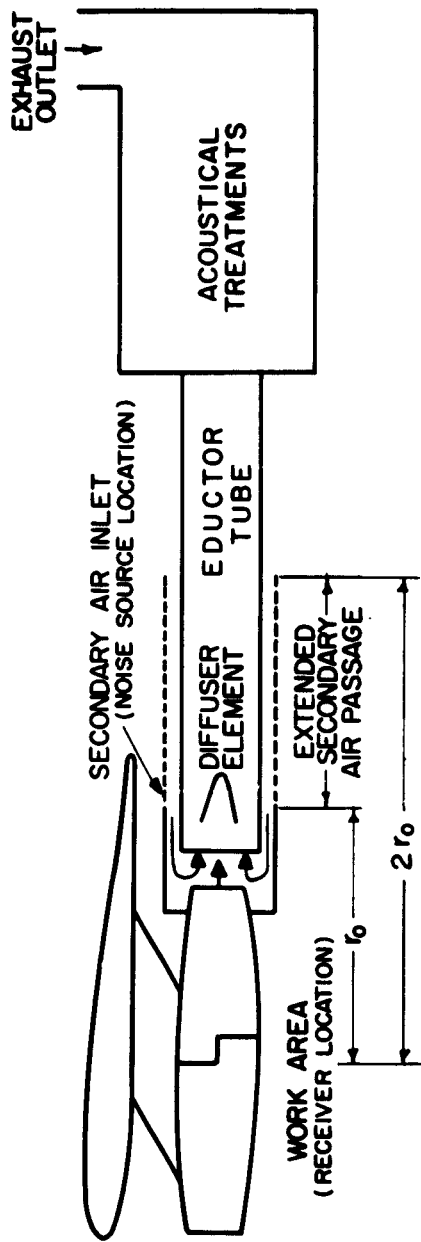


FIG. 6 AN EXAMPLE OF REDUCING NOISE LEVELS BY INCREASING SEPARATION BETWEEN SOURCE AND RECEIVER.

and parallel to the ground, so that most of the noise energy is radiated upwards. In special cases, however, it may be preferable to point the intake or the exhaust in a horizontal direction. Suppose, for example, that one side of an air base is bounded by an unpopulated area, and that the test cell exhausts can be pointed horizontally at that direction. Criteria locations in the opposite direction will then lie as much as 180° from the axis of maximum radiation, instead of only 90° as for vertical stacks.

The probability that horizontal exhausts can be used is usually small. The orientation of test cells and their exhausts is dictated primarily by prevailing wind conditions (see Paragraph B below). Furthermore, a horizontal exhaust or intake may create a hazard to personnel in the surrounding area.

4. Barriers and Walls

The sound pressure levels at the criteria locations can be reduced by interposing a wall or barrier in the path of the sound. The walls may form a complete enclosure, such as a control room, or only a partial enclosure. Partial enclosures are generally not used inside engine test cells. However, ground run-up suppressors may incorporate free-standing walls as noise reduction elements. The walls might be arranged, for example, to form a "run-up pen" for aircraft. As explained in Section V the noise reduction afforded by a "run-up pen" may be quite small at large distances. At nearby positions, however, the noise reduction required can sometimes be achieved adequately and economically using these partial enclosures (see Reference 9).

Free-standing walls can be used to reduce the noise exposure of personnel working near ground run-up suppressors.

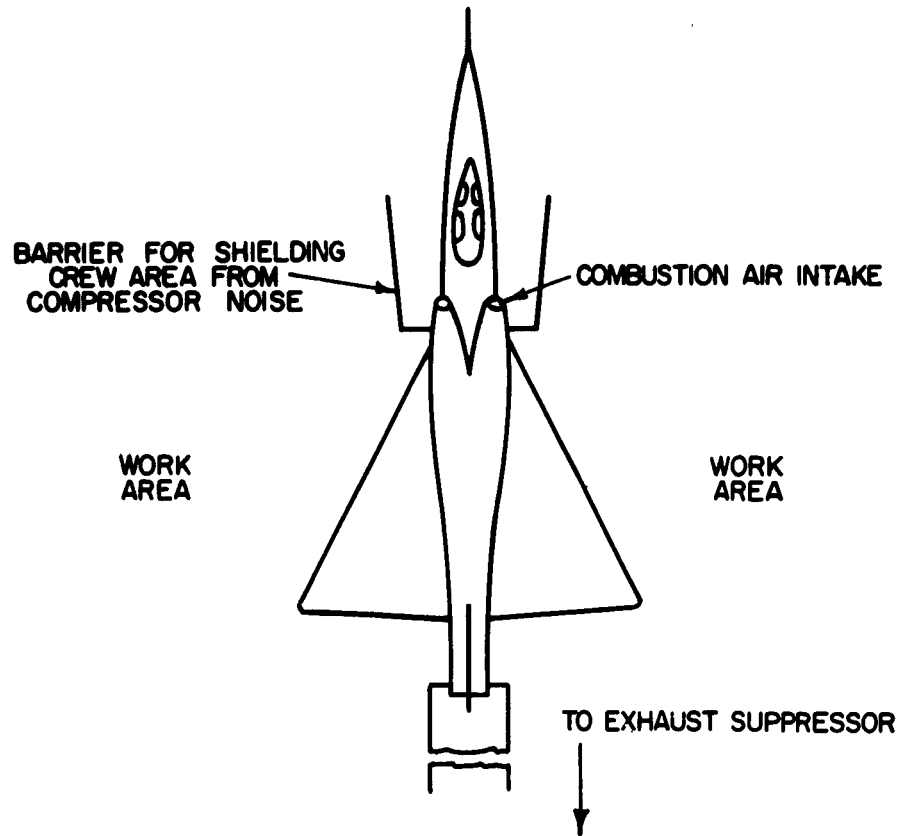


FIG. 7 AN EXAMPLE OF THE USE OF BARRIERS FOR NOISE REDUCTION.

For example, barriers might be used around the air intake of a jet airplane to reduce the high-frequency compressor noise in personnel areas around the plane, as is indicated in Fig 7.

5. Acoustical Treatments in Air Passages

The amount of noise reduction that can be produced by acoustical treatments in air-flow passages is essentially unlimited. Large amounts of reduction by this method, however, can be very costly, especially if the passage must accommodate large volumes of air, at high temperature, with low pressure drop. It is very important, therefore, to utilize fully all of the noise reduction that can be obtained by modification of the source, by increasing the distance between source and receiver, by directivity, and by barriers. When all such possible measures have been incorporated, the remaining noise reduction requirements must be met by acoustical treatments. Thus acoustical treatments should be considered as a last resort, not as a starting point, in the design of a test facility.

A wide selection of such treatments is available. Appendix C contains data on the performance of many types of acoustical treatments, including parallel acoustical baffles, zig-zag baffles, acoustically lined bends, special combination treatments and proprietary mufflers. The selection of appropriate acoustical treatments, for various noise reduction requirements for engine test cells and ground run-up suppressors, is discussed in Sections IV and V. Because of the complexity of the problem, the reader should study the introductory sections of Appendix C before using the data given there.

6. Room Absorption

The use of acoustical absorbing materials for noise reduction in rooms is fully discussed in many texts^{11/} and shall not be considered in detail here. Absorption coefficients for many acoustical materials that may be used in engine test facilities are published by the Acoustical Materials Association^{10/}. In the design of engine test facilities such materials are primarily used to minimize standing wave and reverberation phenomena in spaces adjacent to the test section of test cells or hush houses.

Investigation of many contemporary jet engine and reciprocating engine test facilities indicates that designers tend to overestimate the effectiveness of absorbing materials as a noise control measure. One encounters control rooms in which almost all ceiling and exposed wall surfaces are covered. There is a limit beyond which application of additional acoustical materials provides negligible noise reduction in a room. Covering entire wall surfaces with absorbing materials not only involves a large initial expense for a small increase in noise reduction, but, in addition, increases maintenance costs.

An indication of the limitations on the addition of acoustical absorbing materials to a room may be had by studying the formula applicable to a particular case, namely a control room adjacent to the test section of a jet engine test cell (see Fig 2). This formula is^{11/}

$$SPL_2 = SPL_1 - TL - 6 + 10 \log S_w + 10 \log_{10} \left(\frac{1}{S_w} + \frac{4}{R_2} \right) \text{ db (6)}$$

where

SPL_2 = sound pressure level in decibels in the control room measured 2 to 3 feet from the

wall separating the test section and the control room. It is assumed that the entire wall is radiating sound into the control room uniformly.

SPL_1 = sound pressure level in decibels in the test section averaged over a plane a few feet from the wall.

TL = transmission loss in decibels of the separating wall.

S_w = area in square feet of the separating wall common to the two rooms.

R_2 = room constant = $\bar{a}_{CR}S$

\bar{a}_{CR} = average absorption coefficient in the control room. It is calculated from the individual absorption coefficients in the control room ($a_1, a_2, a_3 \dots$) of every surface (with areas, respectively, $S_1, S_2, S_3 \dots$), by the formula:
 $\bar{a}_{CR} = (S_1 a_1 + S_2 a_2 + S_3 a_3 + \dots) / S$. The quantity S is the total area of the floor, walls, and ceiling and equals $S_1 + S_2 + S_3 + \dots$

We see that after $\bar{a}_{CR}S$ becomes greater than $4S_w$, there is no further gain from adding absorbing material to the room. Of more importance, before this limit is reached, a doubling of the amount of absorbing material produces only a 3 decibel reduction in the SPL in the control room. Hence, going from a coverage of, say, one-third of the total surface area of the room up to two-thirds decreases the noise level by no more than 3 decibels. A doubling in cost of the installed

material (at least) results in a barely noticeable change.

Example:

Consider a control room, 10 ft high by 20 ft wide by 30 ft long that is immediately adjacent to an engine test cell. Assume that one wall (10' x 30') is common to the test cell and the control room. The entire ceiling of the control room is treated with an acoustical material that has an absorption coefficient $\alpha_1 = 0.7$ in the 600-1200 cps band. The remaining surfaces of the room have an average absorption coefficient $\alpha_2 = 0.04$. The room is occupied by four persons, each of whom contributes an absorption of $a_p = 5$ sabins in the same frequency band. The average sound pressure level a few feet from that wall, in the test cell, is 140 db. Assume that the common wall is 1 ft of concrete, with a transmission loss of 55 db in the 600 to 1200 cps frequency band. Find the average sound pressure level in the control room in the 600 to 1200 cps band.

First determine the value of R, the room constant:

Ceiling Absorption:

$$600 \text{ square ft} \times 0.70 = 420$$

Absorption of other Surfaces and People:

$$1600 \text{ square ft} \times 0.04 = 64$$

$$4 \text{ people} \times 5 = \underline{20}$$

$$\text{TOTAL} \qquad R = 504 \text{ sabins}$$

Using Eq (6) we obtain,

$$\begin{aligned} \text{SPL}_2 &= 140 - 55 - 6 + 25 + 10 \log_{10} \left(\frac{1}{300} + \frac{4}{500} \right) \\ &= 104 - 20 = 84 \text{ db.} \end{aligned} \qquad (7)$$

Doubling the amount of absorbing material would increase R to about 900 sabins. Hence,

$$\begin{aligned} \text{SPL}_2 &= 104 + 10 \log_{10} \left(\frac{1}{300} + \frac{4}{900} \right) & (8) \\ &= 104 - 21 = 83 \text{ db.} \end{aligned}$$

In other words, doubling the amount of absorbing material reduced the noise level by only an additional decibel.

7. The Concept of Balanced Design

The noise flow diagram of Fig 1 shows that noise energy in engine test facilities travels from the source to the receivers over several paths, such as air intake passages, gas exhaust passages, and test section walls. If all noise paths to a particular receiver location deliver the same amount of noise to that location, the facility is said to be acoustically balanced with respect to that location. The most economical solution to a noise control problem is usually one that is at least approximately balanced with respect to all relevant receiver locations.

A perfectly balanced design is almost never achieved in practice, at least not in all frequency bands. The noise reduction characteristics of different walls and acoustical treatments in air passages generally vary in different ways with respect to frequency. Noise "inputs" to different walls and air passages, on the other hand, have approximately the same frequency characteristics. Consequently, a design can be balanced only in a limited frequency range, perhaps two or three octaves wide.

If a design is grossly unbalanced, there is probably an excessive amount of acoustical treatment in some part of the facility -- at least for some frequency bands. If, for example, the noise level contribution from the intake in certain frequency bands is 20 db below the contributions from

all other components, the noise reduction of the intake treatment could be reduced by 10 to 15 db, in those bands, without significantly increasing the total noise level at the receiver point. Clearly, one should attempt to avoid a grossly unbalanced acoustic design.

A slightly unbalanced design, in some cases, may be desirable. In an engine test cell, for example, one might find that the noise radiated through the concrete walls of the cell just equals the criterion noise levels. In such a case, for reasons of economy, the noise radiated from the intake and exhaust openings, to exterior locations, should be made 10 or more db lower than the noise radiated from the cell walls to the same locations. If the design were to be absolutely balanced, the noise radiated through the walls would have to be about 5 db below the criterion levels, which would require doubling the thickness of the walls (e.g., from 12 in. to 24 in.). Alternatively, one might specify a multiple wall structure to enclose the entire test cell. The additional cost of the walls, required to achieve a balanced design in this case, would usually be far greater than the additional cost of reducing the intake levels from 5 db below the criterion to 10 db below the criterion.

Similarly, test cell designs are purposely unbalanced with respect to the contributions from the intake and the exhaust. Exhaust acoustical treatments, which must withstand high temperature and velocity of the exhaust gases are generally much more expensive than intake acoustical treatments. For this reason, a minimum amount of exhaust acoustical treatment is used, such that the contribution from the exhaust will usually exceed the contribution from the intake by 5 to 10 db.

B. Environmental Considerations

1. Environmental Requirements for Acoustical Treatment*

The allowable temperatures and velocities in exhaust gas passages are usually limited by the durability of acoustical treatments in those passages. At high exhaust gas temperatures and high exhaust gas velocities, acoustical materials may deteriorate rapidly. Table IV gives the maximum allowable temperatures for several types of fibrous materials.



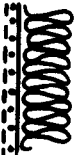
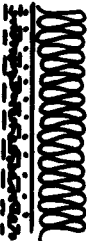
TABLE IV

<u>Material</u>	<u>Maximum Allowable Temperature °F</u>
Fibrous materials	
Some mineral wools (e.g., J-M Airacoustic)	125-150
Wool felts	150-200
Some hair felts	200-250
Bonded glass fibers ^a (Microlite, PF Fiberglas Aerocor, Ultralite, Ultrafine)	350-400
Asbestos Fibers (J-M Spintex and Spincoustic)	800
Unbonded glass fibers (TWF and TWL Fiberglas)	1000-1100
Mineral wool felted block (Baldwin Hill rock wool)	1200
Basalt wool (Hoeganaes Sponge Iron Corp)	1450
Vitreous fiber-silica (H. I. Thompson Refrasil)	1800-2000
Refractory fiber (J-M Thermoflex)	2000

^a In these materials, the temperature limits generally apply to the binder; the glass fibers themselves are good to about 1000° F. After the binder melts, the glass fibers may have a tendency to sift under vibration.

* The information in this section is taken from Reference 12.

TABLE V

Cross Section	Maximum Allowable Velocity in ft/sec
	Perforated metal facing Acoustical blanket ^a 35-75
	Perforated metal facing Glass-fiber cloth Acoustical blanket ^a 75-100
	Perforated metal facing Wire screen Glass-fiber cloth Acoustical blanket ^a 100-200
	Perforated metal facing Scrubbe ^b -one inch thickness, (Galvanized steel-wire, brass, monel, stainless) Perforated metal facing Wire screen Glass-fiber cloth Acoustical blanket ^a 200-300
Other materials--Haydite block, ceramics, bricks, etc.	300-400

a Selection of an acoustical blanket will depend on the gas temperature (see Table IV). In general, PF Fiberglas board should not be used in velocities which exceed 75 fps because the binder has a tendency to sift owing to the effects of vibration.

b A patented product manufactured by Industrial Sound Control Department, Metal Products Division, Koppers Co., Baltimore, Maryland.

The values given in this table are tentative and may change as more field experience is accumulated. These values are useful for guiding the design of acoustical structures, and in most instances are believed to be conservative.

The gas velocities given in Table V represent average values for smooth, diffuse gas flow (no flow separation) at grazing incidence only. If high-velocity gradients (turbulence) exist near the surfaces of the protective facings, such as might be encountered in 90° bends or in the vicinity of sharp edges or sharp constrictions, local gas velocities might be expected to increase to values several times the calculated average velocities. It is generally wiser not to place acoustical structures where the gas turbulence is high, because erosion is highly probable. If acoustical structures are used in turbulent gas streams, extreme care should be exercised to protect the porous filler materials as much as possible.

The thickness of the perforated protective facing material shown in Table V is governed both by gas temperature and by gas velocity. The thickness ranges from about 20 ga for normal room temperature and a maximum velocity of 75 fps, to about 12 ga for temperatures of 450° and a velocity of 300 fps. The perforated facings should be at least 20 percent open. In the case of the last item in Table V, the inner perforated facing should be about 40 percent open. The information given in Table V applies to acoustical panels that are installed in sections about 3 ft in length. If smaller sections of perhaps half this length are used, the given limits may be somewhat increased.

Recently acoustical treatments have been developed which do not incorporate fibrous materials. The velocity

limitation for such acoustical treatments is generally imposed not by erosion or destruction of the panel, but instead by the generation of noise resulting from turbulent air flow through these treatments, or by static pressure drop limitations.

2. Environmental Requirements for Engines

Among the environmental factors that influence the geometry and selection of acoustical treatments for engine test facilities are the allowable static pressure drop in the intake treatment (sometimes called "cell depression"), the allowable static pressure at the exhaust orifice of the jet engine and the need for avoiding recirculation and re-ingestion of exhaust gases.

The allowable static pressure drop varies with the function of the test facility. Typical ranges of allowable pressure drops are 2 to 4 in. of water for jet engine manufacturers' test cells and 6 to 8 in. of water for air training command facilities. The allowable static pressure drop must be determined from the operational requirements for an engine in the test cell (see Ref 7).

The static pressure at the exhaust orifice affects the tailpipe temperature and the thrust of the engine. Furthermore, in some jet aircraft, cooling air is drawn through the fuselage and over the tailpipe, by virtue of the static pressure at the exhaust being less than the ambient pressure. Hence a positive pressure cannot be tolerated. Thus, the static pressure requirements at the jet orifice must be carefully investigated. The appropriate requirements must be obtained from the engine and/or aircraft manufacturer.

The fresh air entering the jet engine must not be contaminated with exhaust gas from the engine. Care must be taken to discharge the exhaust gases from the test facility at a sufficient distance to prevent them from mixing with the intake air. Recirculation and re-ingestion of the combustion products create a regenerative process; the temperature of the intake air increases, and causes an increase in the exhaust gas temperature, which in turn causes an increase in the intake temperature. Safe operation of the engine becomes impossible. Re-ingestion can be prevented by discharging the exhaust gases at a height well above the air intake and by orienting the test facility so that the exhaust outlet is downwind of the air intake for the prevailing wind at the site.

A septum should be used to divide the test section of a test cell from the exhaust acoustical treatment, in order to prevent internal recirculation of combustion products.

SECTION IV TEST CELL LAYOUT AND DESIGN

Each test cell presents special acoustical and operational requirements that can be satisfied in numerous ways. The number of possible solutions is limited only by the imagination of the designer. However, certain principles are applicable to each design problem. The emphasis in this section is, therefore, primarily centered upon principles to be followed in the solution of the special problems in engine test cell design. Examples are given to show methods of applying the principles to solve each problem. The examples are not intended to be the only solution to each problem. They represent one possible solution.

A. Basic Planning

A jet engine test facility includes many spaces other than the test cells proper. These spaces can be classified in terms of noise criteria. The criterion levels for personnel in work spaces are found from the speech communication requirements (Ref 2) or from the conservation of hearing requirements (Ref 3).

The acoustical criterion levels generally will be lowest in the control room, as personnel in the control room may be required to converse with a high degree of intelligibility in order to operate the engine and to record its performance. If the control room also functions as a classroom, as it will in Air Training Command facilities, then an instructor must be able to converse with 10 to 20 students, and the acoustical criteria will be even lower.

Many test facilities require an engine preparation area in which final adjustments are made on the engine prior to

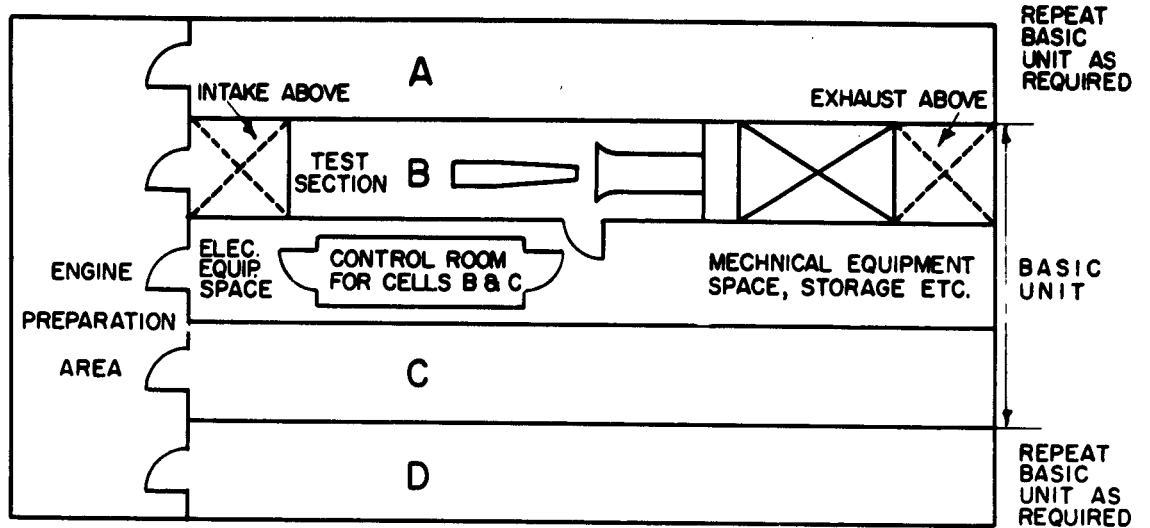
its installation and operation in the test cell. The acoustical criterion in this area is not as stringent as those for control rooms.

A support equipment area for the engine must also be provided. The support equipment may include fuel and oil pumps, 400 cycle electrical power supplies, DC power supplies, water metering equipment, and perhaps equipment for water-alcohol injection. In these support equipment areas, the acoustical criteria are not stringent.

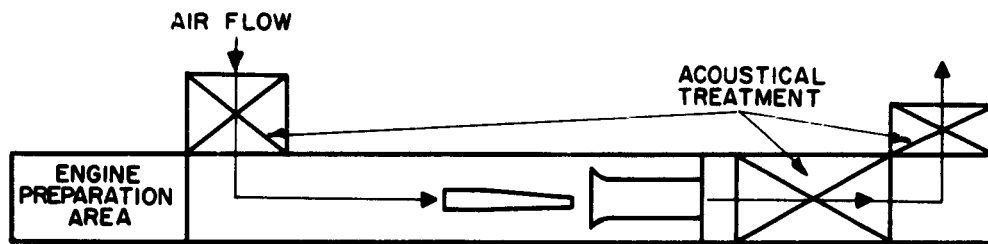
The acoustical engineer should work with the architect-engineer from the time of the initial conception of the facility. Insofar as possible, it is desirable to arrange the facility so that the areas where the criteria levels are the highest are located near the areas having the highest noise levels. Thus spaces for support equipment are best placed near the exhaust section, while control rooms and engine preparation areas should be located near the intake end of the test section.

A preliminary layout for a test cell is given in Fig 8. The control room is located adjacent to the test section and the mechanical equipment room is located adjacent to the exhaust area. Radiation of noise to distant locations through all of the side walls (except, of course, for the side walls of the two end test cells) is prevented by the mechanical and electrical equipment rooms.

The "U" shape, shown in the elevation drawing at the bottom of Fig 8 is popular because noise reduction is obtained by the directive radiation of sound from the vertical stacks. In addition, a vertical exhaust stack



P L A N



E L E V A T I O N

FIG. 8 A PRELIMINARY LAYOUT FOR AN ENGINE TEST FACILITY - I.

minimizes personnel hazards and re-ingestion possibilities associated with the exhaust and allows easy and direct access from an engine preparation area to the front of the cell. Engine access doors or air intakes on the side of the test section are usually inconvenient and inefficient. For some special situations, test cells are constructed with horizontal intakes and removable acoustical treatments to allow engine access. While this method of construction provides a workable solution for certain problems, great expense may be required to make it acoustically effective.

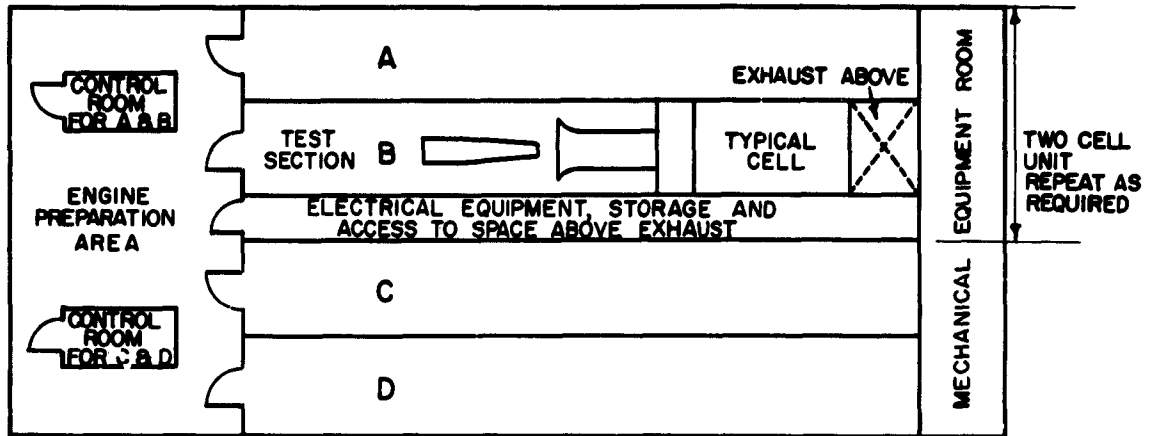
If the noise reduction requirements are very great (i.e., the control room is to be a classroom and a very large afterburning engine is operated), the scheme shown in Fig 9 could be used. The control room is now located in front of the test section rather than to the side, and the separation between the control room and the test section walls has been increased. The mechanical equipment spaces are moved to the rear of the exhaust so that essentially no noise will be transmitted through the rear wall of the test cell to the surrounding area.

The intake acoustical treatment is "folded back", as indicated in Fig 9, allowing more space for acoustical treatment in the air passages. The exhaust stack is higher to allow more room for acoustical treatment and to separate the exhaust from the intake to prevent recirculation.

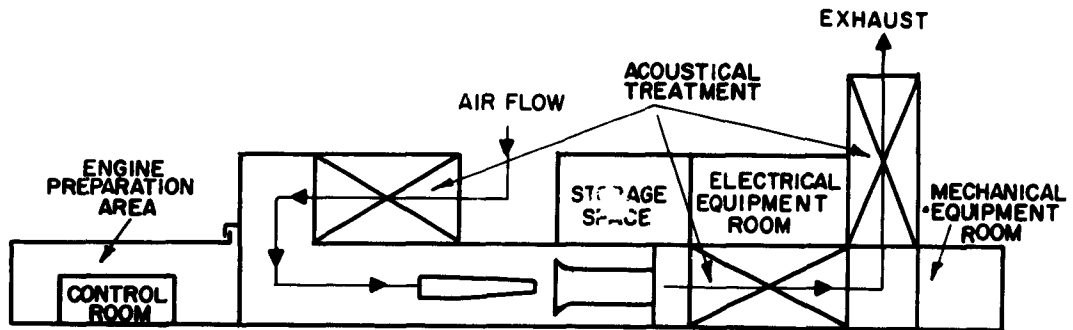
B. Control Room Design

1. General Discussion

The very large noise reduction usually required between the test section and the control room dominates all aspects of control room design. Noise reduction requirements for



PLAN



ELEVATION

FIG. 9 A PRELIMINARY LAYOUT FOR AN ENGINE TEST FACILITY - II.

control rooms are frequently as large as 80 to 100 db. The implications of a 90 db noise reduction are illustrated by stating the noise reduction as a simple ratio rather than a number of decibels. A noise reduction of 90 db means that only one part in a billion (10^9) of the sound energy impinging on the walls of the test section is transmitted into the control room.

To assure that only one part in 10^9 reaches the control room, the acoustical engineer must consider anything connecting the test cell to the control room as a potential noise transmission path. For example, instrumentation cables, power cables, the heating and ventilating system are all potential noise transmission paths. Even the ground itself transmits noise from one room to another.

The total amount of space required for a control room is set by the number of operators required for the engine, the number and size of instrumentation consoles, etc., but, the geometry and materials of the walls enclosing the required space should be based on acoustical requirements.

2. Wall Design

A fundamental consideration in the design of control rooms for engine test cells is seen from Eq 6, which can be rewritten as:

$$NR = TL - 10 \log_{10} \left(\frac{1}{4} + \frac{S_w}{R} \right) \quad (9)$$

in which, NR is the noise reduction of the wall

TL is the transmission loss of the wall

S_w is the area of the wall through which noise is being transmitted, and

$R = S\bar{\alpha}/1-\bar{\alpha}$, where S is the total surface area of the receiving room, and $\bar{\alpha}$ is the average statistical sound absorption coefficient for all surfaces of the room.

If S_w/R is much less than $1/4$, the noise reduction is 6 db greater than the transmission loss. If S_w/R is greater than $3/4$, the noise reduction is less than the transmission loss. Therefore, a basic objective in planning a control room is to have the common wall between the test section and the control room S_w as small as possible. As illustrated in Section III, there should be enough acoustical absorbing materials in the room so that R is about the same as, or slightly greater than, S_w .

The noise reduction requirements for the walls between a control room and the test section usually cannot be met by a single wall structure of a practical thickness. Thus, the test cell designer must use double wall structures in an attempt to meet the noise reduction requirements.

To emphasize the severity of the noise control problem between the test section and the control room, we shall temporarily divert from wall design in order to estimate the approximate range of the noise reduction requirements in present-day and near-future test cells. First, let us assume a relatively high criterion in the control room, NC-60A.

This criterion curve specifies noise levels that will permit easy person-to-person speech communication with a raised voice at 1 to 2 ft, or slightly difficult speech communication at 3 to 6 ft. The engine in the test section is assumed to have a PWL of 175 db. The approximate

octave-band noise reduction requirements* for this condition are given in Fig 10.

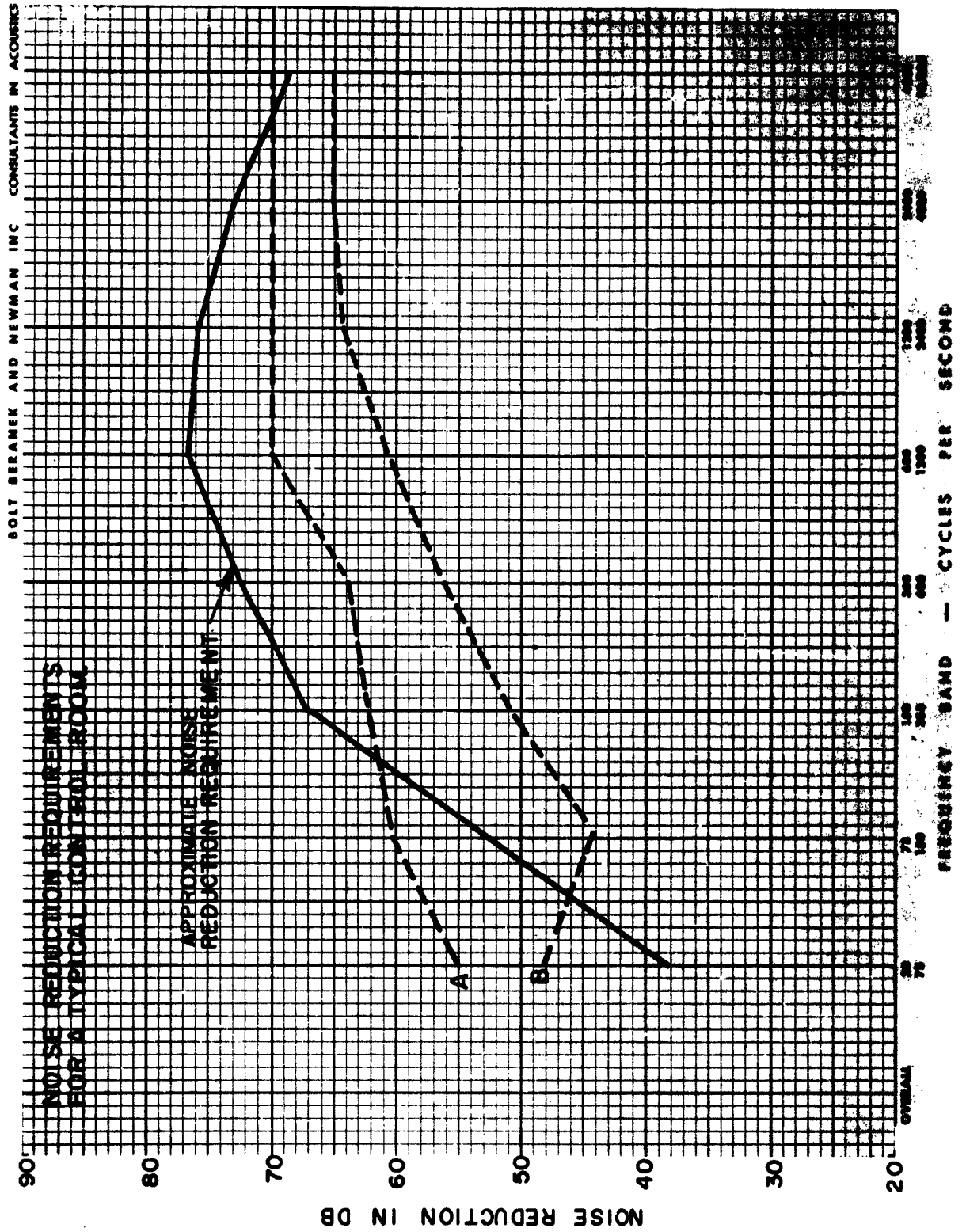
The curve labeled A in Fig 10 is the average of the measured transmission loss (assumed equal to the noise reduction) for three of the best double wall control room structures which are reported in Volume Three. The double walls each consisted of a 12 in. poured concrete wall, a 4 in. air space and about 8 in. of solid concrete block. The curve labeled B in Fig 10 is the measured transmission loss of a single 12 in. thick concrete wall (average of data from two installations). These data clearly show that neither a single 12 in. concrete wall nor the double wall structures encountered in present day test cells provide adequate noise reduction.

For a control room which serves as a classroom, the criteria will be about 20 db lower and the PWL may be 10 db greater than those given. Thus, the noise reduction requirements could be as much as 30 db greater than those shown!

Measurements of transmission loss of double walls for many control rooms in jet engine and reciprocating engine test cells have shown that the transmission loss actually obtained for double walls in practice is very much less than the values which would be predicted from present day theory^{13, 14/}. The discrepancy between the predicted values of transmission loss and the values obtained in practice could usually be attributed to obvious flanking paths, such as instrumentation ducts, poorly sealed doors, and poorly gasketed windows. However, there were no obvious flanking paths which could be detected aurally in the control rooms

*The noise reduction requirements are only approximate because the area of the test section influences the average noise levels.

FIGURE 10



from which curve B in Fig 10 was derived. The low values of transmission loss may result from wave-coincidence phenomena in the walls, from standing waves between the walls, from large amounts of sound energy in air waves traveling over the walls near grazing incidence, or from transmission of sound from one wall to the other through the footings.

Although the discrepancies between the anticipated noise reductions and the measurements are large, some features of the theory of double walls are useful to show ways of designing double wall structures similar to those measured, but with larger transmission losses.

References 13 and 14 show that the transmission loss may be increased by (1) increasing the separation between the walls, (2) "splaying" the two walls with respect to one another so that they are not parallel, (3) attaching a heavy acoustical blanket to one wall surface in the air space.

In regard to (1) above, a large air space, say about 18 in., almost entirely eliminates the possibility of inadvertent mechanical ties between the walls during construction. Any ties that may occur can be located and removed, since a man can walk between the walls. Also, a large space between the walls allows adequate space between the footings of each wall for proper vibration isolation. This is an exceedingly important consideration as the 70 db limit of Fig 10 could be the result of the tie between the two leaves of the double wall.

In regard to (2) above, the walls are splayed so that waves transmitted at some "coincidence" angle, θ , from one wall, will strike the second wall at another angle, $\theta \pm \phi$,

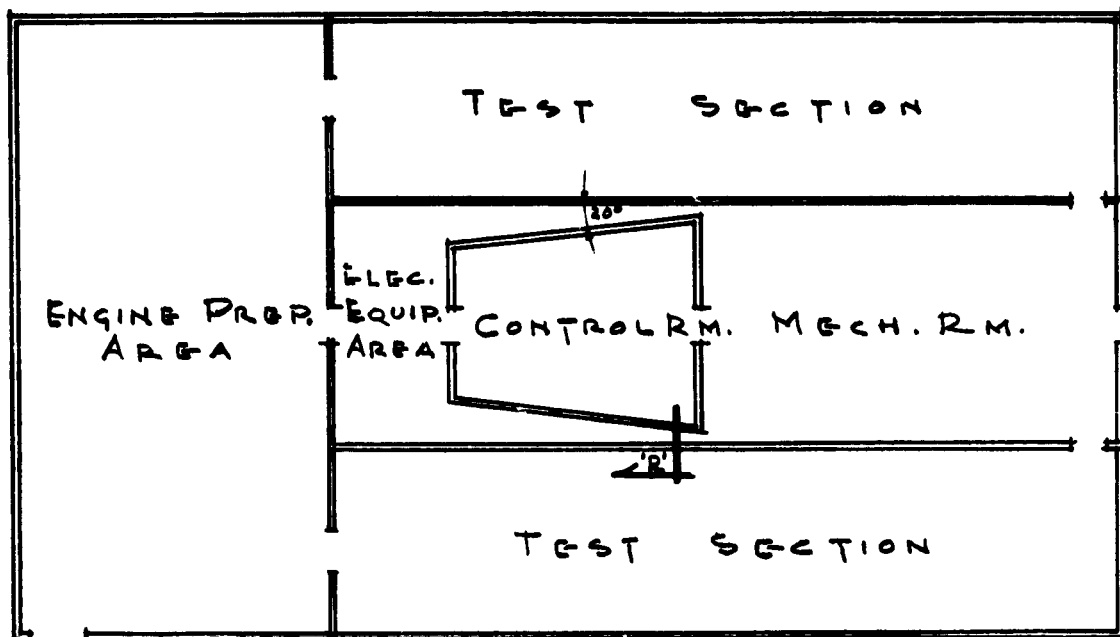
where θ is the acute angle between the two walls. If the velocity of propagation of bending waves in both walls is about the same, then the coincidence effects at the angle $\theta \pm \theta$ should be small. If the air space between the walls opens to large open space (see Fig 8) then splaying the walls also tends to minimize standing wave effects by directing sound energy out of the air space.

In regard to (3) above, the acoustical blanket is added in the air space both to minimize standing waves between the walls and to absorb sound energy near grazing incidence.

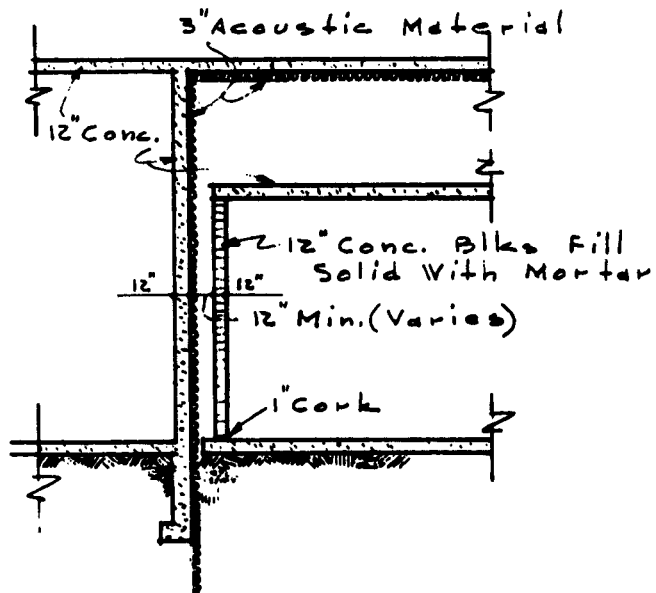
If these three modifications are made, and if in addition, special precautions (described in the following sections) are taken in the design of windows, ventilating systems, instrument ducts, and other accessories entering the control room, the transmission loss of the wall structure should be about 10 to 15 db greater than that shown in Fig 10 (curve A).

Figure 11 shows a structure which incorporates the proposed changes. Note that there are no penetrations between the test section and the control room. All penetrations should be made through a control room wall which leads to a "buffer zone" such as mechanical equipment spaces or the engine preparation area.

The double wall structure of Fig 11 can be built to satisfy noise reduction requirements of the order of magnitude of those shown by the upper curve in Fig 10, but what can be done to satisfy even larger noise reduction requirements? In view of the usual proximity of footings of the test section and the control room, the many cables,



FLOOR PLAN



SECTION R

FIG. II A DOUBLE WALL STRUCTURE FOR A CONTROL ROOM.

etc. which lead from the test section to the control room, and other facilities which enter the control room, there is little reason for hoping for noise reductions greater than 80 db or so from a test section to a control room. Therefore, the designer must consider alternatives.

When very large noise reduction requirements (over 80 db) are encountered in the initial calculations, the designer should reconsider the basis for the selection of a given criterion. Frequently, the criterion is based on speech communication requirements. Reducing the noise levels in the control room is not the only way to obtain good speech communication conditions. Speech communication could also be improved by the use of high quality headphone-microphone systems. The criterion levels might be increased as much as 20 to 40 db if high quality moving coil headphones and moving coil or condenser microphones, designed especially for communication in high noise levels, were used at all times during engine operation. The cost of such equipment, even for 10 to 15 students, would be small compared to savings in cost of construction.

If criterion levels are determined only by requirements for the conservation of hearing for the engine operator, the simple expedient of requiring use of ear plugs or muffs or both could be considered in lieu of complex wall structures.

If, after due study, it is decided that the criterion levels remain low, then the possibility remains of locating the control room at a distance from the test section. One possibility is to locate the control room in front of the test section (see Fig 9), in the engine preparation area.

The noise reduction resulting from the sound passing through the two sets of walls separated by a large distance

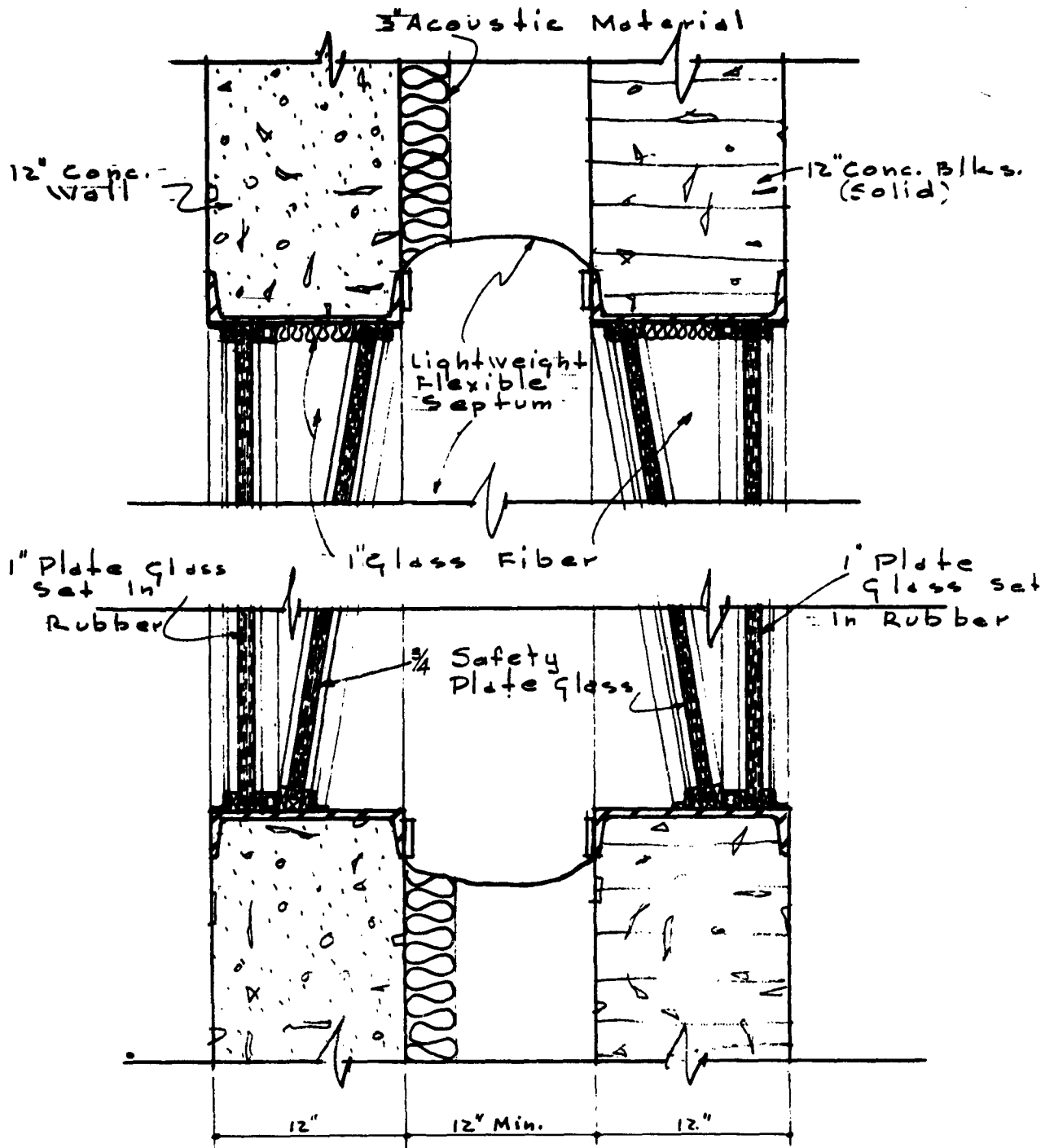
will usually be about the sum of the noise reductions of each wall, provided no transmission occurs through the ground between the footings or through other paths.

A closed-circuit television system could provide for observation of the engine. Such a system would be well suited for teaching purposes in Air Training Command Cells.

3. Window Design

Windows that have transmission losses as great as double walls are both difficult to construct and are expensive. Therefore, the first principle in window design is to minimize the window area in the double wall between the control room and the test section. Actually, only a very small window area is required to allow the engine operator to see the engine. Most control rooms in contemporary test facilities contain several windows, of which one is used by the engine operator and generally the others are used only by casual observers. Where possible, the latter should be located in buffer zones such as the equipment storage spaces, mechanical equipment spaces, engine preparation areas, etc.

Construction details and transmission loss curves obtained from field measurements on several multiple pane windows are given in Appendix D. In this section, some general considerations for window design are presented. In Fig 12, a typical multiple pane window construction is shown. Several significant features should be noted. The windows adjacent to the air space are inclined partly for optical reasons and partly to make the heights of the two panes in each wall different. If the ratio of the heights and the widths do not have integral values, each pane of glass will



WINDOW DETAIL

FIG. 12 A MULTIPLE PANE WINDOW DETAIL

have different normal modes of vibration, and excitation of those modes by sound energy will not result in very large decreases in transmission loss, at least for the first few modes. Furthermore, the inclination of the windows minimizes standing wave phenomena at high frequencies.

Note that the thicknesses of the panes of glass in the wall are not equal, so that wave coincidence phenomena* do not occur in each pane at the same frequency and the resulting coincidence "dips" in TL are minimized.

Frequently, a barrier of some sort encircles the entire window area in the air space between the double walls. The purpose of such a structure is to keep dirt and moisture off of the windows that face the air space. Such structures inevitably provide a mechanical link between the two double walls and should therefore be avoided insofar as possible. If some provision is necessary for keeping dirt and moisture out**, a very light weight flexible material should be used. If the material is sufficiently thin, the effective volume of air between the windows is immense and the transmission loss of the windows at low frequencies will be much greater.

4. Doors

Personnel doors to control rooms should not be located in the common wall between the test section and the control room. Rather, they should be located in walls which lead to buffer zones such as mechanical equipment spaces and engine preparation areas. Some possible locations for

* Some recent preliminary experiments by one of the authors indicate wave coincidence phenomena can be very significantly reduced by use of safety plate glass.

**If the air space between the walls is wide enough for a man to enter, no such provision will be necessary.

personnel doors are shown in Fig 13. Note that in each example, personnel must go through at least two doors in passing from the control room to the test cell. The doors in each case are separated by a large space to minimize the effects of any leaks around the perimeter.

Doors should be selected that have a transmission loss comparable to that of the wall in which they are placed. No transmission loss data for doors are given in Appendix D. However, almost all manufacturers of sound insulating doors can provide transmission loss values which have been obtained by independent laboratories. Because the effectiveness of doors is greatly influenced by the quality of the gasketing at the perimeter, great pains must be taken during installation of the door to assure that the door is hung correctly and that all gaskets and seals are properly adjusted.

5. Wall Penetrations

The wall structure of a control room is penetrated in many places by heating and ventilating ducts, electric power supply cables and many instrumentation cables. Each penetration is a potential path for the transmission of sound energy into the room.

The problems related to the heating and ventilating system can be greatly alleviated by providing a unit heating and air conditioning system in the control room. A unit system requires much smaller ducts, as most of the air is recirculated and only a small amount of fresh or stale air need be conducted to or from the control room. If a central heating and ventilating system is used, then all of the treated air must be brought to and from the control room and relatively large duct work is required.

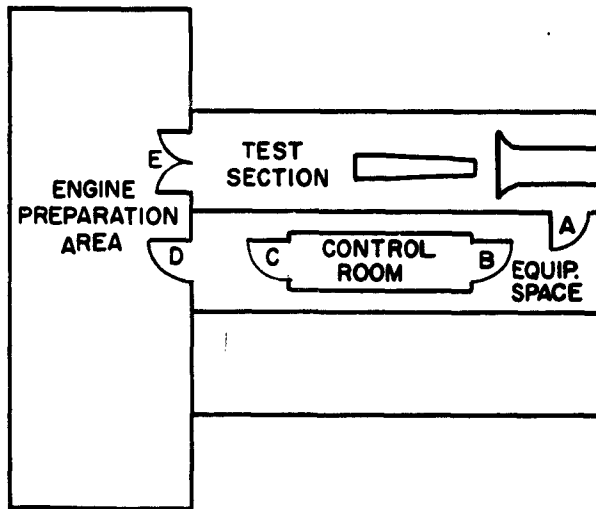


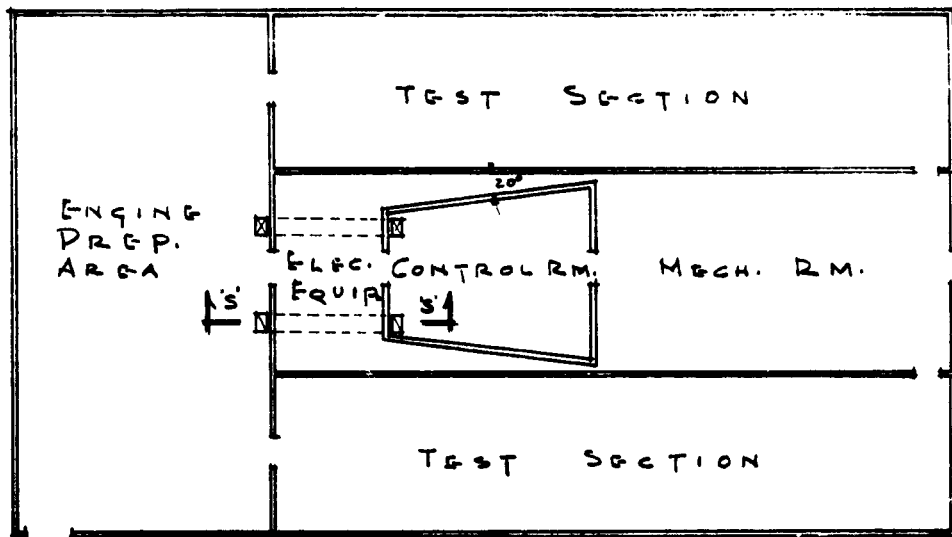
FIG. 13 SOME POSSIBLE LOCATIONS FOR PERSONNEL DOORS FROM CONTROL ROOM TO TEST CELL.

Two methods of satisfying the air conditioning requirements are illustrated in Fig 14. In the first method, (see Fig 14) the supply and return ducts pass by an overhead path from the engine preparation area to the control room through the mechanical room. The duct is supported from resilient hangers and is equipped with a lined bend at the outer end. In the second method, the supply and return ducts travel from the engine preparation room to the control room by an underground path.

For the first method, the penetrations of the walls are constructed as shown in the "penetration detail". The penetrations of the wall are made oversize and the resulting open area is packed with a flexible glass fiber material and is sealed on both sides with a caulking compound. The ductwork is covered with 1 to 2 in. of dense plaster to prevent transmission of sound into the duct walls. Also shown in the sketch for the overhead duct are three alternative paths A, B and C by which sound can enter the duct system and, hence, the control room. A is the opening of the duct itself while B and C are through the duct side-walls.

In the second method, the required air ducts run below grade underneath the slabs. The detailing of the penetrations of the slab should be the same as those for the wall. Note that there are vibration breaks just below the slab both in the control room and in the engine preparation area. In addition, there is a vibration break in the Fiberglas filled channel which encircles the control room.

The primary considerations in the design of the overhead duct are:



FLOOR PLAN

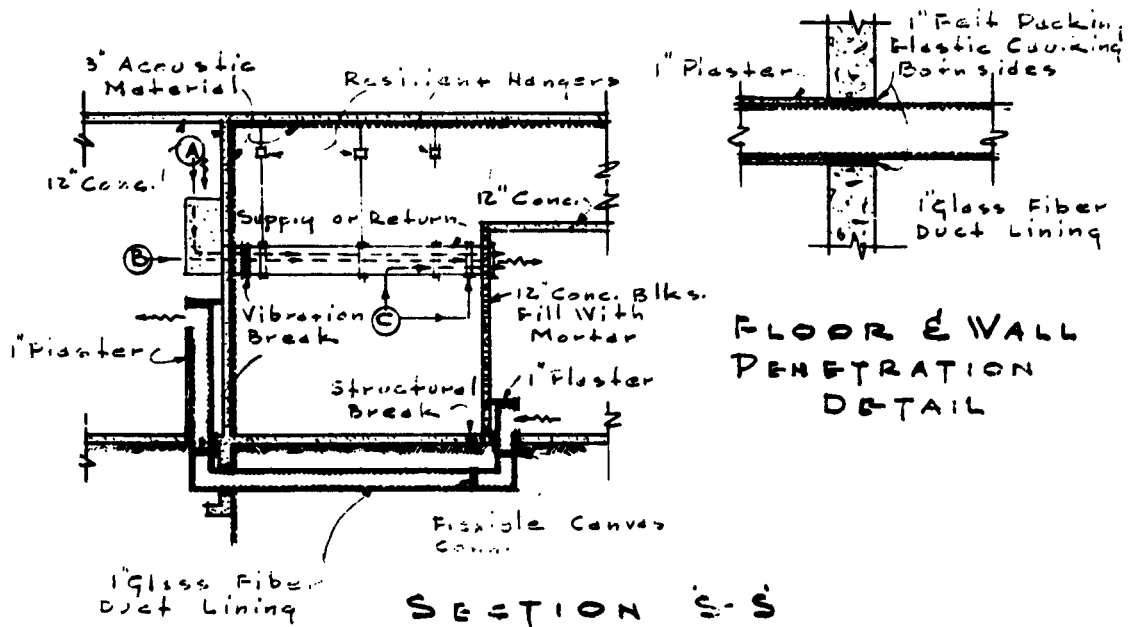


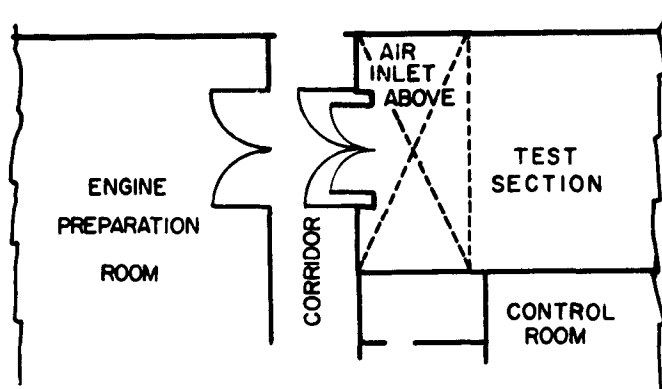
FIG. 14 VENTILATION DETAILS FOR A CONTROL ROOM.

1. The total noise levels transmitted over paths A, B, and C in Fig 14 into the control room must be lower than or approximately equal to the noise levels transmitted to the control room through the double wall.
2. The ductwork should not mechanically tie the wall of the control room to the exterior wall. Where possible, a vibration break, such as that indicated, should be made to prevent transmission of vibrational energy.

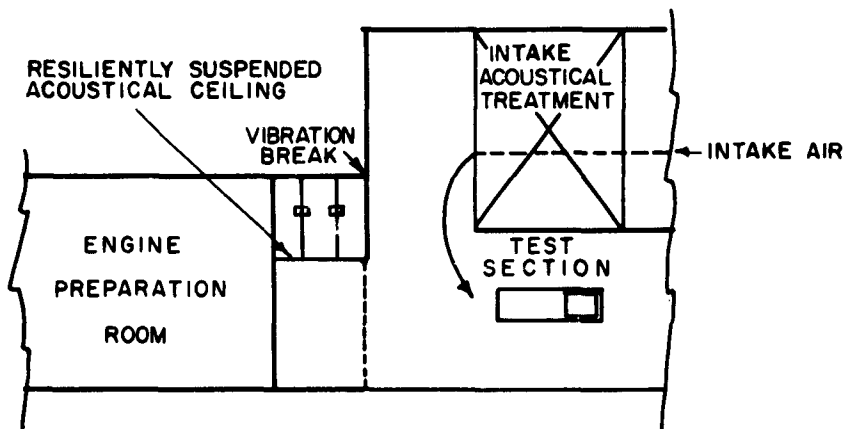
C. Engine Preparation Area

Test facilities that are used for production testing or for testing overhead engines may require an engine preparation area. The acoustical criteria in this area are relatively high and the noise reduction requirements are usually not too stringent. In some cases, however, where large after-burning engines are to be tested or where many test cells may be operating simultaneously, a more elaborate wall construction may be required.

Figure 15 shows one solution to such a problem. In this case, the test cell designer used a corridor 6 ft wide between the preparation room and the test section as a buffer zone. Note, also, in this case, that double doors are used between the test section and the corridor. These double doors are tied together by a common concrete frame. Thus, the full benefits of multiple wall construction are not obtained. However, a double door system such as this one is advantageous in that the effects of acoustical leaks around the perimeter are greatly reduced, particularly if there is some acoustically



P L A N



E L E V A T I O N

FIG. 15 TEST SECTION AND ENGINE PREPARATION AREA FOR A CONTEMPORARY TEST CELL.

absorbing material around the edges between the doors. The transmission loss from the test section to the preparation room should be very nearly equal to the algebraic sum of the separate transmission losses of the two walls, at least for frequencies above 150 cps.

In the engine preparation area, there are no other very important acoustical principles to be followed. As in all large spaces, a moderate amount of acoustical material is desirable to control reverberation.

D. The Test Section

1. Basic Structure

The design of the engine test section includes many features that are basically not acoustical considerations although in some instances they serve certain acoustical purposes. For example, the engine is usually mounted on a large "inertial block" and there is no significant vibration energy transmitted to the test cell structure.

The walls of the test section are usually reinforced concrete 12 in. thick in all areas except those directly opposite the engine. The walls directly opposite the engine are usually 18 to 24 in. thick and may in addition be lined with a steel plate, 1/2 to 1 in. thick. This massive structure provides protection for personnel in the control room in the event of explosion, or disintegration of the turbine or the compressor of the engine.

2. Door Locations

Doors to the test section must provide access for engines and for personnel. As discussed in the sections on basic

planning and control room design, no doors should penetrate the common double wall between the test section and the control room.

Engine access doors are most conveniently located in the front wall of the test section. Engine access doors in the side walls of the test section necessitate large areas for turning the engine as it moves out of the test section into a preparation area and also require more complex mono-rail crane systems.

The static pressure in the test section is below ambient atmospheric pressure during engine operation. This cell depression can be used to force the doors in the test section against the gaskets. If the doors are hung so that they swing out, away from the test section, the force on the door created by cell depression can be quite large. For example, if the cell depression is 4 in. of water, the air pressure on the door is of the order of 20 lbs/sq ft or about 2000 lbs for a typical engine access door. For a personnel door, the total force would be of the order of 500 lbs.

3. Instrumentation and Support Equipment

Details for wall penetrations by wires, pipes and conduits should be handled in the same manner as for the heating and ventilating ducts (Paragraph B-5). In particular, all penetrations should be oversized and the remaining open area should be packed with Fiberglas and caulked with a non-hardening material. All penetrations of the wall should be made from the test section to a buffer zone such as support equipment and accessory rooms. No penetrations should lead directly to the control room or to the exterior of the test cell.

4. Heating and Ventilating

Provision must be made in all engine test cells for ventilation of the test section, because of the explosion hazards associated with the volatile jet engine fuels. In northern climates there must be provisions for heating the test section during the winter months.

The noise reduction requirements for ventilating air passages leading from the test section to the exterior are the same order of magnitude as the noise reduction requirements for the combustion and cooling air intake. Fortunately, however, the ventilating system needs to operate only when the engine is not operating. Therefore, the ventilating air system may be designed with motor operated doors or hatches which close during operation of engine. The noise reduction in the ventilating air system can be obtained then by the use of a "massive barrier" rather than the use of absorptive or reactive ducts. An arrangement for test section ventilating and "purging", used in one instance, is shown in Fig 16.

5. Miscellaneous

In the test section, the sound pressure levels are typically between 140 and 160 db overall. These sound pressure levels are large enough to create serious vibration problems for all equipment in the test section. The sound induced vibration tends to loosen bolts, screws, light bulbs, etc., in the test section. Sheet metal screws in items such as space heaters are particularly vulnerable to noise induced vibration. All equipment located in the test section should be fastened with lock washers on all screws and where possible structures should be riveted or the screws and bolts should be welded together.

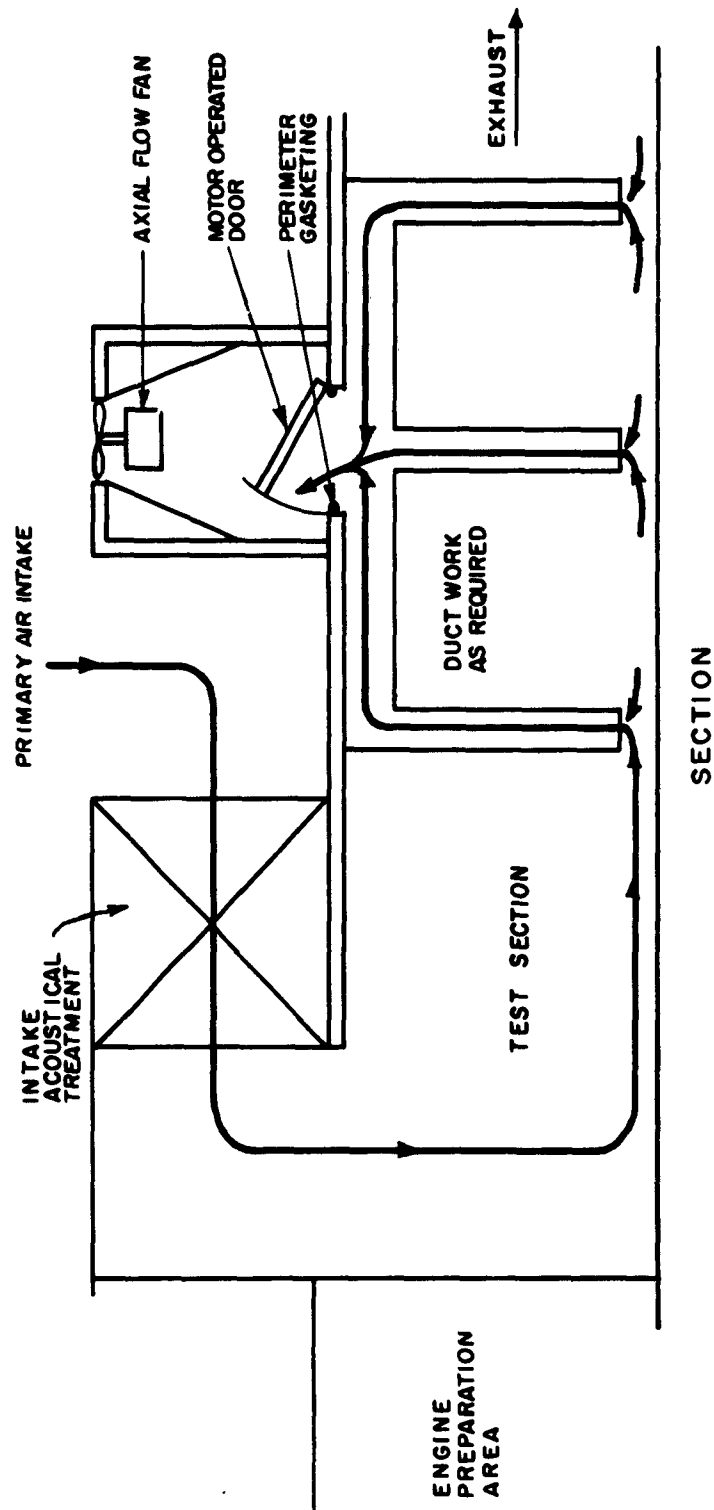


FIG. 16 A METHOD FOR ACHIEVING NOISE CONTROL IN A TEST SECTION VENTILATION SYSTEM.

F. Augmentor Tube

The design of the augmentor tube is primarily an aerodynamic problem. The length of the augmentor tube must be great enough to assure complete mixing of the jet exhaust gases with the cooling air so that the exhaust acoustical treatment will not be exposed to extremely high temperatures. Generally, the requirements for secondary air flow will require that the ratio of a diameter to length for the augmentor tube is about 5 or more. As the diameter of the eductor tube is several times the diameter of the engine for aerodynamic reasons, the eductor tube will generally be long enough so that the apparent source of jet noise will be in front of the exhaust acoustical treatment even for the lowest frequencies of interest.

If for some reason, the augmentor tube is very short, then a heavy grid should be placed near the exit of the augmentor tube to force the mixing of the exhaust gases with the cooling air before they reach the acoustical treatment.

F. Intake and Exhaust Acoustical Treatments

1. Selection of Treatments to Meet the Noise Reduction Requirements

Noise reduction data for many acoustical treatments for engine test cells are given in Appendix C. All of these treatments may be used either in intakes or in exhausts. The facing materials used for the treatments can be selected on the basis of the data given in Tables IV and V of Section III. The facing selected will not materially affect the noise reduction data provided the acoustic impedance of the facing is small compared with the impedance of the treatment itself (the usual case).

The type of acoustical treatments selected for use in a test cell will depend upon the required noise reduction as a function of frequency. Lined ducts with relatively large openings and thick linings are generally used to obtain noise reduction at the lower frequencies. Although the primary purpose of large lined ducts is low frequency noise reduction, a significant amount of high frequency noise reduction is also obtained, particularly when the duct follows a bend or is adjacent to the test section.

For noise reduction in the mid-frequencies, thick (1 ft or more) parallel baffles may be used. Where high frequency noise reduction is needed, thin parallel baffles are frequently employed.

Noise reduction over a relatively wide frequency range can be obtained by use of thick zig-zag or wavy baffles. Several of the proprietary acoustical treatments for which noise reduction data are given in Appendix C also employ zig-zag, wavy or helical air paths to obtain broad band noise reduction. The use of such structures may eliminate the need of a section of thin baffles to obtain high frequency noise reduction.

When selecting treatments, it is generally convenient to begin by attempting to fulfill the low frequency noise reduction requirements. When these requirements are fulfilled, it will be found that the high frequency requirements are significantly diminished. One may then select additional acoustical treatments to achieve the required high frequency noise reduction.

One will note by studying the data in Appendix C that for

a fixed thickness of acoustical treatment, the noise reduction generally increases with decreasing open spacing. However, the open spacing cannot be decreased indefinitely because of the requirement for a given amount of open cross-sectional area. As the percentage of open area is decreased, the noise reduction per foot increases, but the total cross-sectional area must increase. The total cost for the acoustical treatments per se will generally decrease with decreasing percentage area. The cost of the concrete structure required to enclose the acoustical treatments will increase with decreasing open area because the total cross-sectional area increases. A minimum cost solution is found by a trial and error process.

2. Structural Considerations for Acoustical Treatments

The acoustical performance and useful life of the treatments for which data are given in Appendix C may be seriously impaired if certain construction techniques are not followed. First, in baffles or ducts, a horizontal septum should be put into the baffles every two or three feet. This septum will prevent the fibrous material from settling to the bottom of the structure.

Second, vibration breaks in the structure of the acoustical treatment must be employed, if large noise reduction values are to be obtained. The maximum recommended length between vibration breaks is given for each type of acoustical treatment on the data page facing the noise reduction curves. If vibration breaks are not employed, then noise reduction may be limited by flanking transmission through the structure of the acoustical treatment.

Third, the acoustical panels used for duct and baffle structures should be fabricated in lengths not more than about 3 ft long if the data in Tables IV and V are to be used. If larger lengths are used, the maximum allowable velocities may be decreased.

Fourth, the acoustical treatments which are located near the test section will be subjected to vibration that is induced by the large noise levels. All fasteners used in the construction of the treatment should be welded or safety-wired to prevent the fasteners from becoming loose. Ramsets should not be used for attaching the acoustical treatment to the concrete structure. Several instances are reported in which this type of fastener has failed when used for this purpose.

In addition to vibration breaks in the acoustical treatments, vibration breaks may be required in the structure enclosing the acoustical treatment. Vibration breaks should be used whenever the noise reduction through the air passage is within 10 db of the noise reduction of the enclosing structure. For example, the transmission loss of a 12 in. concrete wall is about 50 db in the 150 to 300 cps band. If an acoustical treatment that is enclosed by a concrete structure 12 in. thick is to have a noise reduction greater than 40 db in the 150 to 300 cps band, then a vibration break will be required in the concrete structure. The vibration break should be a flexible material which is caulked with a non-hardening compound to prevent acoustical leaks.

G. Some Remarks on Aerodynamic and Thermodynamic Design

In this section, we shall attempt to outline some of the

fundamental aerodynamic and thermodynamic conditions which obtain throughout a test cell, and how these conditions affect the noise control components that are used. The primary purpose of this section is not to provide the acoustical engineer with all of the information required for designing for the proper aerodynamic and thermodynamic conditions. We shall only attempt to outline certain parameters which are important and to indicate the order of magnitude of the pertinent parameters. The final refined design which incorporates satisfactory aerodynamic and thermodynamic design considerations in an efficiently executed noise control design is obtained through close cooperation between the aerodynamicist and the acoustical engineer. The principles outlined in this section will aid the acoustical engineer in arriving at a preliminary acoustical design which will require a minimum of modification by the aerodynamicist. Reference 7, which considers these problems in more detail, is especially recommended to the test cell designer.

1. The Intake Section

In the intake section, the static pressure drop from the exterior of the cell to the test section imposes a relatively low limit on the allowable velocity. The velocities required in most intakes to satisfy the pressure drop limitations are usually far below the velocity limitations imposed by the acoustical treatments or by self-noise considerations. Furthermore, no special thermodynamic considerations exist as the intake air is at ambient temperature.

The pressure drop in the intake system can be reduced by the use of turning vanes in bends, and by fairing baffle and duct structures. Bends and abrupt changes in cross-sectional areas at the beginning and end of acoustical

treatments or duct structures are one of the major sources of turbulence and pressure drop at the intake system.

Turning vanes in bends leading to the test section will have negligible effect on the acoustical effectiveness of the bends and may significantly lower pressure drops. The noise field in the test section is essentially random and, hence, large noise reductions are not obtained from the bends even without turning vanes (See Appendix C).

2. The Test Section

The size of the test section and the location of the engine in the test section with respect to the intake treatment have only very minor effects on engine operation. If the test section is relatively small and the air velocity through the test section is fairly large, air flow past the engine creates a drag force which decreases the measured value of thrust. In most engine test cells, this apparent thrust loss is of little concern. By appropriate experimental tests, the magnitude of the drag force can be estimated. The drag force added to the measured thrust will give the total thrust of the engine.

The engine is usually located so that the primary air intake is at least 10 ft from the air intake. The turbulence created by the bend then has negligible influence on the engine operation.

Test facilities for experimental engines may require very accurate measurements of mass flow. A distance of 20 to 25 ft may be required between the bend and the air intake of the engine for an "air straightener" tube and a

bell-mouth which are used for mass flow measurements.

3. Augmentor Section

The purpose of the augmentor section in a test cell is to induce secondary air flow into the exhaust section. The jet engine and the augmentor form a "jet pump" which draws the secondary air into the cell and forces the exhaust gas mixture through the exhaust acoustical treatment. The ratio of cooling air to combustion air is a function of many variables. The most important of these are: The ratio of the length of the eductor tube to the diameter of the eductor tube; the ratio of the jet exhaust diameter to the eductor tube diameter; the velocity and temperature of the jet exhaust; the geometry of the eductor tube; and the position of the jet exhaust in relation to the entrance to the augmentor tube. The ratio of secondary to primary air must be about 2 or 3 to 1 in contemporary engine test cells. To obtain this amount of secondary air for present day jet engines, the ratio of the length of the eductor tube to the diameter of the eductor tube usually is about 6-8 to 1. The ratio of the exhaust diameter to the eductor tube diameter is about 2-3 to 1. Thus for a jet engine which has an exhaust diameter of 2 ft, the eductor tube must be of the order of 15 to 20 ft long and must have a diameter of 4 to 6 ft. The total distance from the exhaust of the engine to the input to the exhaust acoustical treatment* will be about 20 - 25 ft.

*It is perhaps interesting to note that the length from the jet exhaust to the acoustical treatment as determined from the aerodynamic requirements is comparable to the length required from acoustical considerations. In both cases, naturally, the required distance is a function of the distance required for complete mixing of the cooling air with the jet exhaust stream.

The distance between the engine and the eductor tube should be variable to allow different types of engines to be used in the test cell. The location of the engine is fixed by the position of the inertial block and, hence, it is necessary to provide a telescoping entrance to the eductor tube. Furthermore, a telescoping entrance allows accurate adjustment of the ratio of secondary to primary air.

4. Exhaust Section

The limits on air velocity through acoustical treatments which are imposed by the limitations of the material and the possibility of self-noise generation are lower than the velocity limitations imposed by exhaust pressure drop requirements, at least in present day test cells. Generally, the temperature limitations imposed by the acoustical materials will be the only restrictions on the exhaust gas temperature. However, new acoustical materials may allow very high exhaust gas temperatures (above 500° F).

H. Analysis and Solution of a Test Cell Design Problem

1. Statement of the Problem

The ideas and techniques suggested in the previous section can be best illustrated by the analysis and solution of a typical test cell design problem. For this design problem, it is assumed that the noise source is a typical J-57 jet engine having the performance parameters described earlier in this section and in Appendix A. The test facilities are to be used for testing these J-57 engines after repair and overhaul. The facility is to consist of four test cells of which no more than two will operate simultaneously. Afterburner operations are not anticipated.

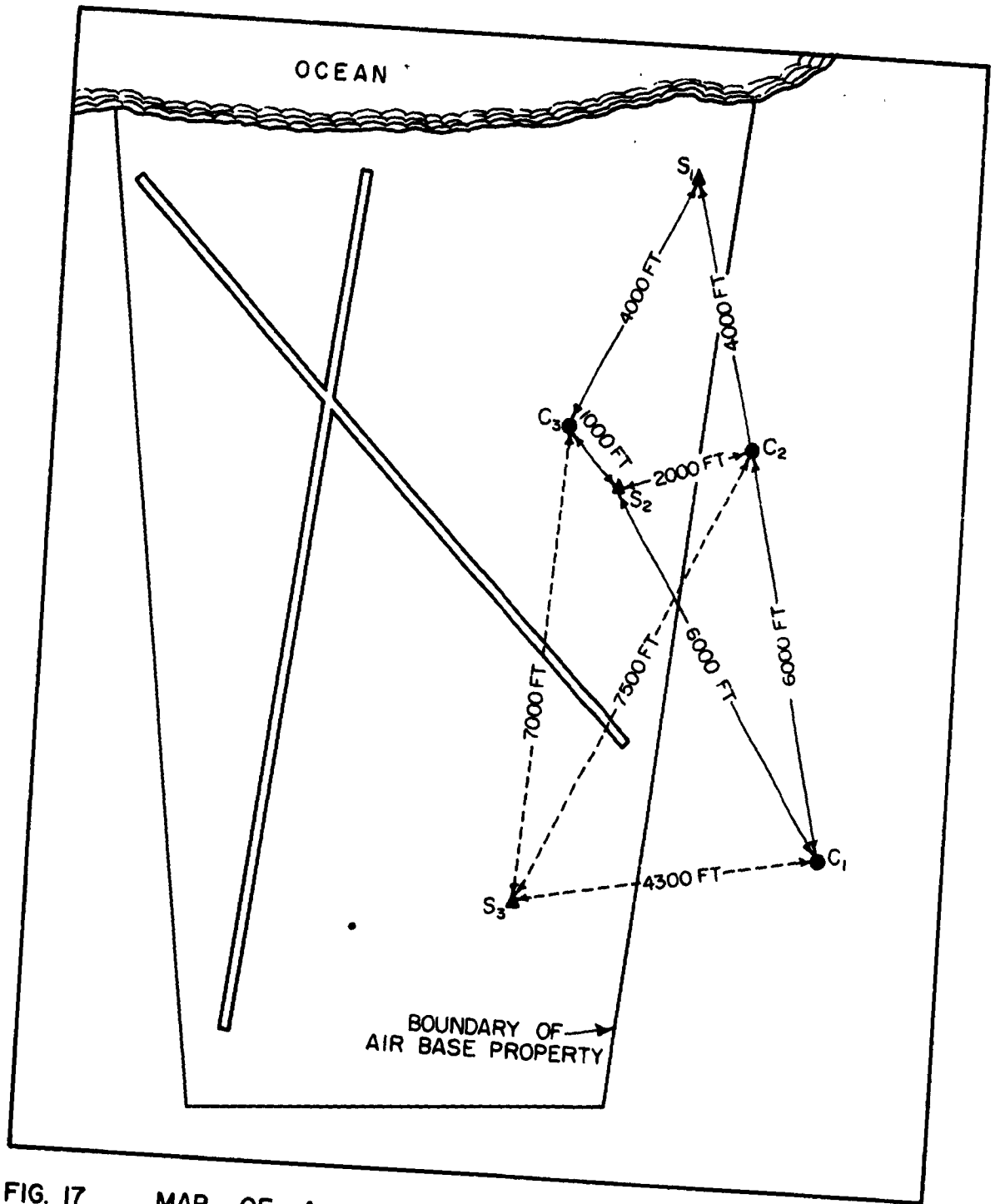


FIG. 17 MAP OF A HYPOTHETICAL AIR FORCE BASE SHOWING SELECTED TEST CELL SITES AND CRITERIA LOCATIONS.

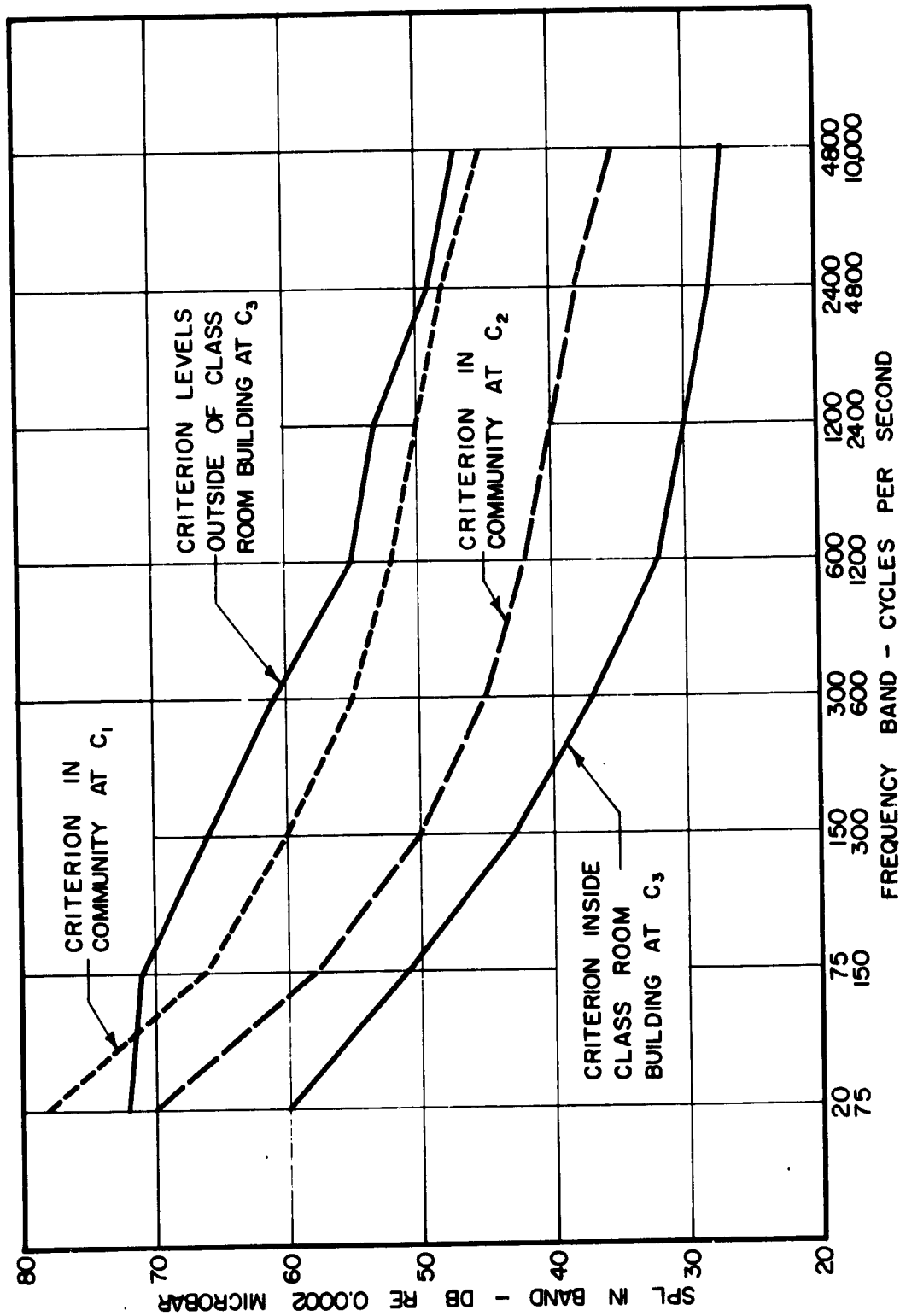


FIG. 18 CRITERIA SOUND PRESSURE LEVELS ON AND AROUND AIR BASE.

The test cells are to be located on the hypothetical air base which is depicted in Fig 17. Facilities and space for the test cells are available at three potential sites which are shown as S_1 , S_2 and S_3 in Fig 17. For this example we shall consider acoustical criteria at the three positions indicated as C_1 , C_2 and C_3 . The criteria noise levels at each of these positions are shown in Fig 18.

The criteria at C_1 and C_2 are the tolerable noise levels outdoors in two neighboring communities. Note that criteria differ by about 10 db. Such a difference may arise because of the different background noise levels in the two communities or because of a difference in the previous history of noise exposure of the inhabitants of the communities. The criterion at C_1 is higher because the community at C_1 is exposed to jet aircraft operations by virtue of its location with respect to the runway (see Refs 5 and 6).

The criteria at C_3 is determined from the acceptable noise levels in an airmen's classroom building on the base. The permissible noise levels inside of the classroom building are assumed to be given by an NC-30 criterion^{2/}. The acceptable noise levels outside of the building are found by adding to the NC-30 levels the noise reduction afforded by the walls. The acceptable noise levels outside have been determined from noise reduction measurements of some typical Air Force building structures (the data used here are taken from Ref 20).

2. Site Selection by Analysis of Noise Reduction Requirements

The noise reduction requirements at the potential sites can be rank ordered by finding the allowable noise levels at 250 ft from each potential site in terms of the criteria

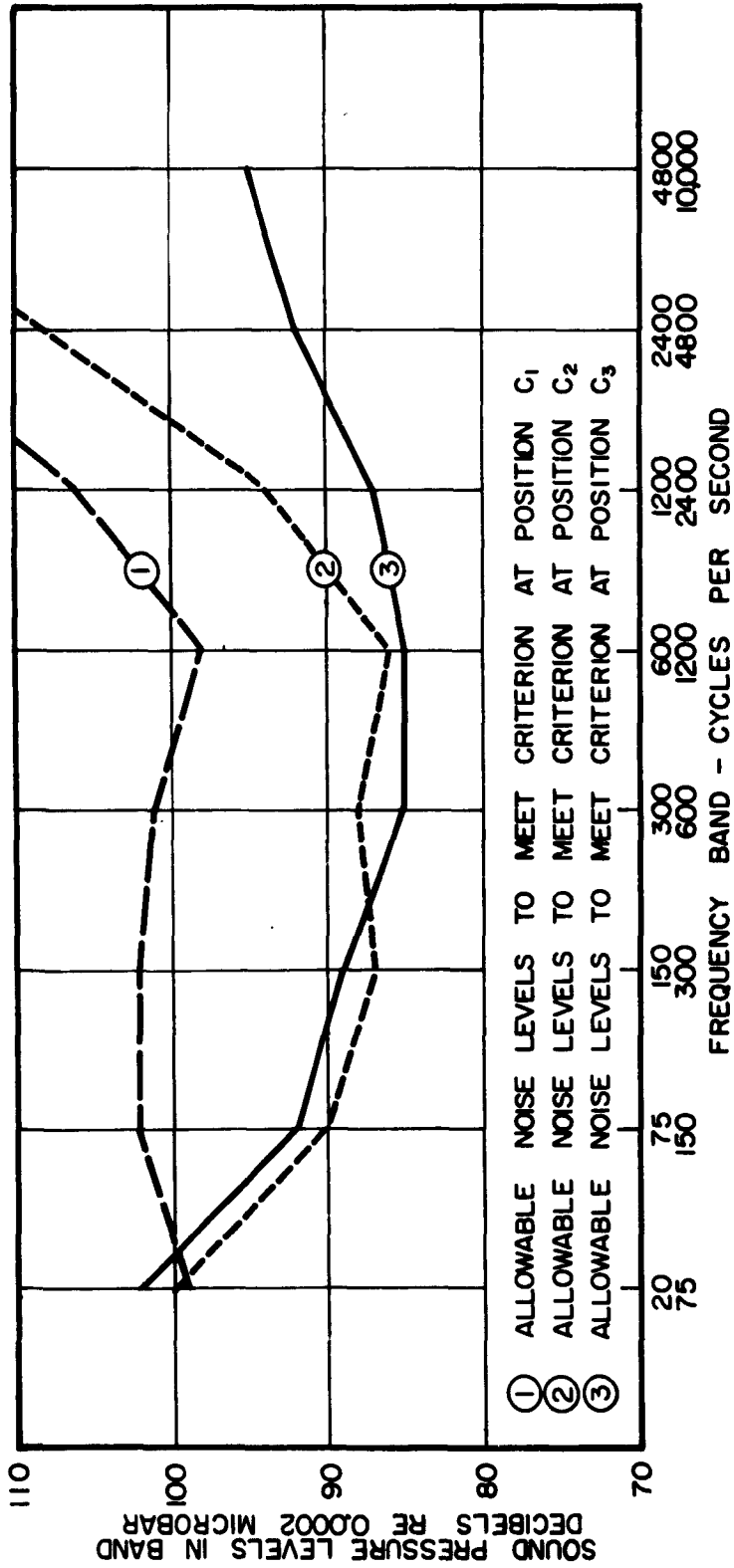


FIG. 19 ALLOWABLE NOISE LEVELS AT 250 FT FROM A TEST CELL LOCATED AT SITE S₃

levels. The site having the highest allowable levels will have the lowest noise reduction requirements. The allowable levels at 250 ft are found by adding to the criteria levels the reduction of sound pressure level with distance.

In Fig 19 the allowable levels at 250 ft from site No. 3 given by curves 1, 2, and 3, respectively, are imposed by the values of the criterion sound pressure levels at position C_1 , C_2 and C_3 . The allowable noise levels at 250 ft from this site are of particular interest as the maximum allowable noise levels for all octave bands do not result from the criterion at a specific location. In the 20-75 cps octave band, for example, the lowest allowable noise level results from the criterion at C_3 . In the 75-300 cps octave bands, the lowest levels result from the criterion value at C_2 . In all higher octave bands, the lowest levels are imposed by the criterion at C_1 .

The maximum allowable noise levels shown in Fig 20, at each of the sites, were obtained by adding to the criteria at the various positions the spreading losses from the site location to the criteria locations as given in Fig 4.

The noise levels at 250 ft from the reference test cell are also shown in Fig 20*. Figure 20 shows that site No. 3 is the most desirable site by a fairly wide margin. Indeed, at site No. 3 essentially no acoustical treatment is required for the intake and only a very small amount is required for the exhaust. At site No. 2, on the other hand, an acoustical treatment which provides noise reduction in all octave bands is required in the exhaust. In the intake,

*These noise levels were obtained by the method outlined in Table II. The operations indicated there have been carried out for all octave bands.

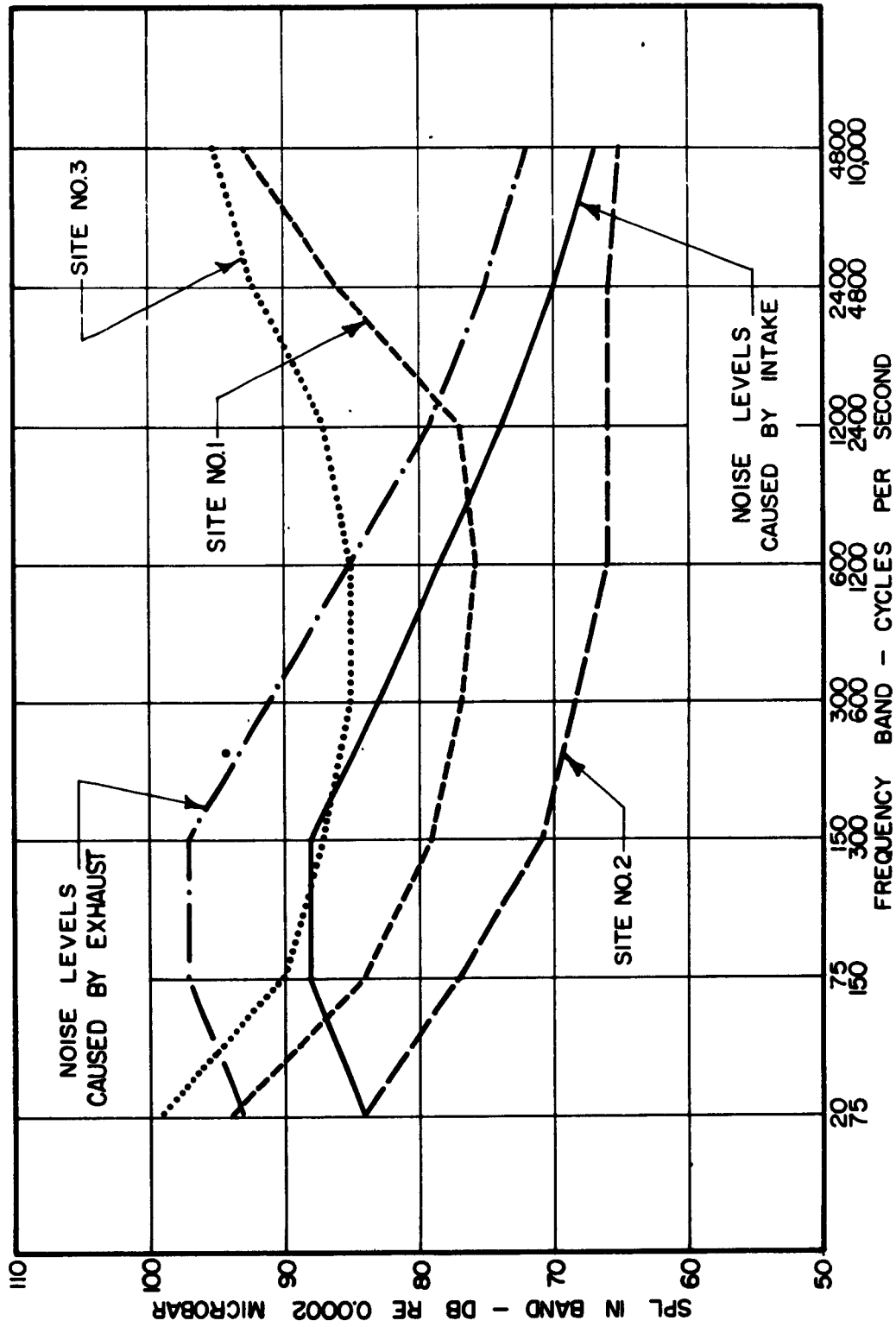


FIG. 20 ALLOWABLE NOISE LEVELS AT 250 FT FROM EACH POTENTIAL SITE COMPARED WITH NOISE LEVELS PRODUCED AT 250 FT FROM REFERENCE TEST CELL.

noise reduction is required in all octave bands except the first.

Thus, the analysis of the noise reduction requirements can indicate how to minimize noise reduction requirements. This example is typical of what might be found on many air bases. The importance of site selection cannot be over emphasized.

Although this example indicates that site No. 3 should be used, we shall assume that site No. 3 is not feasible for other reasons. To finish the problem we shall establish the exact noise reduction requirements for site No. 1 and design a test cell to meet these requirements.

3. Determination of Noise Reduction Requirements for Intake and Exhaust Acoustical Treatments.

The noise reduction requirements for the intake and exhaust acoustical treatments in a test cell at site No. 1 can be determined from the data presented in Fig 20. The acoustical treatments must reduce the noise levels from the intake and the exhaust enough so that their sum is equal to the allowable noise level shown. As indicated earlier in this section, one must generally allow for a contribution from the walls of the test cell as well as from the intake and exhaust; however, in this case, the noise reduction requirements are modest and the contributions from the walls will be negligible (the wall structure will be 8 to 12 in. of concrete for structural reasons).

The noise contribution from either the intake or the exhaust should be 3 db less than the allowable noise levels shown in Fig 20. For example, in the 75-150 cps octave band,

the noise levels caused by the intake for the reference facility are 4 db above the allowable noise levels at 250 ft. Thus, the total noise reduction requirement for the intake acoustical treatment is 7 db. The noise reduction requirement for the acoustical treatments of the reference cell are given in Table VI below.

TABLE VI
NOISE REDUCTION REQUIREMENTS
FOR INTAKE AND EXHAUST ACOUSTICAL TREATMENTS
OF REFERENCE TEST CELL

	20 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 10,000
Intake	0	7	12	10	5	0	0	0
Exhaust	0	16	21	17	12	5	0	0

Table VI indicates that the highest noise reduction requirements are in the 150-300 cps octave band both for the intake and exhaust. The 150-300 cps octave band generally presents the most stringent noise reduction requirements in jet engine test cell design problems.

In the case of the test cell located at site No. 1, it is worthwhile to investigate the possibility of using an L-shaped test cell instead of a U-shape one in order to achieve noise reduction by directivity. The exhaust could be pointed out over the ocean, thus increasing the directivity losses to the criteria locations. The increase in directivity would be to a certain extent compensated for by the elimination of the unlined bend. For this example, the noise reduction requirements would be the same in the first 2 octave bands, but would be smaller in all octave bands above 150 cps.

For a horizontal exhaust system in an L-shaped cell, the noise reduction requirements would be as given in Table VII.

TABLE VII
NOISE REDUCTION REQUIREMENTS FOR EXHAUST ACOUSTICAL
TREATMENT OF A TEST CELL WITH HORIZONTAL EXHAUST
(SINGLE CELL OPERATION)

	20 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 10,000
1. Decrease in NR from Elimination of Bend	4	4	4	4	4	4	4	4
2. Increase in NR by Directivity	3	4	6	7	9	10	10	10
3. Net change in NR	+1	0	-2	-3	-5	-6	-6	-6
4. New NR Requirement for Exhaust	0	16	19	14	7	0	0	0
5. Original NR Requirement for Exhaust	0	16	21	17	12	5	0	0

Line 3, or a comparison of lines 4 and 5, indicates that the use of a horizontal exhaust lowers the noise reduction requirements in all frequency bands above 150 cps. One will find (see below), however, that the most critical noise reduction requirement is that in the 75-150 cps band. In meeting this noise reduction requirement, the noise reduction requirements in all higher frequency bands will be exceeded. Thus acoustically, the horizontal exhaust is not extremely advantageous. If an exhaust diffuser is used to satisfy the low frequency requirements,

or if the noise reduction requirements for the "U" shaped cell are somewhat greater in the high frequencies, a horizontal exhaust may be quite advantageous.

A horizontal exhaust system may be advantageous from a structural viewpoint, particularly for areas in which the load-bearing capacity of the soil is low. A horizontal exhaust system will provide a more uniform distribution of the load which needs less structural reinforcing and fewer clusters of piles or caissons.

To this point in the example, we have considered only the operation of one test cell. If operation of more cells is envisioned, then the noise levels at the various criteria locations will increase and the noise reduction requirements must correspondingly increase. The increase in noise reduction requirements for the operation of three cells is anticipated, for example, then the noise reduction requirements will increase by $10 \log_{10} 3$, or 5 db. For the remainder of the example we shall use the noise reduction requirements given in Tables VI and VII which have been derived for single cell operation.

4. Solutions of Design Problems

The required noise reductions for the intake or the exhaust can be achieved by using conventional acoustical treatments or by using jet stream modifiers to accomplish a reduction of the noise radiated by the jet engine. Two solutions to this problem will be presented for comparison of these two techniques.

The noise reduction requirements for the exhaust and intake acoustical treatments can be satisfied by a variety of acoustical treatments. A modest length of almost any of the treatments shown in Figs C-6 through C-19 will satisfy the noise reduction requirements above 300 cps. A relatively long length of most treatments is required to satisfy the noise reduction requirements in the 75-150 and 150-300 cps bands.

When selecting acoustical treatments to achieve noise reduction one should select a treatment whose noise reduction spectrum approximates the spectrum of the noise reduction requirements. In this way an economical acoustical design will usually be obtained. For this example, a treatment which has a maximum noise reduction in the 150-300 cps band should be used. A duct structure such as that depicted in Fig C-19 might be desirable. Two such ducts placed side by side would provide about the required 125 sq ft of open area.

The noise reduction requirements can be met with less acoustical treatment if part of the treatment is placed in the horizontal portion of the exhaust duct and part of the treatment is placed in the vertical portion of the exhaust. When arranged in this manner, the noise reductions of the two sections of acoustical treatments are simply additive and the advantages of the "end effects" are realized twice (see Appendix C, Section 4). The noise reduction requirements given in Table VII could be satisfied by an 8 ft duct in the horizontal section and a 4 ft duct in the vertical section. The noise reduction of this system is given along with the noise reduction for 12 ft of continuous duct in Table VIII. The acoustical effectiveness of separating treatments by a bend can be further illustrated by noting that at least 16 ft of continuous duct are required to meet

the noise reduction requirements which have been satisfied by the 12 ft of duct used in two sections.

TABLE VIII
NOISE REDUCTION FOR LINED DUCTS IN THE EXHAUST

	Frequency Band in CPS							
	20 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 10,000
Noise Reduction for 12 ft of Ducts as Located in Fig 21a	15	17	22	18	15	15	15	15
Noise Reduction for 12 ft of Continuous Lined Ducts	12	14	18	16	11	11	11	11
Noise Reduction for 16 ft of Continuous Lined Ducts	14	17	22	19	14	11	11	11

The noise reduction requirements for the intake acoustical treatment can be met with about 6 ft of the same type of lined duct placed in the vertical portion of the intake duct. The resulting geometry is depicted in Fig 21a (p. 92).

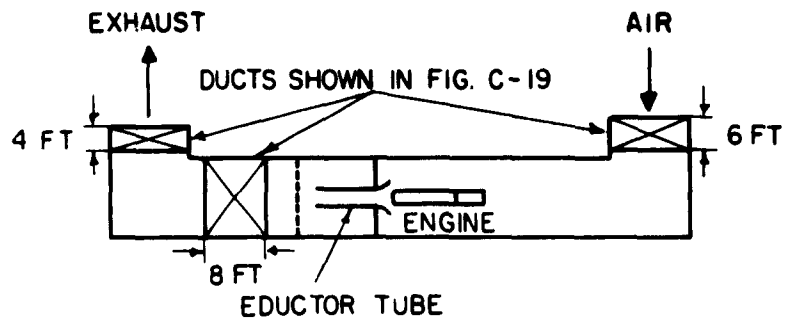
As an illustration of the effectiveness of jet stream modifiers assume that a simple device such as that depicted in Fig E-3 is used in the test cell. This device has been designed as an experimental noise reduction device for in-flight suppression. Therefore, noise reduction has not been the sole design objective. Weight, thrust loss, etc. have also been considered. Nonetheless, significant reductions in acoustic power are obtained. The original noise reduction requirements, the approximate noise reduction of this device and the noise reduction requirements

for a test cell incorporating this device are given in Table IX.

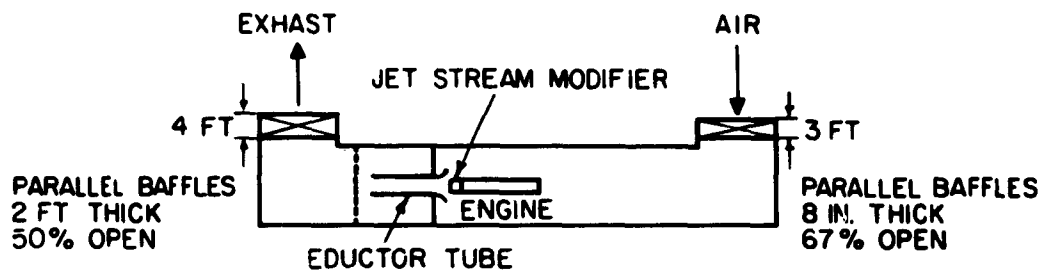
TABLE IX

REVISED NOISE REDUCTION REQUIREMENTS FOR A TEST CELL
INCORPORATING A JET STREAM MODIFIER

	20 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 10,000
1. Original Noise Reduction Requirements for Exhaust Acoustical Treatments	0 -	16	19	14	7	0	0	0
2. Original Noise Reduction Requirements for Intake Acoustical Treatments	0	7	12	10	5	0	0	0
3. Power Reduction by Jet Stream Modifier	9	12	14	8	7	2	0	0
4. Revised Noise Reduction Requirement for Exhaust Acoustical Treatment (1-3)	0	4	7	9	5	3	0	0
5. Revised Noise Reduction Requirement for Intake Acoustical Treatment (2-3)	0	0	0	2	0	0	0	0



a.



b.

FIG. 21 TWO SOLUTIONS TO THE TEST CELL DESIGN PROBLEM.

Table IX clearly illustrates that the required acoustical treatment for a cell with this jet stream modifier is significantly less than for the cell without acoustical treatment. The revised noise reduction requirements for the exhaust could be satisfied with 4 ft of baffles 2 ft thick and having 50% open area. These baffles should be placed beyond the bend in the exhaust stack so that they are not exposed to the direct blast from the jet.

The intake treatment requires almost no acoustical treatment. It should be remembered, however, that the directivity indices on which the analysis is based have been obtained from measurements of intake and exhaust stacks, which contained acoustical treatment. The noise radiation from such a stack is directed primarily vertically. Oblique noise radiation had been suppressed by the acoustical treatments preceding the exhaust or inlet opening. In order to obtain from this design the same values of directivity, a modest amount of acoustical treatment is required. Three ft of parallel baffles, 8 in. thick and 67% open would be sufficient to eliminate the oblique noise radiation.

A section of the test cell incorporating the jet stream modifier in the above outlined acoustical treatments is shown in Fig 21b. The acoustical treatments in this design are significantly less than those shown in Fig 21a. The cost of the design shown in Fig 21b could be further reduced by decreasing the cross section and the open area through the intake and exhaust sections. The reference test cell cross section was based on typical design values for cells with much longer acoustical treatments (12 to 24 ft). Because the acoustical treatments here are quite short, the linear velocity allowed may be increased. In any case, the cross

section for the design in Fig 21b can always be less than the cross section for the design in Fig 21a because shorter lengths of acoustical treatment are required in 21b.

To summarize, the use of a jet stream modifier affords a reduction in cost by decreasing the amount of acoustical treatment required and by allowing reductions in cross sectional area. These advantages may be compensated by slight changes in engine performance induced by the jet stream modifier.

SECTION V

AIRCRAFT RUN-UP NOISE SUPPRESSORS

Aircraft run-up noise suppressors may have many different configurations. A run-up noise suppressor may be a simple exhaust diffuser which costs a few thousand dollars or it may be a complete enclosure for an aircraft which costs several hundred thousand dollars. Generally, the basic configuration of a run-up suppressor is dictated by the magnitude of the noise reduction requirements. For given noise reduction requirements, however, the configuration will vary depending upon the aerodynamic and thermodynamic requirements at the intake and at the exhaust of the aircraft.

The various types of noise suppressors are described and classified into five types. Factors affecting the selection or design of a run-up suppressor are also discussed. These factors include noise reduction requirements, operational requirements, such as portability and adaptability, and aerodynamic and thermodynamic requirements.

A. General Design Considerations

A first design consideration is the amount of noise reduction provided by a run-up suppressor. A second, and equally as important, consideration is that of the operational flexibility of a run-up noise suppressor, since a run-up suppressor that is acoustically effective may be operationally useless. For example, can it be moved easily from place to place or is it a permanent installation? If it is a closely coupled type of suppressor, how quickly can it be attached to and removed from the aircraft? A third consideration is the effect of the suppressor on the aerodynamic and thermodynamic

conditions at and in the engine. Each of these factors is discussed in this section with regard to their general applicability to the various types of noise suppressors.

1. Noise Reduction Requirements

Generally speaking, the noise reduction requirements of a run-up noise suppressor are set by a consideration of the noise environment in the close field and/or the distant field of the noise suppressor. The close field of a noise suppressor is that area in the vicinity of the aircraft or aircraft suppressor combination where maintenance or operating personnel are apt to be located. In the close field, the objective is usually to reduce the noise levels during engine operation so that maintenance personnel can perform their duties without incurring risk of permanent loss of hearing^{1/}.

In the far field, beyond 100 to 200 ft from the aircraft-suppressor combination, there are a number of acoustical design objectives. Generally speaking, the noise reduction of the run-up suppressor should be adequate to provide acceptable speech communication conditions in nearby offices and work spaces. This is of particular importance in those areas where speech communication is vital; for example, in a control tower where, for reasons of safety, communication should never be interrupted by intruding noise. Further, and this is usually less important in most practical situations, the noise reduction requirements of a run-up suppressor may be influenced by the necessity for reducing run-up noise to acceptable levels in nearby residential areas.

The noise reduction of run-up noise suppressors usually varies appreciably with angular position around the aircraft

suppressor combination. Basically, the reason for this is that the noise field around an unsuppressed jet aircraft is extremely directive; at or near military power the SPL's at about 45° from the jet exhaust axis are as much as 20 to 25 db greater than those forward of the aircraft.

Consequently, for those noise suppressors which produce a non-directive noise field, the noise reduction will also vary appreciably with angle, with the maximum noise reduction being achieved at about 45° from the exhaust axis.

The noise reduction of a run-up noise suppressor not only varies with angle, but also with frequency and position. The noise reduction close to an aircraft may be very different from that achieved at several hundred feet. For example, a Type V-Pen (see below) may provide 15 to 20 db noise reduction at 250 ft from the aircraft, but no noise reduction or perhaps even an increase in sound pressure level at locations close to the aircraft. Because of the complexity of a complete description of the acoustical effectiveness of a noise suppressor, certain simplified designations of noise reduction have been adopted (See Volume One of this report). The close-field noise reduction is equal to the average noise reduction on a close-in rectangle about the aircraft-suppressor combination. The distant-field noise reduction, is given by the average noise reduction on a 250 ft circle in three angular ranges: 0° to 180° , 0° to 90° , and 90° to 180° .

2. Operational Requirements

A run-up suppressor that is very effective acoustically may be of limited usefulness in the field because it is incompatible with operational requirements. There are certain

operational requirements that must be satisfied, and these can be classed broadly into two categories: portability and adaptability. The degree of portability required for a run-up suppressor will be determined primarily by the mission of the base on which they are used. For example, in a Tactical Air Command wing, portability may be so important that only Type III suppressors can be employed. In contrast, at a repair depot portability may be of minor importance and Type I, II, or III suppressors could be used.

The degrees of portability can be described as follows^{15/}:

a. Fixed

A noise suppressor is fixed if it is permanently mounted. Such a suppressor could be made of poured concrete or of similar construction. Moving such a suppressor would probably require rebuilding, utilizing only the acoustical treatment at the new site.

b. Transportable

A transportable suppressor can be taken apart, moved, and reassembled. The move would be difficult, but possible.

c. Semi-portable

A semi-portable noise suppressor is mounted on wheels and constructed so that it can be moved fairly easily, usually by means of a motorized tug or truck. Some of the typical examples are: a suppressor mounted on a flat-bed truck; a suppressor mounted on rails; a suppressor mounted on a dolly.

d. Portable

A portable noise suppressor can be moved by 2 or 3 men. A powered vehicle is not required to move it. Included in this classification are suppressors that may be carried to an aircraft and attached by 2 or 3 men.

The adaptability of a run-up noise suppressor pertains to whether or not a run-up noise suppressor can be used with different types of jet aircraft, and also its ease of use with any particular type of aircraft. Adaptability is, of course, an extremely important consideration at air bases where a number of different types of aircraft operate.

Adaptability is also extremely important in terms of the amount of time necessary to either move the aircraft in and out of an enclosure or a run-up pen, or the time necessary to couple and uncouple a run-up suppressor to an aircraft.

3. Aerodynamic and Thermodynamic Considerations

The important aerodynamic and thermodynamic variables are basically the same for ground run-up suppressors as for jet engine test cells. Limitations on static pressure drop through air intake and exhaust gas passages are imposed by requirements for satisfactory engine operation. Limitations on linear velocity and temperature in the exhaust gas passages are imposed by the structure and materials used in the acoustical treatment of the air passages.

The general relations between velocity limitations, temperature limitations, and total mass flow requirements are the same as those derived in Appendix F for the reference jet engine test facility. However, the problems of aerodynamic design for ground run-up suppressors are somewhat more numerous because different temperature and velocity requirements may be imposed upon a combustion air passage, a cooling air passage, and an exhaust gas passage. Nevertheless, the various equations may be applied, as is appropriate to each

air passage, once velocity and temperature restrictions are imposed.

In run-up suppressors, the static pressure drop limitations for combustion air are probably about the same order of magnitude as that for engine test cells, namely, 2 to 6 in. of water. The allowable static pressure drop through cooling air passages may depend upon numerous variables. For example, the static pressure at the exhaust gas outlet of the jet engine must be negative if there is induced air flow through the fuselage or the cell for cooling purposes. On the other hand, if the pressure drop is too large, the fuselage or the cell structure may be damaged. Allowable pressures at air intakes and exhaust gas outlets can be obtained only by consultation with engine or airframe manufacturers. Some effects of acoustical treatments on air flow conditions and on engine operation are discussed in more detail in Reference 7.

The limitations imposed on acoustical materials in air passages of ground run-up suppressors are the same as for engine test cells (see Tables IV and V in Section III).

B. Characteristics of Run-up Noise Suppressors

1. Type I Noise Suppressor

The Type I noise suppressor consists usually of two units, an intake suppressor (Type I - In) and an exhaust suppressor (Type I - Ex). In some cases it may consist of only one unit, an exhaust suppressor. These units are either located very close to the aircraft or coupled directly to the exhaust and/or intake openings of the aircraft. They do not enclose the body of the aircraft.

a. Noise Reduction Characteristics. Without an intake suppressor, an average noise reduction of about 20 to 30 db is possible in the angular range from 0° to 180° . With an intake suppressor, an average noise reduction of about 40 db is possible. The upper limit in noise reduction is determined by the amount of noise coming through the fuselage and, hence, will depend upon the aircraft. Noise reductions in the close field are the same order of magnitude.

b. Operational Suitability. Type I suppressors may be permanently fixed, portable, or semi-portable. In general, the noise reduction decreases as mobility increases.

Because the exhaust and intake noise control elements must be connected to the aircraft, the adaptability of the units is generally poor. Frequently, however, a Type I suppressor may be modified for use with another aircraft by changing only the coupling units. The requirement for close coupling of the noise control units to the aircraft makes Type I suppressors somewhat difficult to use. Usually at least 10 to 15 minutes are required to attach or detach a noise suppressor from an aircraft.

c. Aerodynamic and Thermodynamic Considerations. For Type I suppressors, the aerodynamic and thermodynamic considerations are very closely related to the acoustical requirements. If the noise reduction requirements are modest, for example, there will be no need for an intake suppressor, and hence aerodynamic considerations at the air inlet are the concern of the airframe and engine manufacturers only.

The aerodynamic and thermodynamic considerations for the exhaust orifice are also dependent on noise reduction

requirements. The configuration of the secondary air inlet to the exhaust is dependent upon how tightly the exhaust suppressor unit must be coupled to the aircraft. The "degree" of coupling depends primarily upon noise reduction requirements (see Reference 15 for an excellent illustration of this point).

In exhaust gas passages temperature requirements will generally be imposed by the limitations of acoustical materials. As in test cell design, the exhaust gas outlet and the air inlets must be adequately separated to prevent reingestion.

d. Acoustical Design Considerations. The acoustical design procedure for a Type I suppressor is similar to that for a jet engine test cell. A reference noise facility can be assumed to find the far-field noise reduction requirements for the exhaust acoustical treatment. The reference facility in this case would probably be a simple air passage of appropriate cross-sectional area which has an "L" shape so that the exhaust is directed upward. Such a reference facility will be useful for preliminary estimates of noise reduction requirements for the components in the exhaust system. If the initial noise reduction estimates are greater than about 20 db, consideration should be given to the use of an intake suppressor. If the noise reduction requirements are more than 40 db, then a Type I suppressor will probably not satisfy the criteria requirements. In such a case the possibility of using a Type II suppressor should be investigated.

Because near-field directivity characteristics of air intake and exhaust suppressors are not generally known,

the reference noise concept is of limited use for estimating noise reduction requirements in the close field.

2. Type II Noise Suppressor

A Type II suppressor is a structure which encloses the entire aircraft. The intake and exhaust suppressor units are an integral part of the structure of the suppressor and are not directly connected to the airframe. The Type II suppressor may be considered in all aspects as a test cell with a very large test section that contains an entire aircraft.

a. Noise Reduction Characteristics. The noise reduction characteristics of Type II noise suppressors are essentially the same as those for jet engine test cells. The average noise reduction in the distant field can be as much as 50 to 60 db without an exhaust diffuser. If an exhaust diffuser is used, the average noise reduction may be as large as 70 db.

b. Operational Suitability. Type II noise suppressors are almost inevitably fixed. By use of adjustable ramps to assure proper location of the exhaust with respect to the eductor tube, several types of aircraft could be accommodated. The Type II suppressor is relatively easy to use because the aircraft is not tightly coupled to the exhaust system.

c. Aerodynamic and Thermodynamic Considerations. The aerodynamic and thermodynamic considerations are identical to those for a test cell. The air flow in the "test section" must be planned so that the aircraft is not subjected to high velocity turbulent air streams.

d. Acoustical Design Considerations. The acoustical design of a Type II noise suppressor is almost identical to that for jet engine test cells. The reference noise facility described in Section II will provide a good basis for estimating initial noise reduction requirements.

One consideration in the design of Type II noise suppressor systems that is different from that of test cells is the use of acoustical treatments in the test section. The possibility of high noise levels causing fatigue in the aircraft structure should be investigated. If fatigue possibilities are anticipated, it may be desirable to use large amounts of absorptive acoustical treatments in the test section to limit the SPL build-up in the reverberant field.

3. Type III Noise Suppressor

The Type III noise suppressor is characterized by its portability. It is very similar to the Type I noise suppressor in that it may consist of one unit, an exhaust suppressor (Type III - Ex), or two units, an exhaust suppressor and an intake suppressor (Type III - In). The basic difference is that both suppressor units are designed so that they may be readily and quickly put in place and removed by not more than two men. If the weight of each unit exceeds about 150 lbs, the unit must be mounted on a wheel support to enable two men to readily move it. The Type III noise suppressor units may be designed for direct attachment to the airframe or the engine nacelle at the air intake and exhaust gas openings, or they may be designed so that they do not attach directly to any part of the aircraft.

a. Noise Reduction Characteristics. Average distant field noise reductions as great as 30 db can be obtained with a Type III suppressor. To obtain more than about

25 db average noise reduction, a very simple intake suppressor may be required. In the close field the noise reduction is probably about the same.

b. Operational Suitability. The main feature of a Type III suppressor is its high degree of mobility. It is a truly portable device. If the suppressor is attached to the aircraft, adaptability problems will be similar to those for Type I suppressors. The Type III suppressor will generally be easy to use even if it must be attached to the fuselage.

c. Aerodynamic and Thermodynamic Considerations. To attain a high degree of mobility, a Type III suppressor usually incorporates some type of jet stream modifier or diffuser to accomplish noise reduction (see Appendix E). While such devices are extremely efficient acoustically, they tend to significantly modify the aerodynamic environment at the exhaust of the engine. The conditions at the exhaust will be particularly important for engines which operate below super-critical pressure ratios. Again, generalizations are difficult to make, and specific conditions must be investigated for each type of diffuser and each engine. The problem of recirculation may be acute for some Type III suppressors, especially those which radically modify and decelerate the jet exhaust stream.

d. Acoustical Design Considerations. The main element of the light-weight Type III suppressors is an exhaust diffuser element. At present these exhaust diffuser elements are designed by a trial and error process. In general, one would have to rely upon measured data to determine if a Type III suppressor will satisfy acoustical

requirements. The reference noise concepts outlined in Section II are of no assistance in designing Type III suppressors.

4. Type IV Noise Suppressor

The Type IV noise suppressor is a device which is permanently installed on the airframe or engine and is used during flight as well as during ground operation. These devices are to be distinguished from engines especially designed to generate less noise. Some examples of these devices may be seen currently in the advertisements of the major commercial aircraft manufacturers. While these devices have been developed to the point that they impose only minor penalties on thrust and fuel consumption, their application to Air Force aircraft is improbable unless they can be entirely removed from the aircraft at a moment's notice.

a. Noise Reduction Characteristics. The average noise reduction in both the far field and the near field for Type IV noise suppressors is of the order of 5 to 10 db, at least for the present state of acoustical technology.

b. Operational Suitability. The Type IV suppressor is permanently attached to the aircraft engine and therefore has very limited adaptability. It is by definition mobile.

c. Aerodynamic and Thermodynamic Considerations. Considerations for aerodynamic and thermodynamic requirements for Type IV suppressors are beyond the scope of this volume. The effects of the suppressor on the thrust and fuel consumption of the engine are, of course, the

primary considerations.

d. Acoustical Design Considerations. The reference noise concepts presented in Section II cannot be used for the design of Type IV suppressors. While the fundamental purpose of any suppressor is noise reduction, the design of Type IV suppressors is almost entirely based on requirements for satisfactory engine operation.

5. Type V Noise Suppressor

This class of noise suppressors includes a variety of units such as blast fences, blast deflectors, sound reflecting walls, pens for enclosures, or any other type of structure that may reflect or redirect jet engine noise to provide limited noise reduction over a limited area. The particular device must be identified. For example, an aircraft run-up pen used for noise suppression would be identified as a Type V - Pen, Noise Suppressor Assembly. Other special structures would be similarly identified under the general designation Type V.

a. Noise Reduction Characteristics. Type V noise suppressors generally are used where only low average noise reductions are required. However, noise reductions in limited angular ranges and in certain limited areas may be obtained from Type V noise suppressors. For example, a run-up pen may have relatively large noise reductions in areas close to and in front of the pen. Similarly, blast deflecting walls may have reasonable noise reductions in areas near to and behind the wall.

b. Operational Suitability. Most Type V suppressors are readily adaptable to a wide range of aircraft types.

They may be fixed, as a run-up pen, or they may be semi-portable, such as some blast deflectors which may act as exhaust diffusers.

c. Aerodynamic and Thermodynamic Considerations.

Type V run-up suppressors generally are not intimately attached to the aircraft. Thus, the problems associated with pressure drop, velocity, and temperature of gases in air passages are not important. Care must still be taken, however, to assure that recirculation and re-ingestion of combustion products are prohibited. Perhaps the prime advantage of using the Type V suppressor is that the effect of the suppressor on the operation of the engines is generally negligible.

d. Acoustical Design Considerations. The reference noise concepts developed in Section II are only slightly useful for Type V suppressors. The degree to which the reference noise conditions may be applied will depend upon the nature of the device which is used as a Type V suppressor.

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APPENDIX A
ESTABLISHMENT OF NOISE SOURCE LEVELS

In this Appendix methods are given for determining the sound pressure levels at several positions in test cells and ground run-up suppressors. The acoustic power level (PWL)* is first calculated from engine parameters and the sound pressure levels are then found from the power level.

1. Jet Engines

a) Acoustic Power Levels

The acoustic power radiated from a turbojet engine has been found to be proportional to

$$\rho_a A v^8 / c_a^5 \quad (A-1)$$

For computational purposes this proportionality can be written as:

$$W = k \frac{T_j}{T_a} \frac{v^5}{c_a^5} \left(\frac{Mv^2}{2} \right) \quad (A-2)$$

where ρ_a is the density of the ambient air, at the general location of the jet,

A is the area of the jet exhaust orifice,

v is the velocity of the jet relative to the surrounding air,

c_a is the speed of sound in the ambient air,

M is the mass flow of air, which is equal to the weight flow of air, m, divided by the acceleration of gravity, g.

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

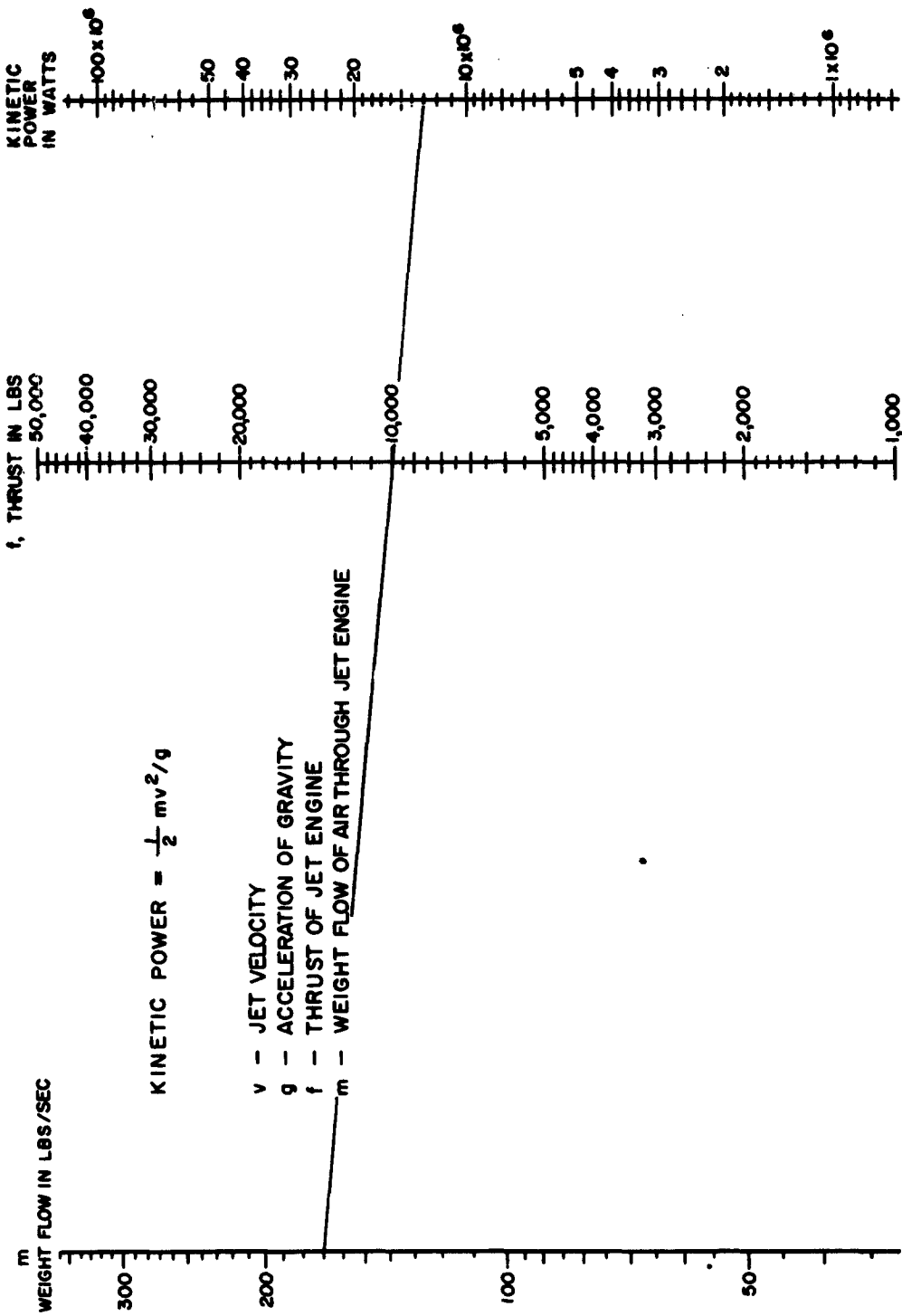


FIG.A-1 NOMOGRAM FOR FINDING KINETIC POWER OF JET STREAM FROM THRUST AND WEIGHT FLOW

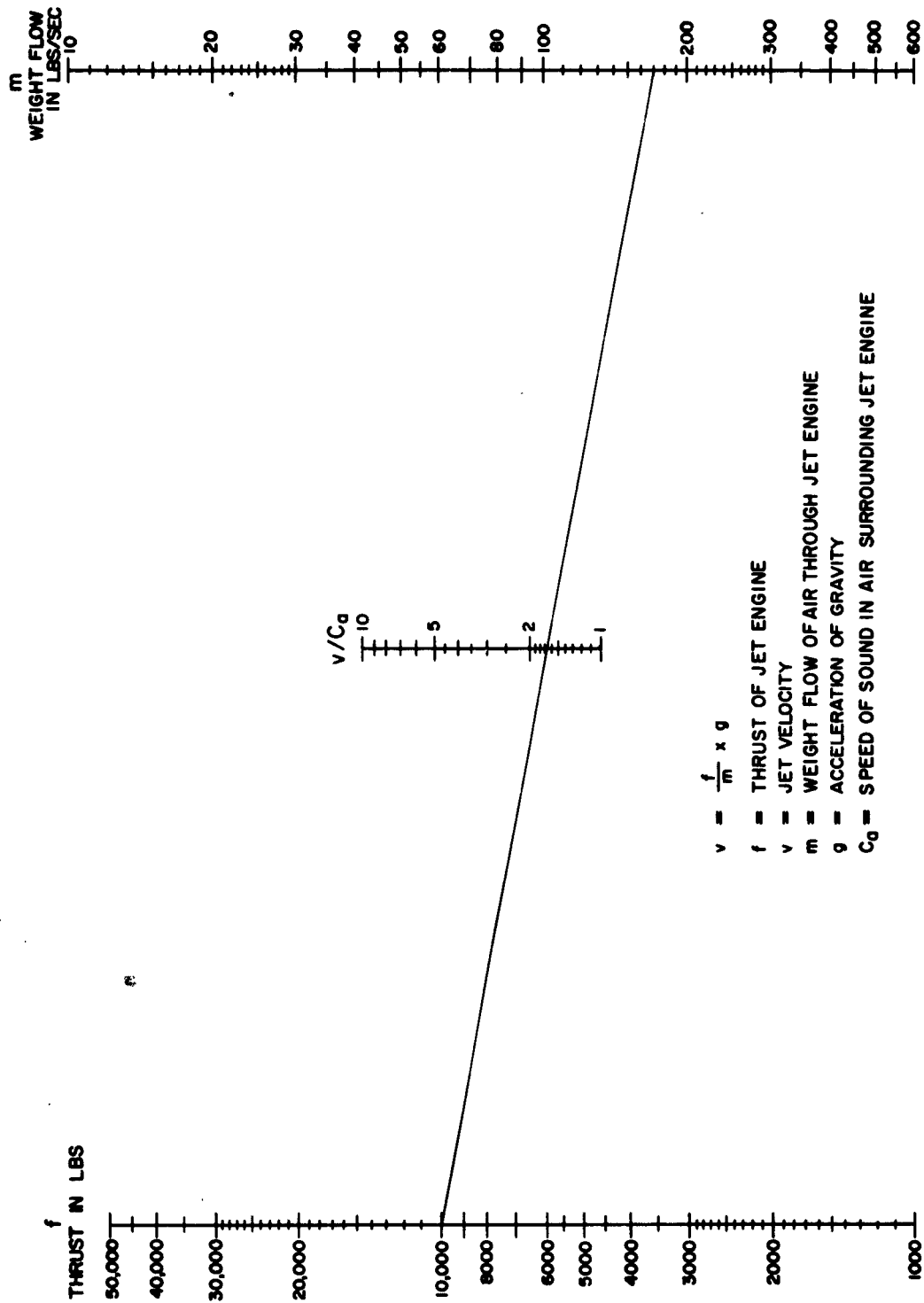


FIG. A-2 NOMOGRAM FOR FINDING JET VELOCITY AMBIENT SPEED OF SOUND FROM THRUST AND WEIGHT FLOW.

k is a constant which has been evaluated empirically^{16/}.

T_j is the static temperature in the jet,

T_a is the temperature of the ambient air.

The quantity $(Mv^2/2)$ is the kinetic (mechanical) power of the jet stream. The ratio of acoustic power, W , to kinetic power $(Mv^2/2)$, measures the efficiency, η , of conversion of the kinetic power of the jet stream to acoustic power. Therefore, the acoustic power may be written as:

$$W = \eta \left(\frac{Mv^2}{2} \right) \quad (A-3)$$

The acoustic power may be found from the thrust and weight flow of the jet engine in four steps. First, the kinetic power is found from the thrust and the weight flow by use of the nomogram in Fig A-1. Second, the ratio of jet velocity to the ambient speed of sound is found from Fig A-2. Third, this ratio is used with Fig A-3 to find the efficiency of conversion, η . Fourth, the kinetic power is multiplied by the efficiency of conversion to obtain the acoustic power in watts. The acoustic power level is found from the acoustic power in watts by use of Eq (A-4):

$$PWL = 10 \log_{10} W + 130 \text{ db} \quad (A-4)$$

These nomograms may also be used to determine the power level of rocket engines, provided the ratio of v/c_a is greater than 2, which condition is satisfied for almost all rocket engines.

In Fig A-2, only two static temperatures are given for jet engines. These static temperatures, 1150°F and 3000°F, apply for most jet engines at military power and afterburner condition, respectively. The 70°F and 5000°F curves are presented

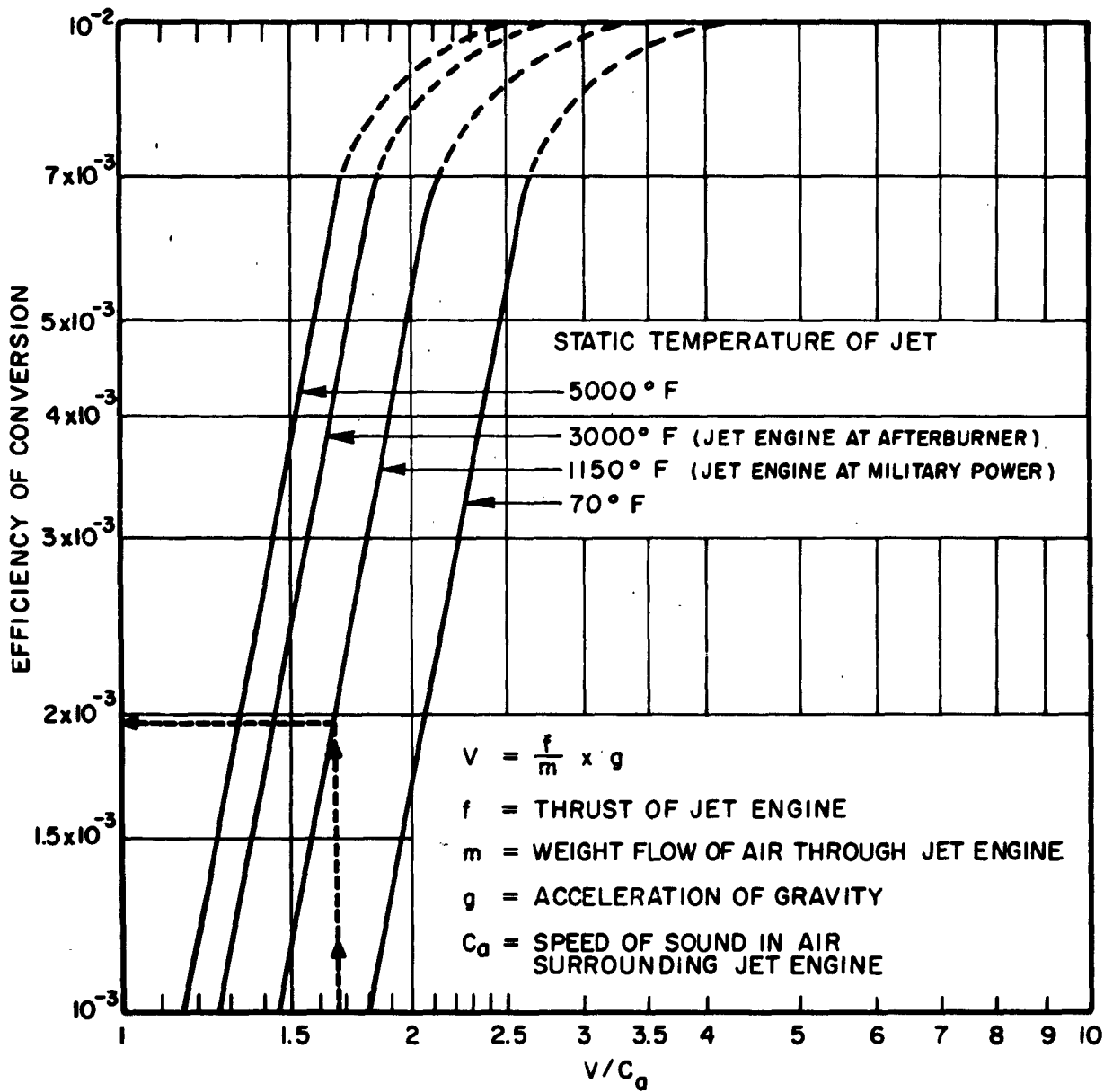


FIG.A-3 EFFICIENCY OF CONVERSION OF KINETIC POWER OF JET STREAM TO ACOUSTIC POWER.

so that interpolation to other temperatures may be carried out if necessary.

To illustrate the use of Figs A-1 through A-3, the acoustic power level of a typical model of the J57 engine is calculated below. The weight flow for the engine at military power is approximately 170 lbs and the thrust is about 10,000 lbs. Figure A-1 is entered at a weight flow of 170 lbs/sec and a thrust of 10,000 lbs. A line connecting these points and extended to the kinetic power line shows the kinetic power is about 13×10^6 watts.

Connecting the points for 10,000 lbs thrust and 170 lbs/sec weight flow, the ratio v/c_a is found to be about 1.7. Entering the abscissa of Fig A-3 at 1.7 and going up to the 1150°F temperature curve (military power) shows the efficiency of conversion to be about 1.9×10^{-3} .

Multiplying the efficiency of conversion times the kinetic power gives an acoustic power, W , of about 2.5×10^4 watts. The estimated power level of this engine is, therefore:

$$\begin{aligned} \text{PWL} &= 10 \log_{10} (2.5 \times 10^4) + 130 \text{ db} \\ &= 10 \log_{10} 2.5 + 10 \log_{10} 10^4 + 130 \\ &= 4 + 40 + 130 = 174 \text{ db.} \end{aligned} \tag{A-5}$$

Measured power levels of the J57 are of the order of 173 to 175 db, which agree with the predicted value.

The PWL derived from Figs A-1 through A-3 can be used only if the engine or eductor tube does not contain a diffusing or mixing device which will modify the PWL of the engine. If a

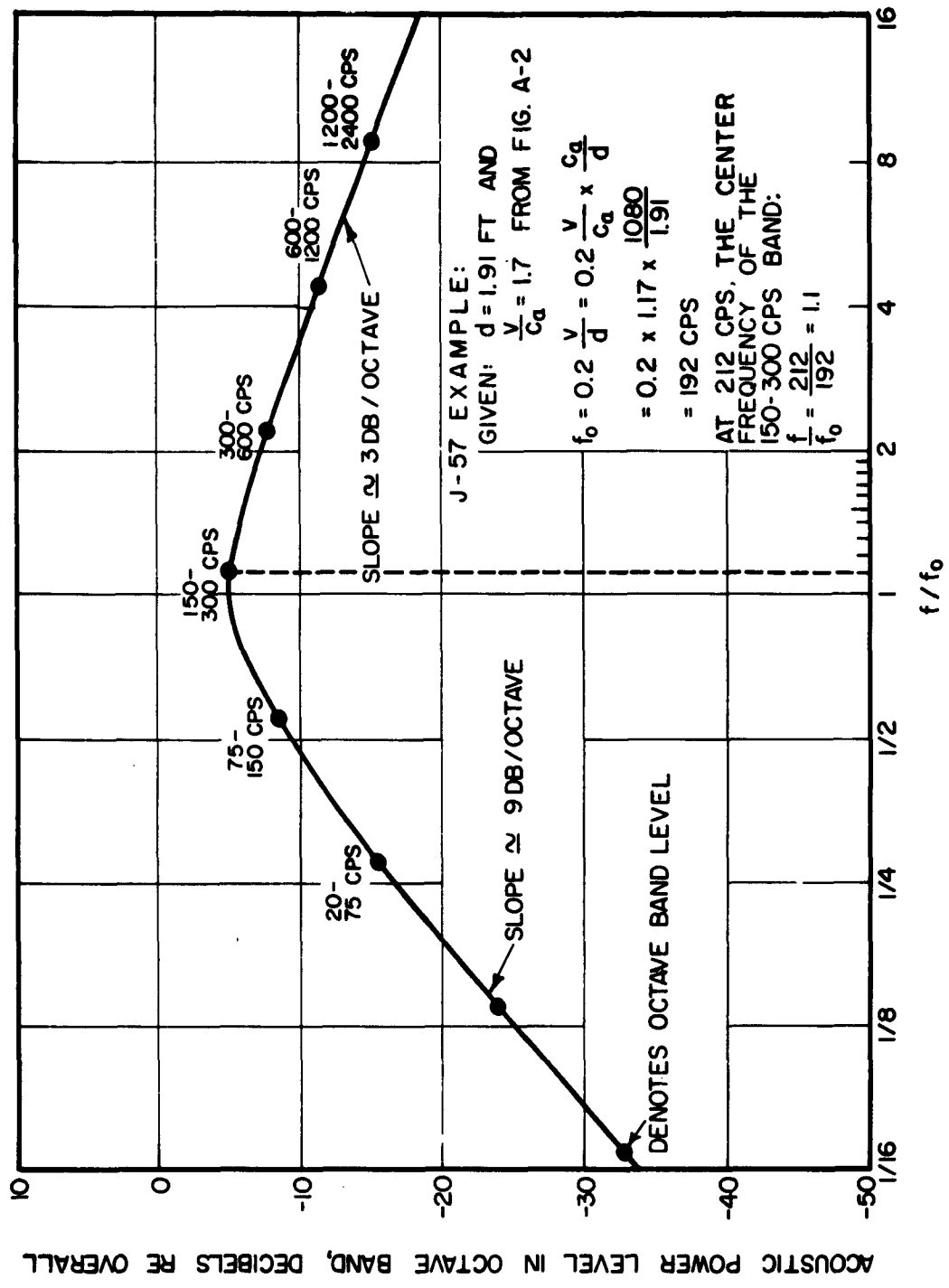


FIG. A-4 A NON-DIMENSIONAL JET SPECTRUM.

diffuser is used, the FWL of the engine-diffuser combination must be used to determine sound pressure levels (SPL)* in the engine test cell (see Appendix E).

The octave band power level spectrum for jet engines is given in Fig A-4. In Fig A-4 the octave band levels are presented on a frequency scale which is the frequency relative to the frequency of the peak value of power level. The frequency of the peak (e.g., $\frac{f}{f_o} = 1$) is

$$f_o = 0.2 \frac{v}{d} \quad (\text{A-6})$$

in which v is the velocity of the exhaust of the jet engine in ft/sec and
 d is the diameter of the jet exhaust orifice in feet.

b) Sound Pressure Levels in Test Cells

The octave band sound pressure levels at positions in a test cell can be found from the octave band power level of the jet engine in the test cell. The relation between the sound pressure level and the power level depends upon the spacing between the jet engine exhaust and the eductor tube, the amount of absorption in the test section, and the dimensions of the test section. In most engine test cells, however, the basic geometries are quite similar and general relations can be derived between octave band sound pressure level and the octave band sound power level. Such relations are given below. These relations have been derived from data obtained in engine test cells in which the secondary or cooling air passes through the

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

test section, and is applicable only for such test cells. In some cells, the engine is coupled very closely to a partition, (say less than 3 in. radial clearance between the exhaust orifice and the partition), which divides the test section from the eductor tube and the secondary air path. The sound pressure levels up to about 2400 cps in the test section of such cells will be lower than the values given here and must be decreased by an amount equal to the net noise reduction of the partition. Above 2400 cps, the SPL's depend upon the compressor noise levels and jet noise very near the exhaust, and hence, the SPL given below will apply.

The octave band sound pressure level at the input to the exhaust acoustical treatment, SPL_{ex} , is equal to:

$$SPL_{ex} = PWL - 10 \log_{10} A_{ex} \quad (A-7)$$

in which

A_{ex} is the open area (in square feet) at the input to the exhaust acoustical treatment, and

PWL is the power level (in octave bands) of the jet engine in free field.

If an exhaust diffuser is attached to the jet engine, the octave band power levels used in Eq (A-7) should be the power level for the diffuser-engine combination. Since not all diffusers afford the same power level reduction, field measurements may be required to find the PWL of the diffuser-engine combination. (See Volume I of this series for measurement procedures and Appendix E for examples of the performance of some typical diffusers.)

In the test section, the sound pressure levels vary slightly with position. The octave band sound pressure levels in the test section can be expressed in terms of the octave band power levels of the engine as follows:

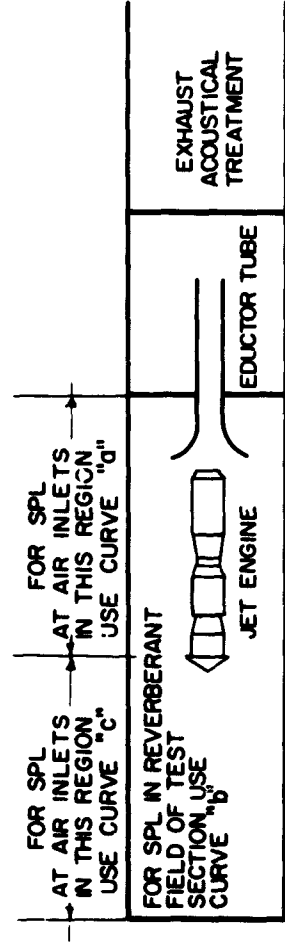
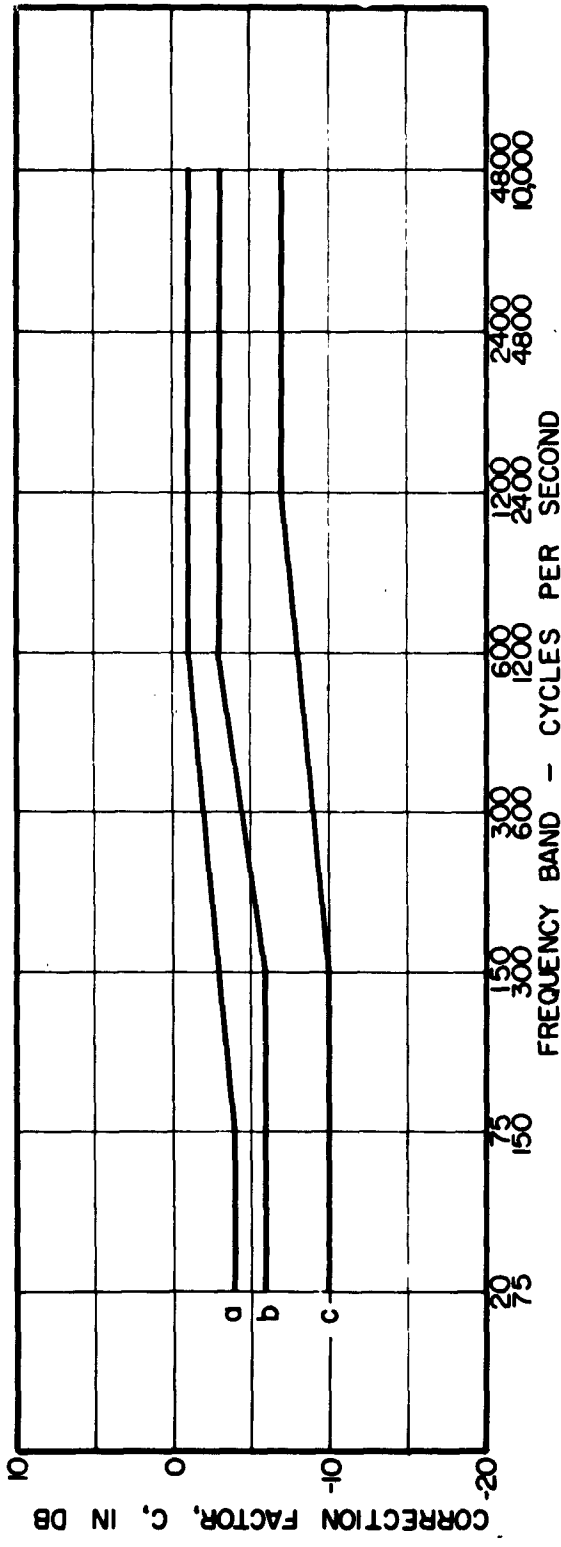
$$\text{SPL}_t = \text{PWL} - 10 \log_{10} A_t + C \quad (\text{A-8})$$

in which SPL_t is the sound pressure level in decibels in the test section,
 PWL is the acoustic power level of the engine in decibels re 10^{-13} watt,
 A_t is the cross-sectional area in square feet of the test section and
 C is a constant which has been empirically derived.

The quantity C varies both with position in the test section and frequency*. Values of C for octave bands of frequency are given in Fig A-5 for various areas in the test section and for various possible locations of air intake openings in the test section.

If, for example, an air intake is located in the area designated as A in the ceiling of the test section, Eq A-7 is used in conjunction with the lowest curve in Fig A-5 to determine the sound pressure level at the input to the acoustical treatments.

* C measures the ratio of the acoustic power radiated towards the exhaust to the acoustic power radiated to the test section and in addition is dependent upon certain acoustical factors in the test section design.



ELEVATION

FIG. A-5 CORRECTION FACTOR FOR DETERMINING SPL IN TEST SECTION OF ENGINE TEST CELLS.
 $SPL_t = PWL - 10 \log A_t + C$

c) Sound Pressure Levels for Ground Run-Up Suppressors

If no exhaust gas diffuser is used, the SPL at the input of the exhaust acoustical treatment will be as given in Eq (A-7) of paragraph b) above. If an exhaust diffuser is used, the comments in paragraph b) apply. That is, field measurements may be required to find the power level and the spectrum of the diffuser-engine combination.

The sound pressure level at the primary air intake depends upon the dimensions of the compressor and the air induction system of the subject aircraft. It will generally be necessary to rely on field measurements to determine the SPL at the primary air intake.

Limited experience has shown that the power levels of the compressor will be of the order of 30 to 40 db below the power level of the jet in the frequency range from 20 - 2400 cps and 0 - 20 db below the power level of the jet in the frequency range from 2400 - 10,000 cps. Therefore, intake noise levels may be neglected for all suppressors whose noise reduction requirements are less than about 30 db in the range from 20 - 2400 cps and 10 db in the range from 2400 - 10,000 cps.

2. Reciprocating Engines

a) Acoustic Power Levels

The acoustic power levels for reciprocating engines can be found from Fig A-6. This chart (Fig 4.1.14 of Reference 13) which was constructed from experimental data, gives the approximate acoustic power levels as a function of propeller tip speed and shaft horsepower. The chart applies to three blade propellers of a diameter approximately equal to 12 ft. Power levels for two and four blade propellers lie approximately 2 db above and below the chart values, respectively.

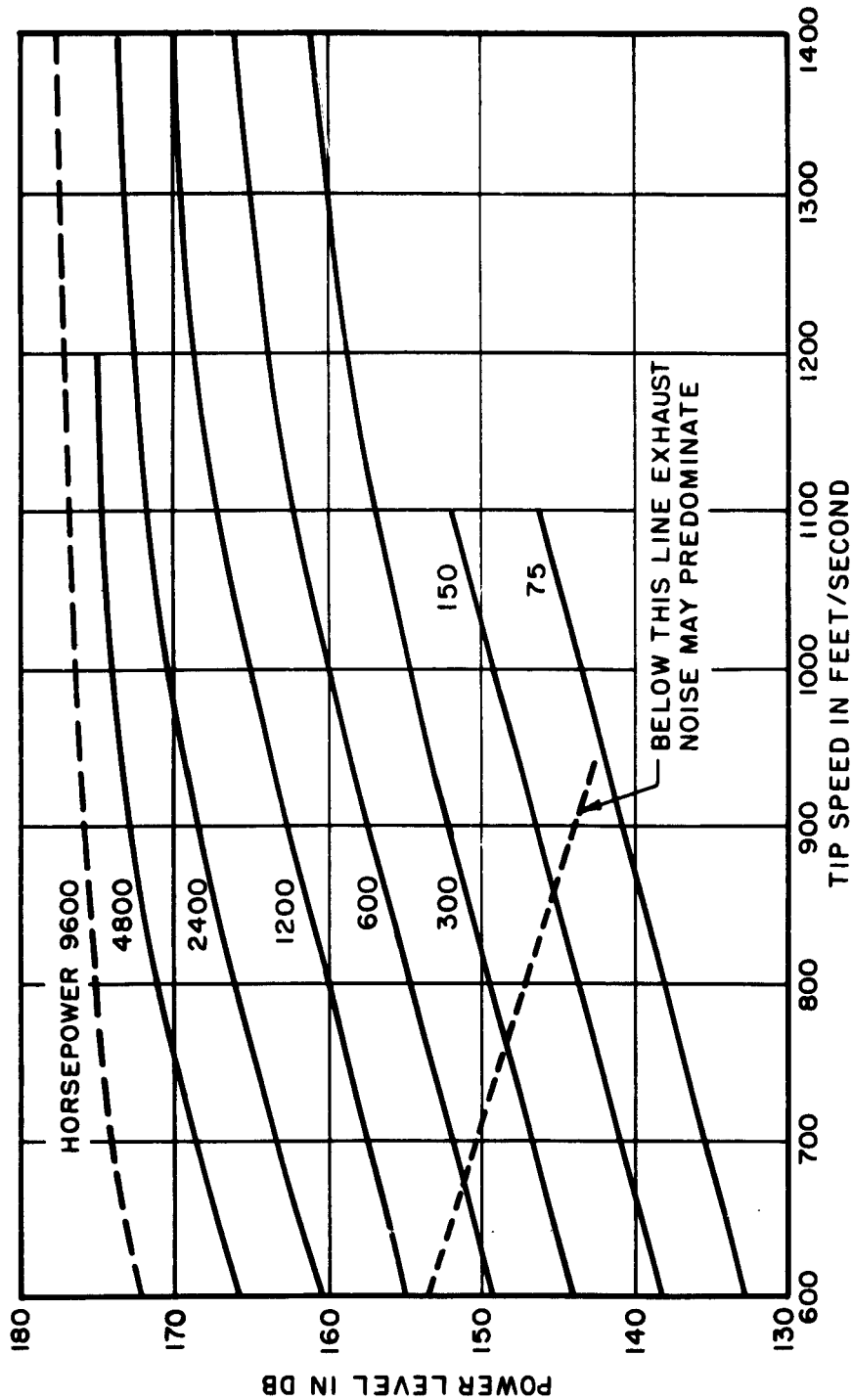


FIG. A-6 DESIGN CHART FOR ESTIMATING POWER LEVELS OF PROPELLER NOISE AS A FUNCTION OF PROPELLER TIP SPEED AND SHAFT HORSEPOWER. CHART APPLIES FOR 3-BLADE PROPELLERS APPROXIMATELY 12 FEET IN DIAMETER. FOR 2-BLADES, ADD 2 DB; FOR 4-BLADES, SUBTRACT 2 DB. FOR DIAMETER CORRECTIONS, SEE TEXT.

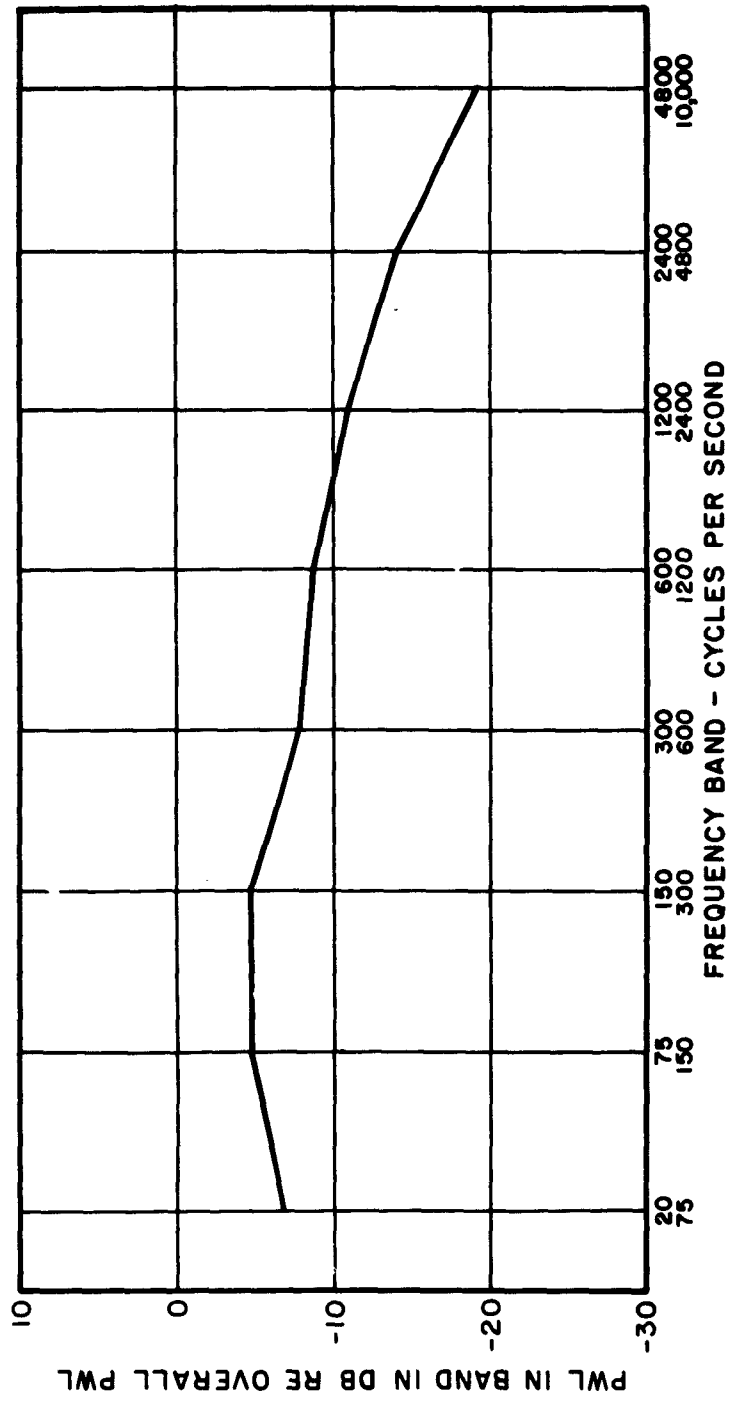


FIG. A-7 OCTAVE BAND PWL DESIGN SPECTRUM FOR PROPELLERS AT OR NEAR MAXIMUM POWER IN TEST CELLS.

This chart can be used for propellers with 10 to 15 ft diameters without significant errors. For propellers of diameter 15-20 ft, the PWL's will be about 2 db lower than the values given in the chart.

b) Sound Pressure Levels in Test Sections

The overall sound pressure level in the reverberant field of the test section is approximately:

$$SPL_R = PWL - 10 \log_{10} A_t \quad (A-9)$$

where A_t is the cross-sectional area in square feet of the test section.

The sound pressure level at the input to both the intake and exhaust acoustical treatments is:

$$SPL_{in} = PWL - 10 \log_{10} A_t - 3 \text{ db} \quad (A-10)$$

The spectrum in the test section and at the inputs to the exhaust acoustical treatment and the intake acoustical treatment is given in Fig A-7. In the first and second octave bands, pure-tone components may predominate. The frequency of the pure-tone components is found from the equation below,

$$f_n = nN/60 \quad (A-11)$$

where n is the order of the harmonic ($n = 1$ for the fundamental, $n = 2$ for the second harmonic, etc.); and N is the number of propeller blades.

3. Turbo-prop Engines

There are two sources of noise from a turbo-prop engine:

noise originating from the propeller, and noise originating from the jet stream. The acoustic power level can be found by summing the contributions from the jet found in paragraph 1 above and the propeller found in paragraph 2 above. Since a large fraction of the mechanical or kinetic power of the jet stream is extracted to drive the propeller, the total acoustic power will result almost entirely from propeller noise.

The geometry of turbo-prop test cells will be similar to that of reciprocating engine test cells, and the sound pressure levels in the test cell may be found from Eqs (A-9) and (A-10) in paragraph 2 above.

APPENDIX B
NOISE REDUCTION BY DIRECTIVITY

One method of reducing the noise levels at some point is to change the directivity of the radiation from a noise source. An obvious and useful way to obtain noise reduction is to direct intake and exhaust stacks so that the gases enter and leave the test cell in a direction perpendicular to the ground. A large fraction of noise energy is thereby radiated upwards.

The directive properties of a noise radiator are expressed in terms of the directivity index which is defined here as:

$$DI = SPL_{av} - SPL(r, \phi, \theta) \quad (B-1)$$

where SPL_{av} is the average sound pressure level at a distance r from the source, and

$SPL(r, \phi, \theta)$ is the SPL at a distance r and elevation ϕ and azimuth θ from the source.

In the distant field of a test cell, say, beyond 250 ft, the directivity index will be independent of distance r . Furthermore, almost all test cells are designed with the stacks pointing vertically to take advantage of directivity as a noise control mechanism. Therefore, only the directivity at 90° from a perpendicular to the ground is of interest.

Directivity indices for vertical exhaust stacks and intake stacks are given in Figs B-1 and B-2 respectively. These directivity curves are average values of directivity in two senses. First, they are averaged over all azimuth angles around the test cell, and second, they represent average values for different types of cells. The value of the directivity index at any azimuth from a particular test facility may vary somewhat from the value shown.

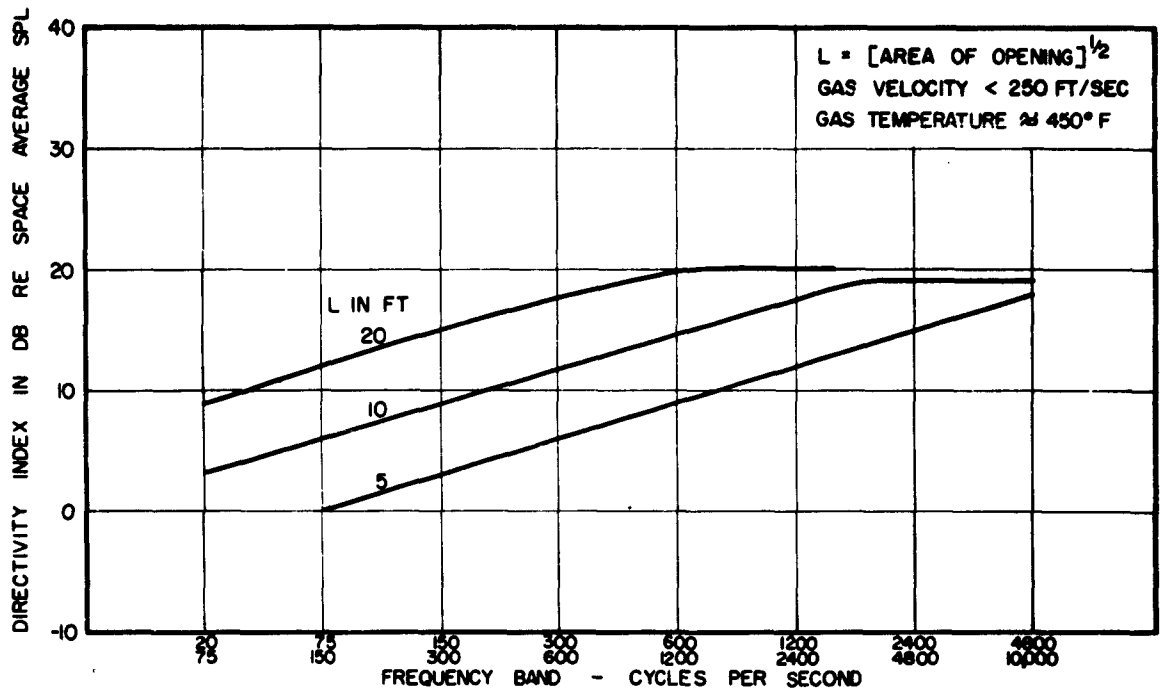


FIG. B-1 DIRECTIVITY INDEX IN THE PLANE OF AN EXHAUST GAS OUTLET.

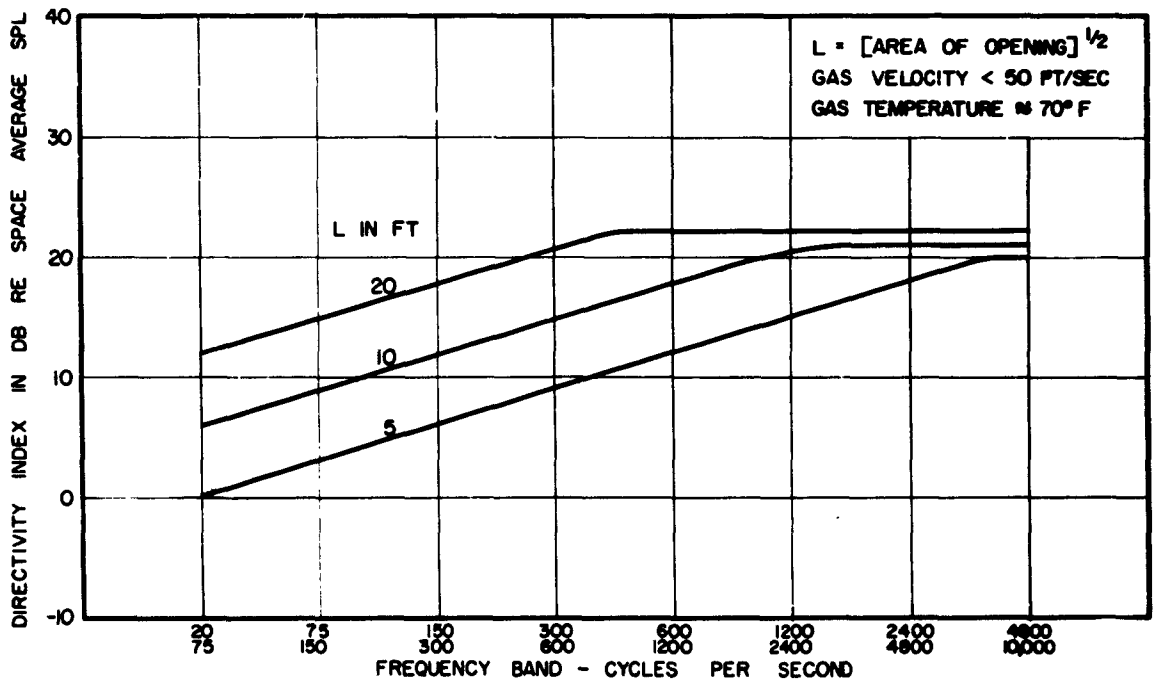


FIG. B-2 DIRECTIVITY INDEX IN THE PLANE OF AN AIR INTAKE OPENING.

In some test facilities the plane of an exhaust gas outlet or an air inlet is normal to the ground. That is, the air enters or leaves the test facility in a plane parallel to the ground. In other test facilities, the air inlets or exhausts lie in a plane horizontal to the ground, but a roof structure is placed above the inlet or exhaust so that the air is forced to enter or leave in a direction parallel to the ground. For either of these two cases, the average value of the directivity index on the 250 ft circle may be taken to be 0 db.

If an air inlet or exhaust lies in a plane perpendicular to the ground then the directivity index on a 250 ft circle enclosing the test facility will vary as a function of an angle. At 0° (directly in front of the opening) the directivity index will be negative (i.e. the sound pressure level at 0° is greater than the average sound pressure level). At 90° the directivity index will be as given in Figs B-1 and B-2. At 180° (to the rear of the air opening) the directivity index will be greater than at 90° . To the author's knowledge, measurements of directivity indices at 180° are not available, at least for engine test cells. However, the directivity index at 180° is estimated to be 1-1/2 times the directivity index at 90° .

APPENDIX C
NOISE REDUCTION THROUGH AIR PASSAGES

This Appendix contains data on the noise-reducing effectiveness of acoustical treatments in air passages. Paragraphs 1-7 inclusive contain definitions, explanatory material, and instructions regarding the applications and limitations of the data, which are compiled graphically in paragraph 8.

1. Definition of Noise Reduction

The acoustical effectiveness of noise control components in air passages is defined here as:

$$L_{hr} = (\text{SPL}_{1_{av}} + 10 \log_{10} A_1) - (\text{SPL}_{2_{av}} + 10 \log_{10} A_2) \quad (\text{C-1})$$

in which L_{hr} is the noise reduction in db,
 $\text{SPL}_{1_{av}}$ is the sound pressure level corresponding to the average sound energy over the input area (A_1 sq ft) of the acoustical treatment*,
 $\text{SPL}_{2_{av}}$ is the sound pressure level corresponding to the average sound energy over the output area (A_2 sq ft)*.

If the input area and the output area are equal, as they usually are, the L_{hr} is given by :

$$L_{hr} = \text{SPL}_{1_{av}} - \text{SPL}_{2_{av}} \quad (\text{C-2})$$

*Methods for measuring and computing this average are given in Volume I of this series.

In this case, the sound pressure level, SPL_{2av} , of the output SPL of an acoustical treatment is simply equal to the sound pressure level at the input, SPL_{1av} , minus the noise reduction, L_{nr} .

The noise reduction, L_{nr} , of an acoustical treatment is not a unique property of the treatment. The noise reduction is dependent on the angle(s) of incidence of sound waves impinging on the acoustical treatment, on the air flow rate through the treatment, on the temperature of the gas passing through the treatment, and on the shape of the noise spectrum of the input. The data given in the following sections are applicable in engine test cells and ground run-up suppressors only under certain environmental conditions. Some general procedures for using these data are discussed in the following paragraphs. Certain limitations and restrictions for the data are given on the page facing each set of noise reduction data in paragraph 8.

The facing page should be read carefully before attempting to use any of these data.

2. The Influence of Temperature on Noise Reduction

The data presented below have been derived from measurements at a specific gas temperature, and are applicable only at the temperature noted on the data page facing the noise reduction graphs. If the data are to be used at a temperature other than that shown on the data page, the data given on the graphs must be shifted in frequency.

The noise reduction values shift upwards in frequency for increases in temperature. Specifically, if the noise reduction is X db at a frequency f_1 , and at temperature T_1 , then the noise reduction will be X db at a temperature T_2 and a frequency f_2 given by:

$$f_2 = f_1 \sqrt{\frac{T_2}{T_1}}, \quad (C-3)$$

in which T_1 and T_2 are absolute temperatures. The absolute (Rankine) temperatures are about 460 degrees greater than the corresponding Fahrenheit temperatures.

For example, if the noise reduction at a frequency of 100 cps and a temperature of 60°F was found to be 20 db, then the noise reduction at a temperature of 450°F would be 20 db at a frequency of:

$$f_2 = 100 \sqrt{\frac{450 + 460}{60 + 460}} = 133 \text{ cps} \quad (C-4)$$

3. Estimation of Octave Band Noise Reduction

The noise reduction data are given as continuous functions of frequency. For design problems, it is necessary to derive the octave band noise reductions from these data. The octave band noise reduction will depend on the slope of the noise spectrum* at the input to the acoustical treatment, and on the slope of the noise reduction spectrum. In Fig C-1, the octave band noise reduction is given relative to the noise reduction at the center of the band (geometric mean frequency), as a function of the slope of the noise reduction spectrum and of the slope of the spectrum.

The geometric mean frequencies for the octave bands are given in Table C-1.

*Noise spectrum slopes presented here and in Fig C-1 are slopes that would be obtained from a plot of sound pressure level in octave or one-third octave bands as a function of frequency. These slopes are 3 db greater than the slope obtained from a plot of SPL per cycle (spectrum levels) as a function of frequency.

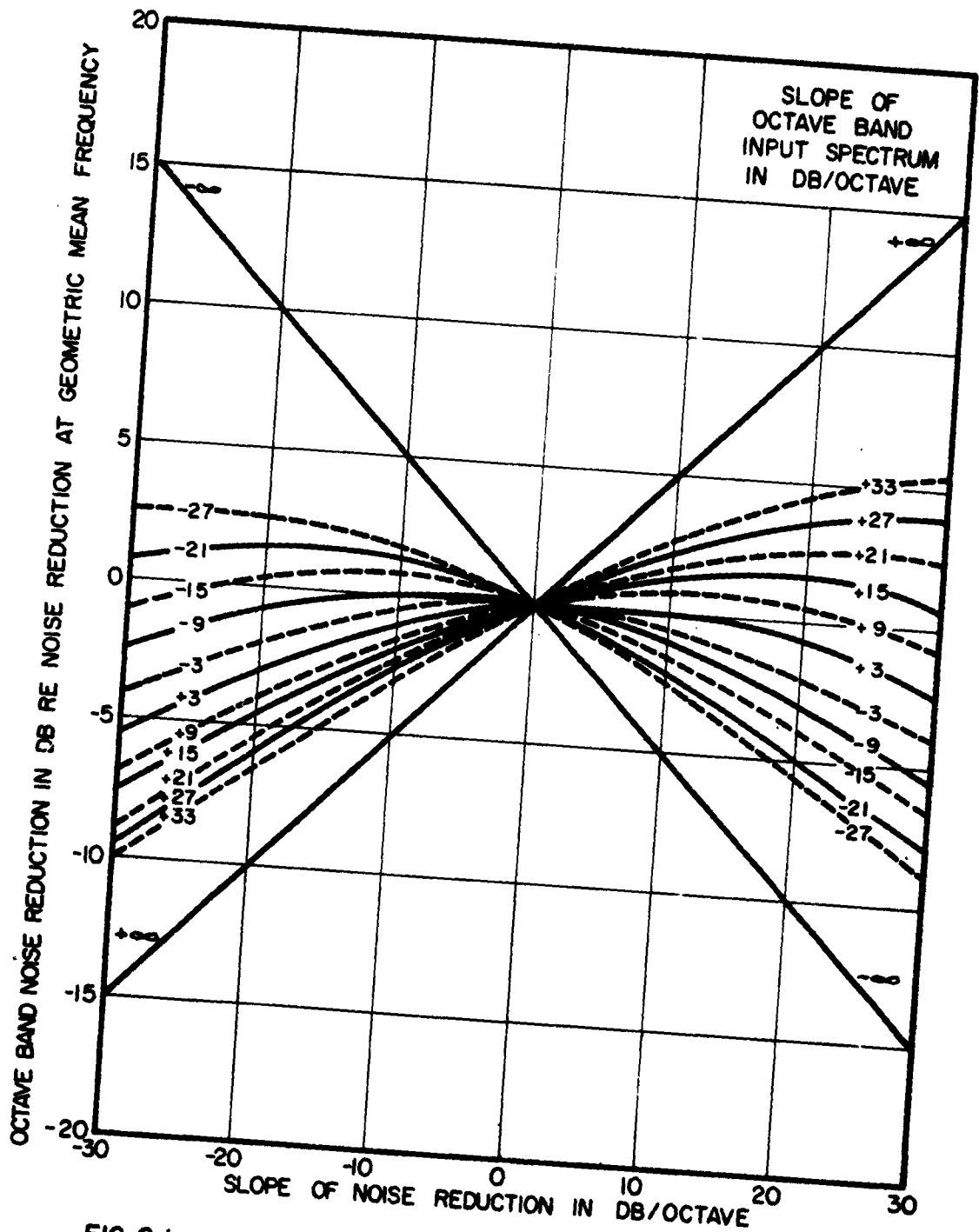


FIG. C-1 OCTAVE BAND NOISE REDUCTION AS A FUNCTION OF THE SLOPE OF THE NOISE REDUCTION AND INPUT SPECTRA

TABLE C-1
GEOMETRIC MEAN FREQUENCIES FOR OCTAVE BANDS

<u>Octave Band</u>	<u>Geometric Mean Frequency</u>
37.5 - 75	53
75 - 150	106
150 - 300	212
300 - 600	425
600 - 1200	950
1200 - 2400	1700
2400 - 4800	3400
4800 - 10,000	6800

As an example of the application of Fig C-1, assume that (1) the noise reduction of a component is 21 db at 212 cps (the geometric mean frequency of the 150 to 300 cps band), (2) the slope of the noise reduction spectrum in the 150 to 300 cps band is + 20 db / octave (e.g. 11 db at 150 cps and 31 db at 300 cps), and (3) the slope of the input spectrum is -15 db/octave. Find the octave band noise reduction.

Entering Fig C-1 at the 20 db/octave abscissa and reading up to the parameter curve for a -15 db/octave input, one finds the noise reduction for an octave band to be -4 db relative to the noise reduction at the geometric mean frequency. Therefore for the stated conditions, the noise reduction in the 150 to 300 cps octave band is (21-4) or 17 db.

4. Effects of Air Flow

Except where noted, the noise reduction data presented in

the following paragraphs have been obtained with no flow of air through the acoustical treatments. However, comparison of noise reduction data obtained from many intake treatments has indicated that noise reduction varies slightly with air flow (see Volume III). For the intake treatments with flow velocities in the range from about 30-60 ft/sec, the difference between the noise reduction measured without flow and the noise reduction measured with flow is given in Table C-2 below.

TABLE C-2
DIFFERENCE BETWEEN NOISE REDUCTION MEASURED
WITH AND WITHOUT FLOW

		Octave Band Frequencies in cps							
		20	75	150	300	600	1200	2400	4800
		75	150	300	600	1200	2400	4800	10000
Noise Reduction without Flow Minus Noise Reduction with Flow		-3	-2	-1	0	0	1	2	3

If straight (not zig-zag or curved) baffles and duct structures are employed in an intake, the numbers tabulated in Table C-2 can be added to the SPL at the output of the intake treatment to correct for the effects of flow.

Even less data exist for straight baffle and duct structures in exhaust acoustical treatments. The values given in Table C-2 however, may be added to the SPL's at the output of the exhaust as a first approximation to a correction for flow in the exhaust.

The effect of air flow on the noise reduction of zig-zag

and curved structures appears to be even greater than the values shown in Table C-2. On the page facing each data graph in paragraph 8 below, estimates are given of the effects of flow on the particular zig-zag or curved structure acoustical treatment.

5. Combinations of Acoustical Treatments

A casual inspection of the noise reduction curves for any of the acoustical treatments will show that the noise reduction in decibels is not doubled each time the length of the acoustical treatment is doubled. For example, at 600 cps the noise reduction of 6 ft of 4 in. thick baffles spaced on 16 in. centers is about 23 db. The noise reduction of 12 ft of the same baffles at 600 cps is only 38 db and not 46 db. Thus shorter lengths are more effective on a db/ft basis than are longer lengths. In engine test cells the noise field at the input to the acoustical treatments generally contains a large fraction of noise energy which impinges obliquely on the baffles. This noise energy is attenuated in a relatively short distance. Thus, on a db/ft basis the noise reduction is higher for the initial sections of the acoustical treatment.

One obvious thought then is to separate two 6 ft baffle sections by an air space of a few feet to obtain (at 600 cps) 46 db from 12 ft of baffles instead of only 38 db. Experimental data show such a result is not obtained. In general, attenuations of sections of individual treatments will add, arithmetically, only if

- 1) the treatments are of grossly different geometry such as ducts following baffles, thick baffles following thin baffles or inversely, etc.
- 2) the treatments are separated by a bend.

If either of these two conditions are met the noise field at the second acoustical treatment will also contain a large fraction of acoustical energy which strikes the baffles at an oblique angle and the noise reductions of two treatments will add arithmetically.

6. The Effects of Location and Orientation of Acoustical Treatments

a) Location with Respect to the Noise Source

The apparent location of the source of noise radiation from a jet engine is primarily to the rear of the exhaust orifice. The apparent location is farther to the rear for lower frequency energy than for high frequency energy. For turbojet engines, the apparent source of noise in the 20-75 cps band may be as much as 8 exhaust diameters to the rear of the exhaust orifice. Thus for an engine with an exhaust pipe of 2 ft diameter, the apparent source of noise radiation in the 20-75 cps band would be approximately 16 ft down stream of the exhaust orifice.

If, for example, a lined duct 10 ft long were placed immediately behind the jet engine, there would be very little noise attenuation in the 20-75 cps octave band, because the apparent location of most of the noise source for that band would be about 6 ft past the acoustical treatment. Therefore, for jet engines, an exhaust acoustical treatment will be useless in the 20-75 cps band unless it is more than 8 diameters downstream of the exhaust orifice.

b) Orientation of Acoustical Treatments with Respect to Bends

In Fig C-2, the geometry of a typical bend is shown. Sound waves are assumed to be travelling in the direction indicated by the arrow.

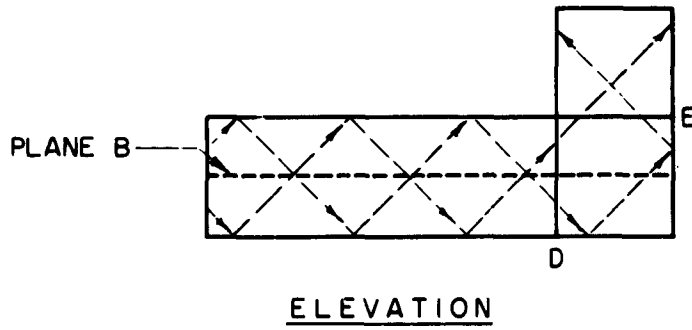
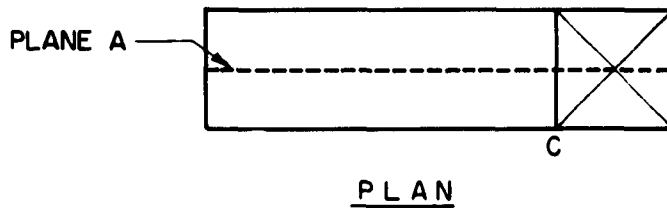
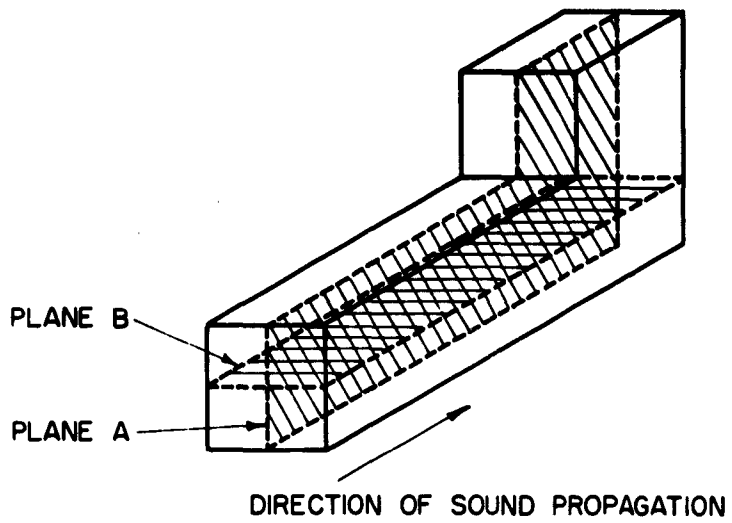


FIG. C-2 NOMENCLATURE AND A PLAN AND SECTION FOR A TYPICAL BEND.

1. Orientation of Acoustical Treatments Following Bends

The noise reduction of acoustical treatments with rectangular cross sections is influenced by the orientation of the treatment with respect to the bend. For baffle structures whose major planes are parallel to plane A of Fig C-2, the noise reduction will be that given in the data sheets which follow. If the baffles are oriented so that their major plane is normal to plane A, then the noise reduction at high frequencies (those for which $d/\lambda > 1$) is greater than the noise reduction shown on the data sheets. However, limited data indicate that the noise reduction in the mid frequencies is significantly less than that shown on the data sheets if the baffles are normal to plane A. Because high frequency noise reduction can easily be obtained by other methods such as offsetting the baffles, there is little acoustical justification for such orientation. Furthermore, the air velocity distribution through baffles oriented normal to plane A is far from uniform. The maximum linear velocity in some of the channels may be as high as twice the average linear velocity with a resulting tendency toward high pressure drops.

11. Orientation of Acoustical Treatments Before Bends

Where possible, baffle structures before bends should be parallel to plane B of Fig C-2. If an adequate length of such baffles (adequate is defined in the data section on bends) precede the bend, then the noise reduction of the bend will be increased. While such an orientation of baffles is structurally more complex than with the baffles located parallel to plane A, the increased noise reduction at high frequencies may, in some cases, justify the structural complexity.

7. Procedures for Extrapolating Noise Reduction Data

The data presented on the following pages include a wide

range of thicknesses, lengths, and widths. However, for some problems, it may be desirable to use structures of dimensions other than those presented. It would be an impossible measurement task to obtain the noise reduction of every conceivable lined duct even if only ducts of practical sizes were studied. Fortunately, theories and measurements have led to methods for scaling and extrapolating which are of great engineering utility. In the three paragraphs below, methods are presented for:

- a) Extrapolating to obtain the noise reduction of treatments of longer lengths than those shown, and interpolating between the given lengths.
- b) Scaling to obtain the noise reduction of geometrically similar structures, and
- c) Varying the open dimensions of baffles and ducts while maintaining a constant thickness of the lining material.

a) Extrapolation and Interpolation to Other Lengths

The noise reduction of a treatment at any frequency can be expressed as:

$$L_{hr} = a + bl \quad (C-5)$$

where a is an end correction which is caused by the random nature of the incident sound waves,

b is the attenuation per unit length, and

l is the length of the baffles.

The noise reduction for 12 ft of a structure is therefore not twice the noise reduction of 6 ft of a structure. If, for

example, the noise reduction of 6 ft of a structure, L_{nr6} , and the noise reduction of 9 ft, L_{nr9} , of the same structure are given, then the noise reduction for 11 ft of the structure can be found in the following manner:

- 1) The noise reduction of 6 ft of the structure is subtracted from the noise reduction of 9 ft of the structure to obtain the incremental noise reduction for an additional 3 ft.
- 2) The incremental noise reduction for 2 ft of the structure is $2/3$ of the incremental noise reduction for 3 ft.
- 3) The noise reduction for 11 ft of the structure is obtained by adding to the noise reduction of 9 ft of the structure, the incremental noise reduction for 2 ft of the structure.

The operations can be simply summarized by the equation below:

$$L_{nr11} = L_{nr9} + 2/3 L_{nr(9-6)} \quad (C-6)$$

where L_{nr11} is the noise reduction for 11 ft of the structure,

L_{nr9} is the noise reduction for 9 ft of the structure, and

$L_{nr(9-6)}$ is the incremental noise reduction for 3 ft of the structure.

Noise reductions for lengths between those given can be obtained by linear interpolation. If, for example, the noise reduction is 10 db for 12 ft of baffles and 16 db for 16 ft, the noise reduction is 13 db for 14 ft of baffles.

The noise reduction for treatments shorter than the shortest length shown on any graph may be found by assuming noise reduction to be proportional to length (i.e., linear interpolation).

b) Scaling

The noise reduction of parallel baffles which are geometrically similar to those for which the noise reduction is known can be found by scaling techniques. The noise reduction for parallel baffle structures (or lined ducts) can be expressed as a function of the following non-dimensional variables:

$$rt/\rho c, D'/\lambda, H/\lambda, \text{ and } L/D'$$

in which

- r is the flow resistance per unit length of the acoustical material in the baffles,
- t is the thickness of the baffles
- D' is the open width between the baffles,
- λ is the wavelength of sound,
- H is the height of the baffles, and
- L is the length of the baffles.

If each of these dimensionless variables are held constant, then the noise reduction will also remain constant. The variation of noise reduction with the height of the baffles is not generally included as a significant variable. For test cell structures, H does not vary greatly and the variation of H is neglected.

The noise reduction of a structure which is geometrically

similar to one for which the noise reduction is known can be found by the following steps:

- 1) Scale all dimensions of the acoustical treatment for which the noise reduction is known to obtain the desired treatment that is geometrically similar.

For example, the noise reduction of 12' of baffles which are 4 in. thick and 12 in. on centers, could be obtained by multiplying all of the dimensions of 6' long, 2 in. thick baffles, 6 in. on center by 2. In this case, 2 is the scale factor.

- 2) Divide the frequency by the scale factor.

For the example being used, the peak noise reduction occurs at about 2000 cps for the 2 in. thick baffles. Thus, the peak noise reduction for the 4 in. thick baffles will occur at a frequency of $2,000/2 = 1000$ cycles.

- 3) Divide the specific flow resistance (the flow resistance per unit length) of the acoustical lining material by the scale factor.

The total flow resistance is the product of the specific flow resistance and the thickness of the acoustical material. The thickness of the acoustical material is directly proportional to the scale factor and the specific flow resistance is inversely proportional to the scale factor. Thus, the total flow resistance is unchanged by the scaling procedure. The flow resistance of many materials is given by Labate^{12/}.

It is found from experience that the scaling procedure is only approximate. Therefore, it is desirable, where

possible, to obtain the noise reduction of some unknown treatment by scaling down from a larger size and up from a smaller size.

c) Variation of Noise Reduction with Baffle Opening

It may be required, for example, to find the noise reduction of baffles which are 4 in. thick and 16 in. on centers from the noise reduction of baffles which are 4 in. thick and 12 in. on centers. Two such sets of baffles are not geometrically similar so that scaling techniques cannot be directly applied.

An approximate procedure for accomplishing such extrapolations can be derived from an analysis of lined ducts in Ref 13. One finds that the noise reduction for frequencies lower than the peak noise reduction is directly proportional to the open spacing between the baffles.

Thus, for example, the noise reduction of 12 ft of baffles 16 in. on centers ($D' = 12$ in.) and 4 in. thick is $2/3$ of the noise reduction of 12 ft of baffles 12 in. on centers ($D' = 8$ in.). In Fig C-3, the noise reduction of 12 ft of baffles, 4 in. thick and 16 in. on centers is given by curve B, which is just $2/3$ of curve A at each frequency.

The noise reduction at high frequencies does not depend on lining thickness provided that the ratio of wavelength to lining thickness is somewhat greater than 1. The noise reduction in this frequency range depends on the ratio of wavelength to open spacing (which implies frequency scaling), and the ratio of length to open spacing (the length measured in duct widths).

At high frequencies, the noise reduction of 12 ft of baffles

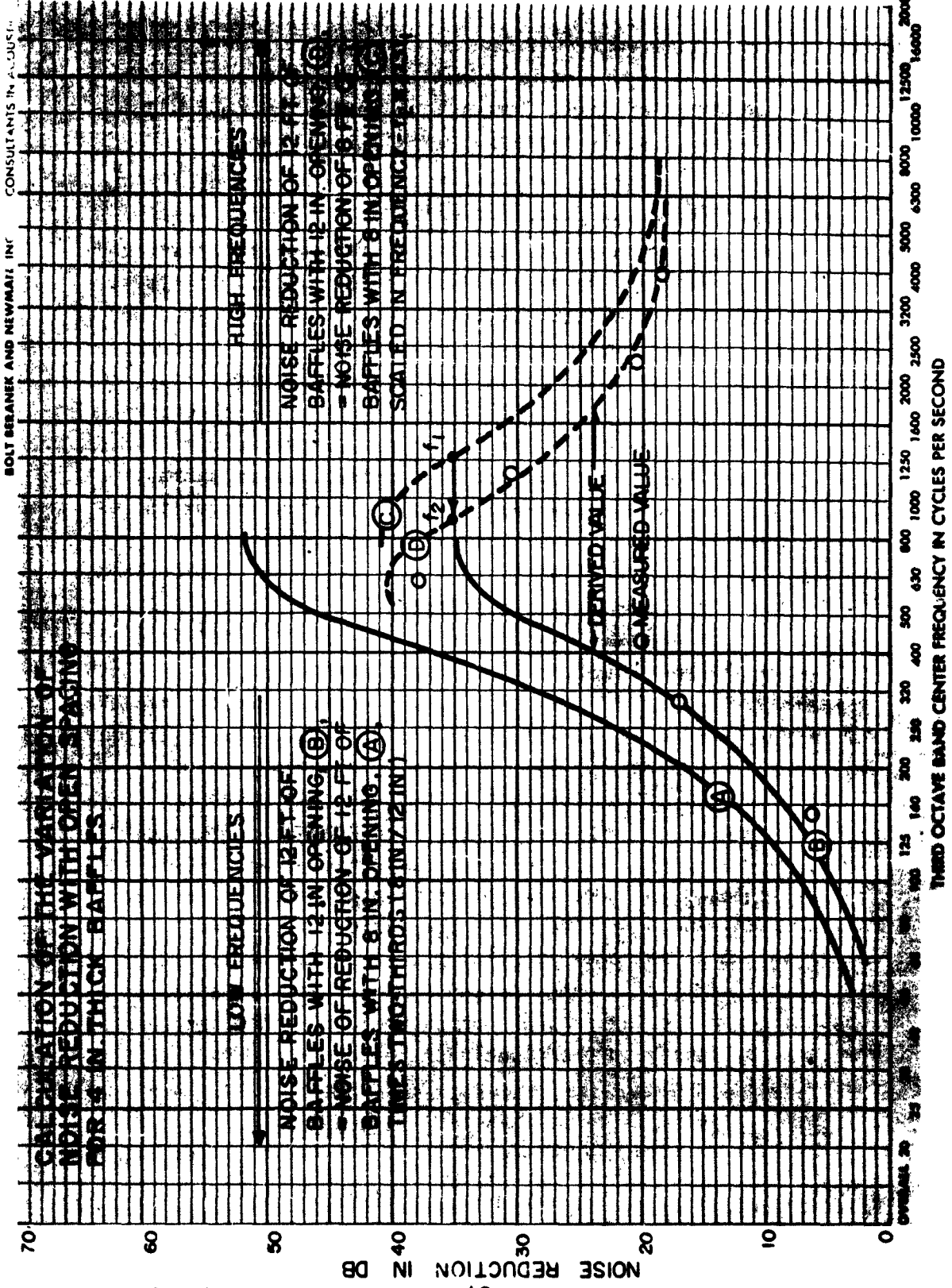


FIGURE C-3

BOLT BRANEK AND NEWMAN, INC. CONSULTANTS IN AUSTIN, TEXAS

16 in. on centers can be obtained from the noise reduction of 8 ft (12 x 2/3) of baffles 12 in. on centers shifted in frequency by a factor of 2/3. The noise reduction of 12 ft of baffles 16 in. on centers is given by curve D in Fig C-3 which is the noise reduction of 8 ft of baffles 12 in. on centers shifted in frequency, as shown in Fig C-3.

It should be borne in mind that this procedure is approximate and the possibility of errors will increase with the range of extrapolation. It is not recommended that the open spacing be varied by more than a factor of two.

8. Noise Reduction Data for Acoustical Treatments

Figures C-6 through C-11 give noise reduction characteristics for proprietary acoustical treatments. These data are not intended to represent all products of all manufacturers. They are primarily data obtained under the Air Force measurement program. Manufacturers should be consulted for other models and types of these treatments.

The data included in graphs C-12 through C-19 are representative data for parallel baffles and lined ducts. These data are based on measurements which were obtained under the Air Force program by methods described in Volume Three of this report. Extrapolation procedures described earlier in this report have been used to obtain data for a wide variety of treatments.

The data are applicable for baffles and ducts made of 2-1/2 to 4-1/4 lb/ft³ glass fiber, with perforated metal facings about 25 to 35% open.

NOISE REDUCTION
FOR
LINED AND UNLINED BENDS

Source of Data.

Volume Three of this Report

Range of Application:

For air passages greater than $\lambda/4$ wide, where λ is wavelength of sound. Valid for entire frequency range of interest if air passage is greater than about 10' x 10'.

Effect of Air Flow:

Negligible.

Effects of Orientation:

See figure opposite

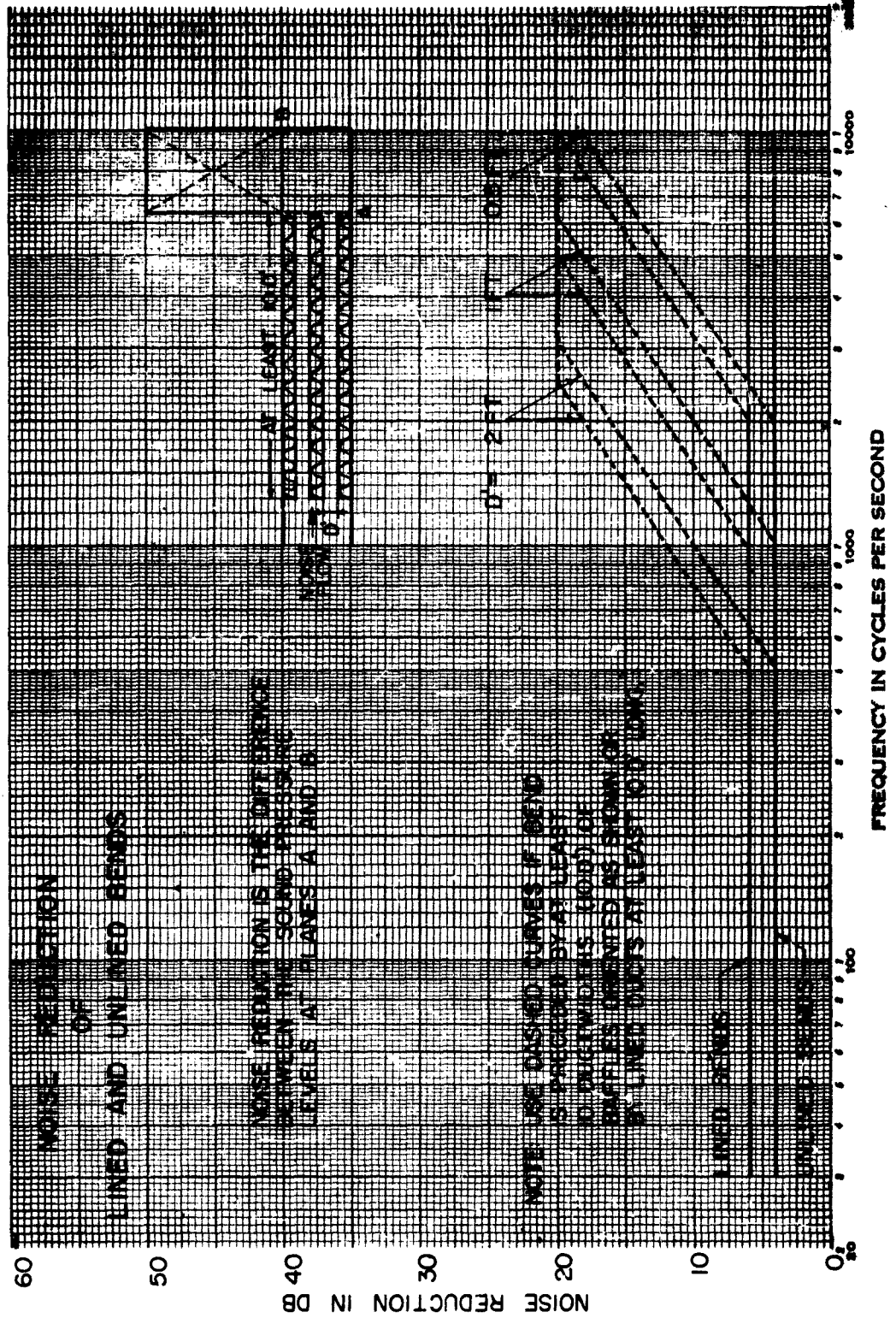
Construction Details:

Lining for lined bends should be about four inches deep.

General Comments:

These data show loss of SPL around 90° bend only. Increase in noise reduction of treatment following bend is not shown. Noise reduction for 180° bends is estimated to be 1-1/2 times the noise reduction of 90° bend. For bends less than 90° , noise reduction is proportional to angle (i.e., noise reduction for 60° bend is 2/3 of noise reduction for 90° bend).

FIGURE C-4



NOISE REDUCTION
FOR
ACOUSTACK
ZIG-ZAG BAFFLES
Industrial Acoustics Company

Source of Data:

I. Dyer^{17/}

Conditions for Measurement:

Measurements made at 60° F and with no air flow.

Effect of Air Flow:

Measured data for treatments of similar geometry show an increase in noise reduction of about 10 db in 20 to 75 cps band and about 5 db in 75 to 150 cps band, independent of direction of air flow and sound propagation.

Effects of Orientation:

Probably negligible.

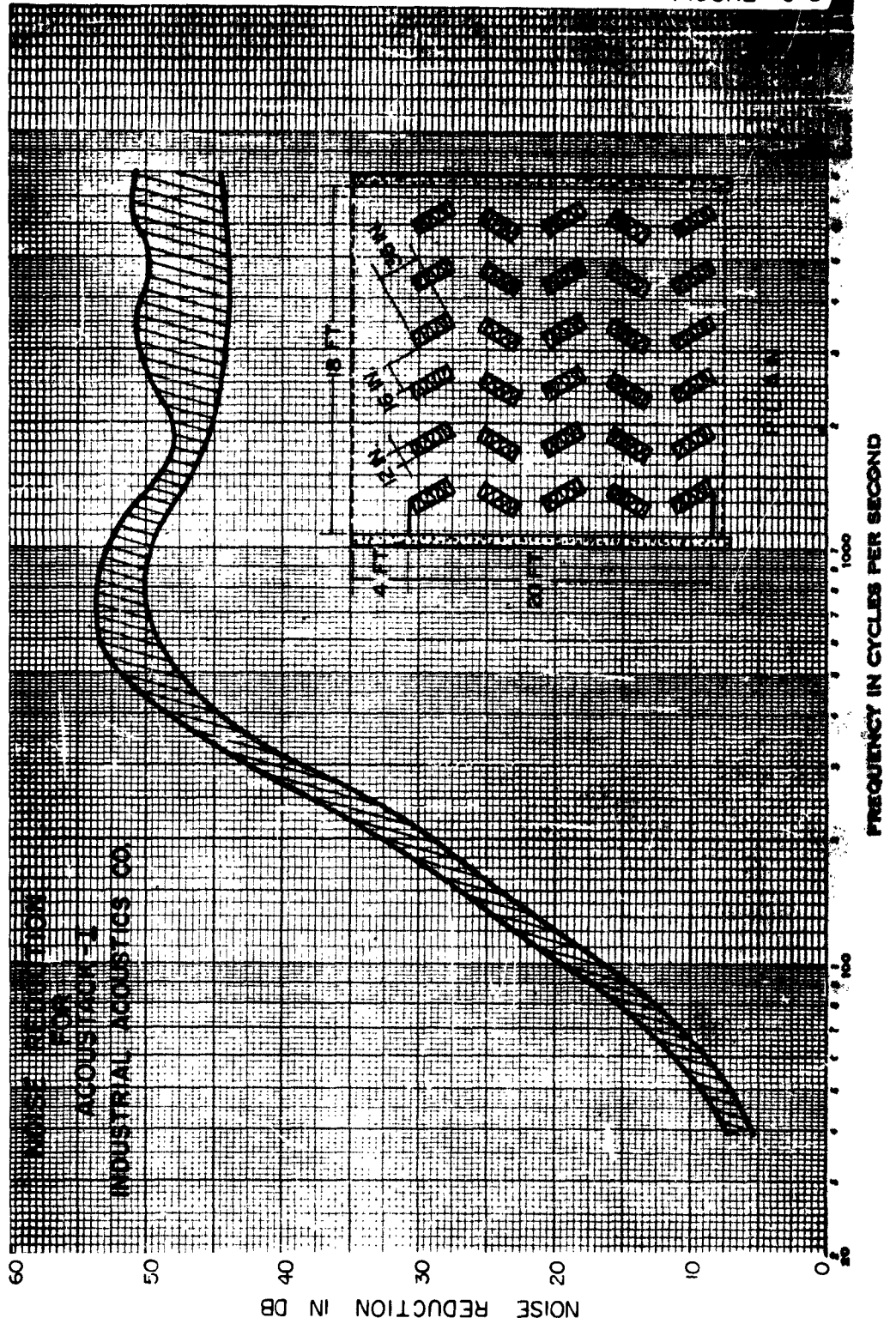
Construction Details:

See sketch; type of glass fiber filling not known.

General Comments:

See following page for data on another Acoustack treatment.

FIGURE C-5



NOISE REDUCTION
FOR
ACOUSTACK
ZIG-ZAG BAFFLES
Industrial Acoustics Company

Source of Data:

Hoover, R. M., 18/

Conditions for Measurements:

Data were obtained at T 70° F and no air flow.

Effect of Air Flow:

Measured data for similar geometries show an increase in noise reduction of about 10 db in the 20-75 cps band and about 5 db in the 75-150 cps band, independent of direction of air flow and sound propagation.

Effects of Orientation:

Probably negligible.

Construction Details:

See sketch; type of glass fiber filling not known.

General Comments:

The data for the 22 ft length were obtained by measurement. The data for 10 and 16 ft were extrapolated from traverse measurements through the treatment.

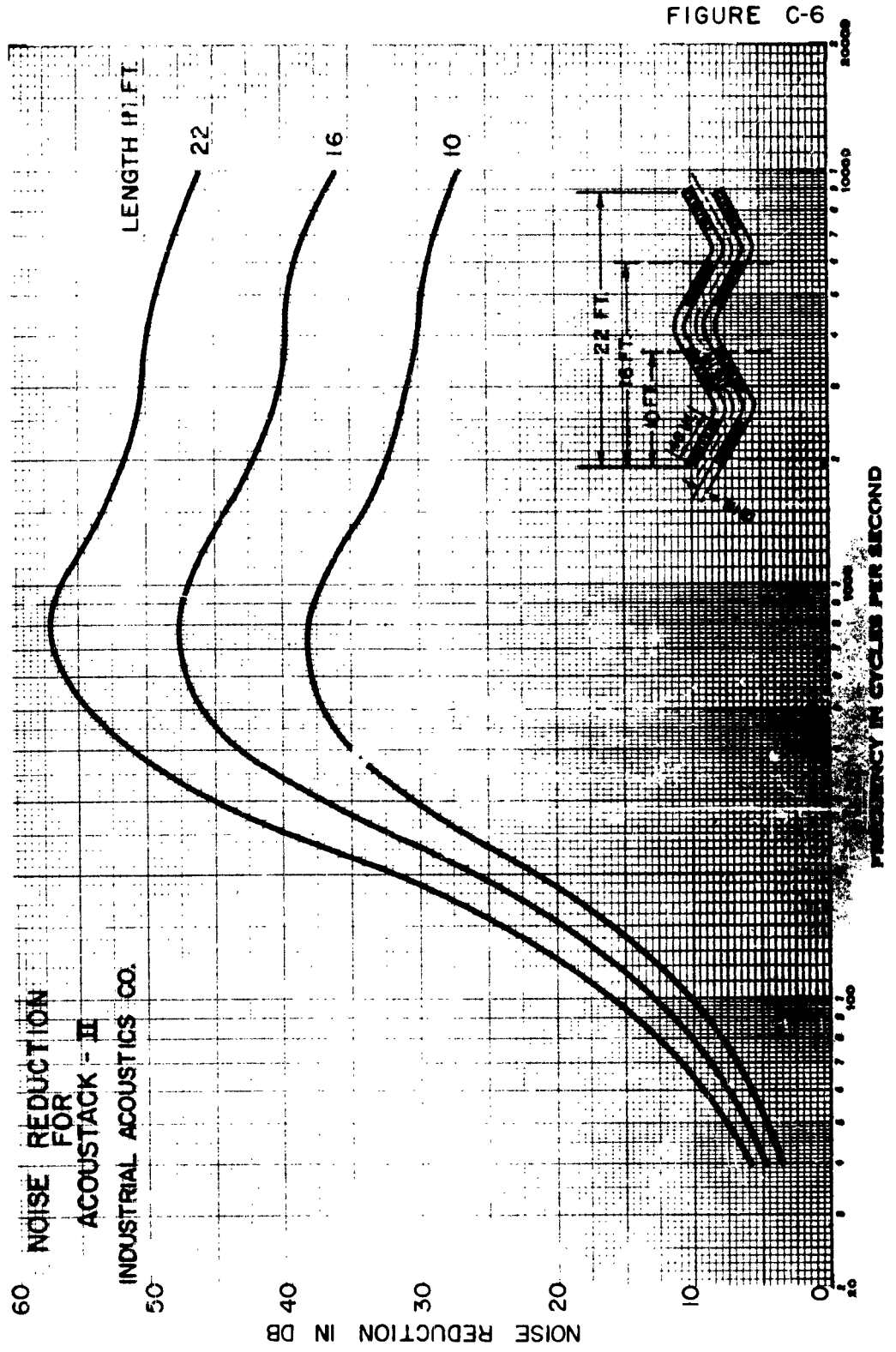


FIGURE C-6

NOISE REDUCTION
FOR
SOUNDSTREAM
Industrial Sound Control Division
Koppers Company, Inc.

Source of Data:

D. N. Keast¹⁹/

Conditions for Measurement:

Ambient temperature about 75°F
Air flow as noted on graph

Effect of Air Flow:

See graph

Effects of Orientation:

Probably negligible

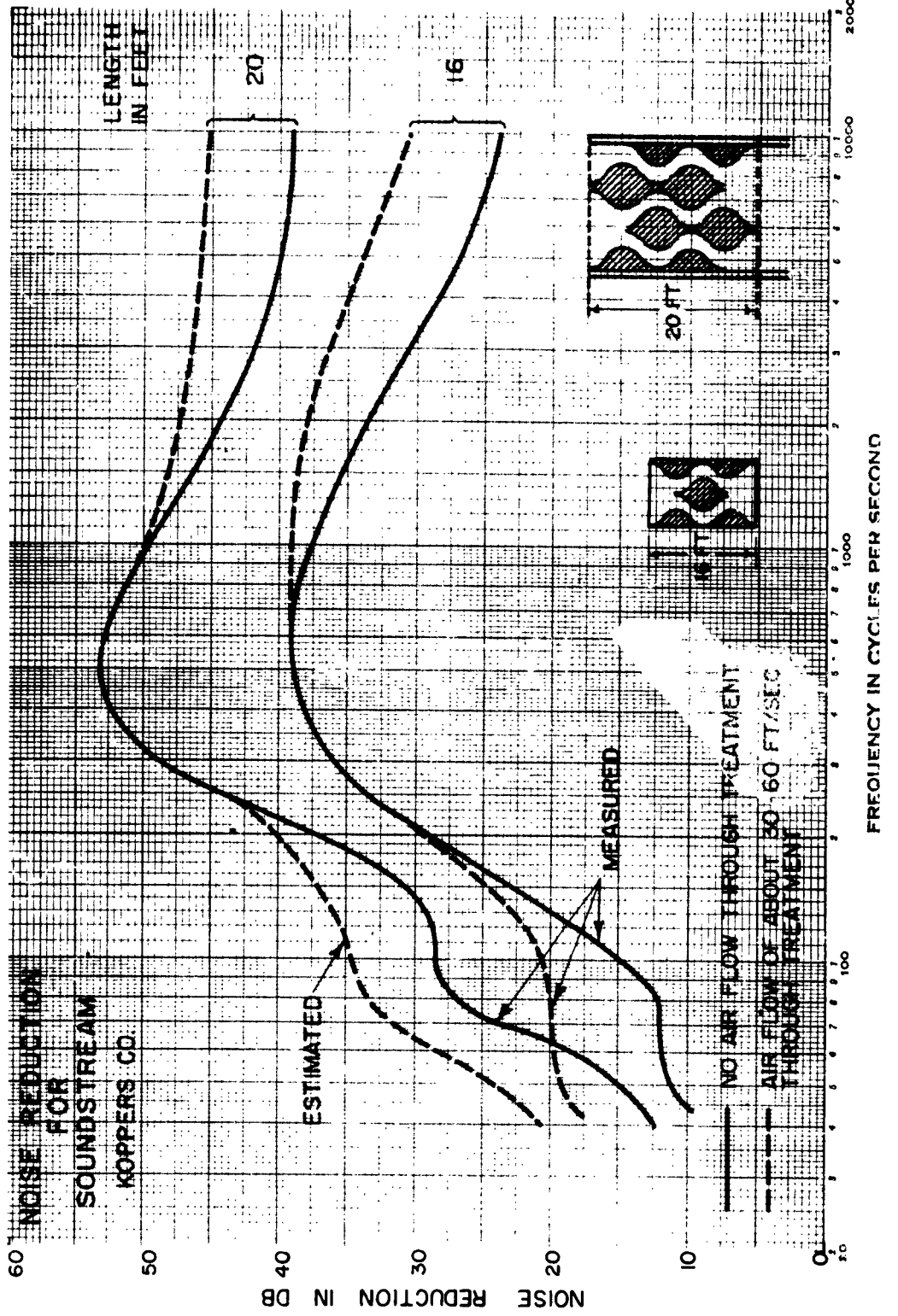
Construction Details:

Depends upon linear velocity through treatment

General Comments:

See also Ref 18 for additional data.
Also available in 8, 12, 24, 32 ft lengths.

FIGURE C-7



NOISE REDUCTION
FOR
HELICAL MUFFLER
Industrial Sound Control Department,
Koppers Inc.

Source of Data:

Dyer, I. 17/

Conditions for Measurement:

Measurements made at 60° F and with no flow

Effect of Air Flow:

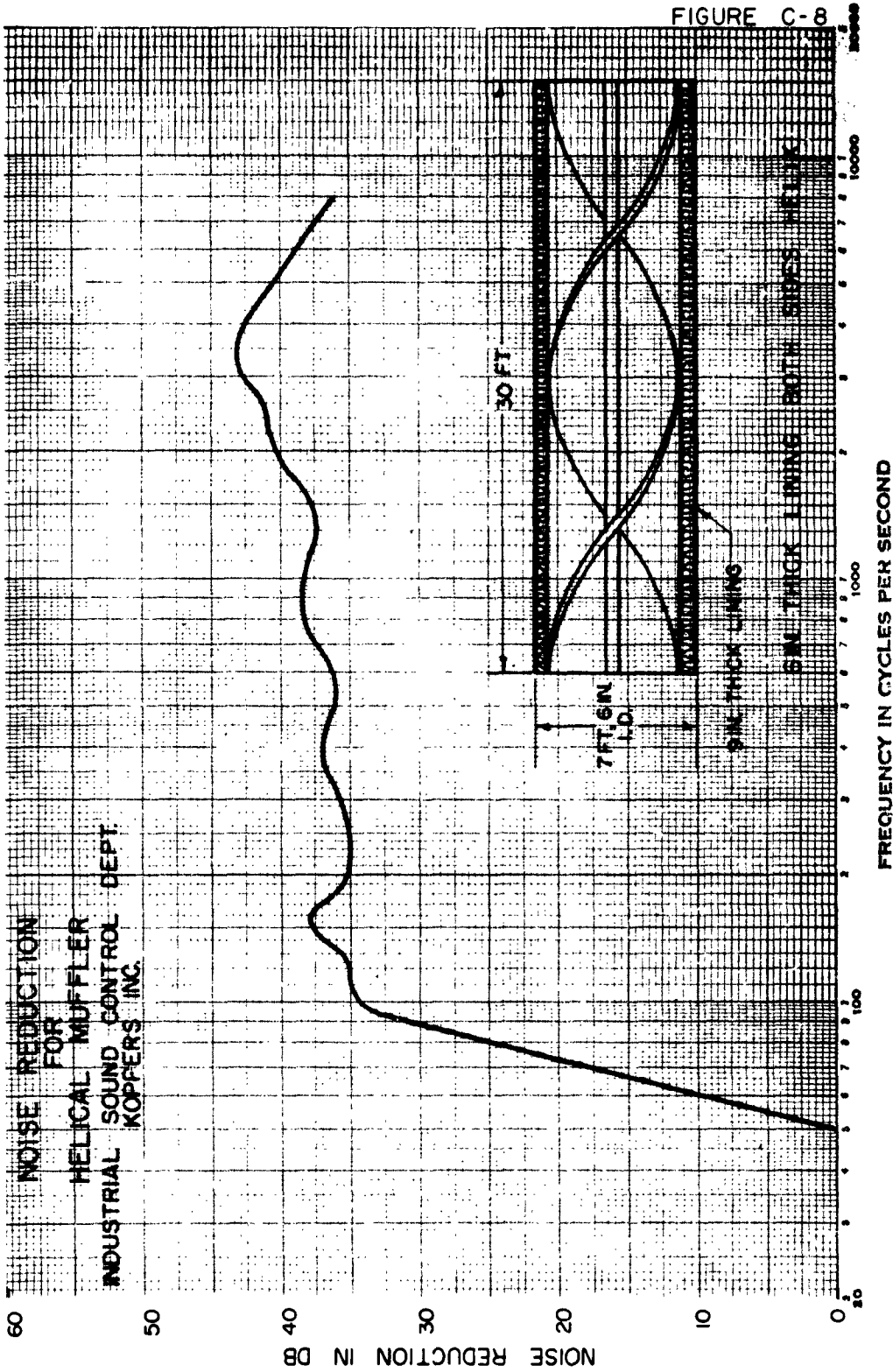
Probably small.

Effects of Orientation:

Negligible.

Construction Details:

See sketch.



NOISE REDUCTION
FOR
PYDEE TREATMENT
Janke and Company

Source of Data:

Dyer, I.^{17/}

Conditions for Measurement:

Measurements made at 60° F and no flow.

Effect of Air Flow:

Not known; probably the same as for parallel baffles.
See Section C-4.

Effects of Orientation:

Negligible.

Construction Details:

See sketch.

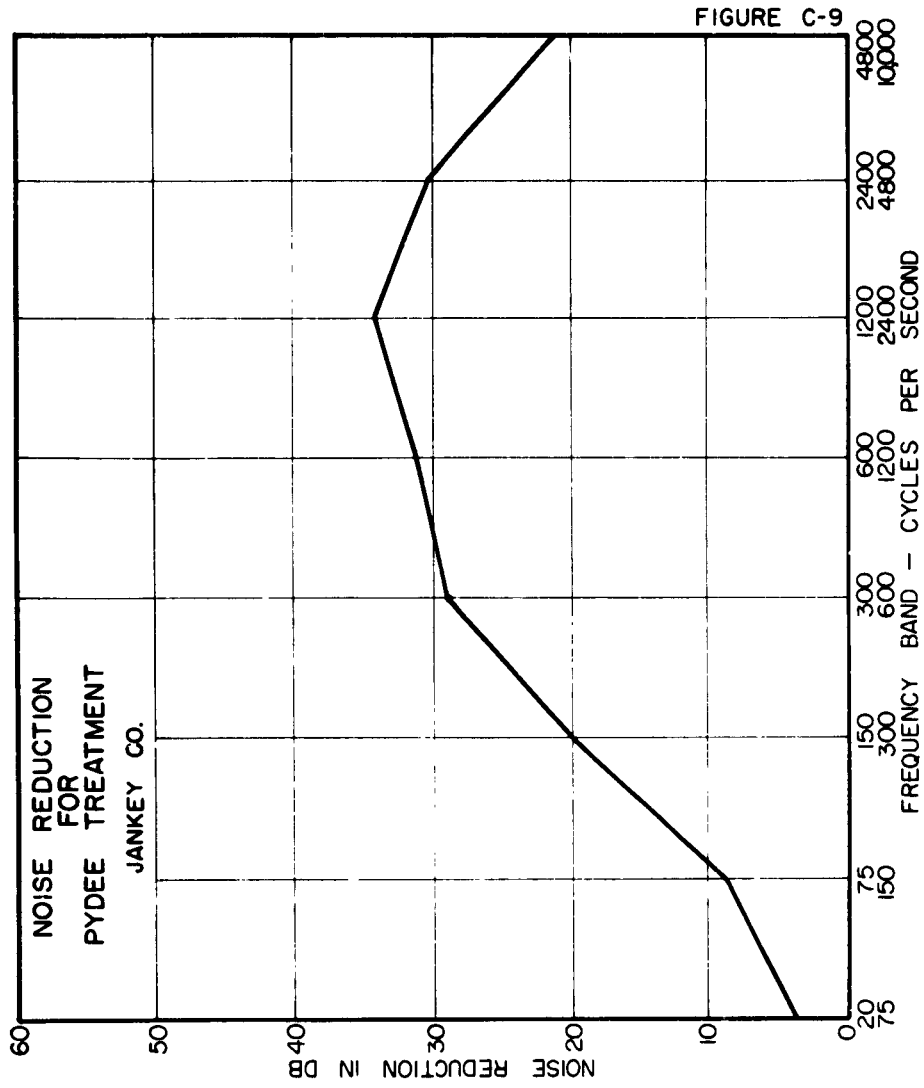
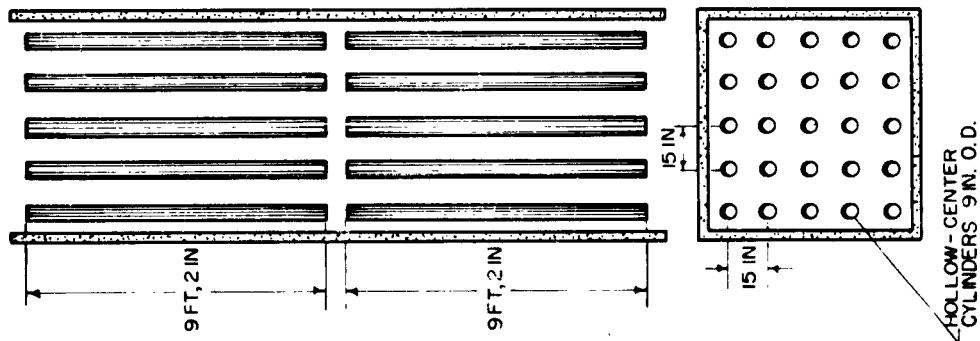


FIGURE C-9



2 IN THICK TW FIBERGLAS LINING
(ENDS OF THE CYLINDERS ARE CLOSED)

NOISE REDUCTION
FOR
WAVY BAFFLES
Kittell-Lacey Inc.

Source of Data:

Dyer, I.^{17/} and additional unpublished data by Bolt
Beranek and Newman Inc.

Range of Application:

Measurements made at 180° F, flow velocity about
80 ft/sec.

Effect of Air Flow:

Measurements with no air flow indicate noise reduction
is about 10 db lower than shown in 20-75 cps band
and 5 db less in 75-150 cps band (for 32 ft treatment).

Effects of Orientation:

Probably negligible.

Construction Details:

See sketch. Density of glass fiber not known.

General Comments:

Measured data for 16 ft length were adjusted to apply
to conditions cited above. Data for 24 ft length
obtained by interpolation.

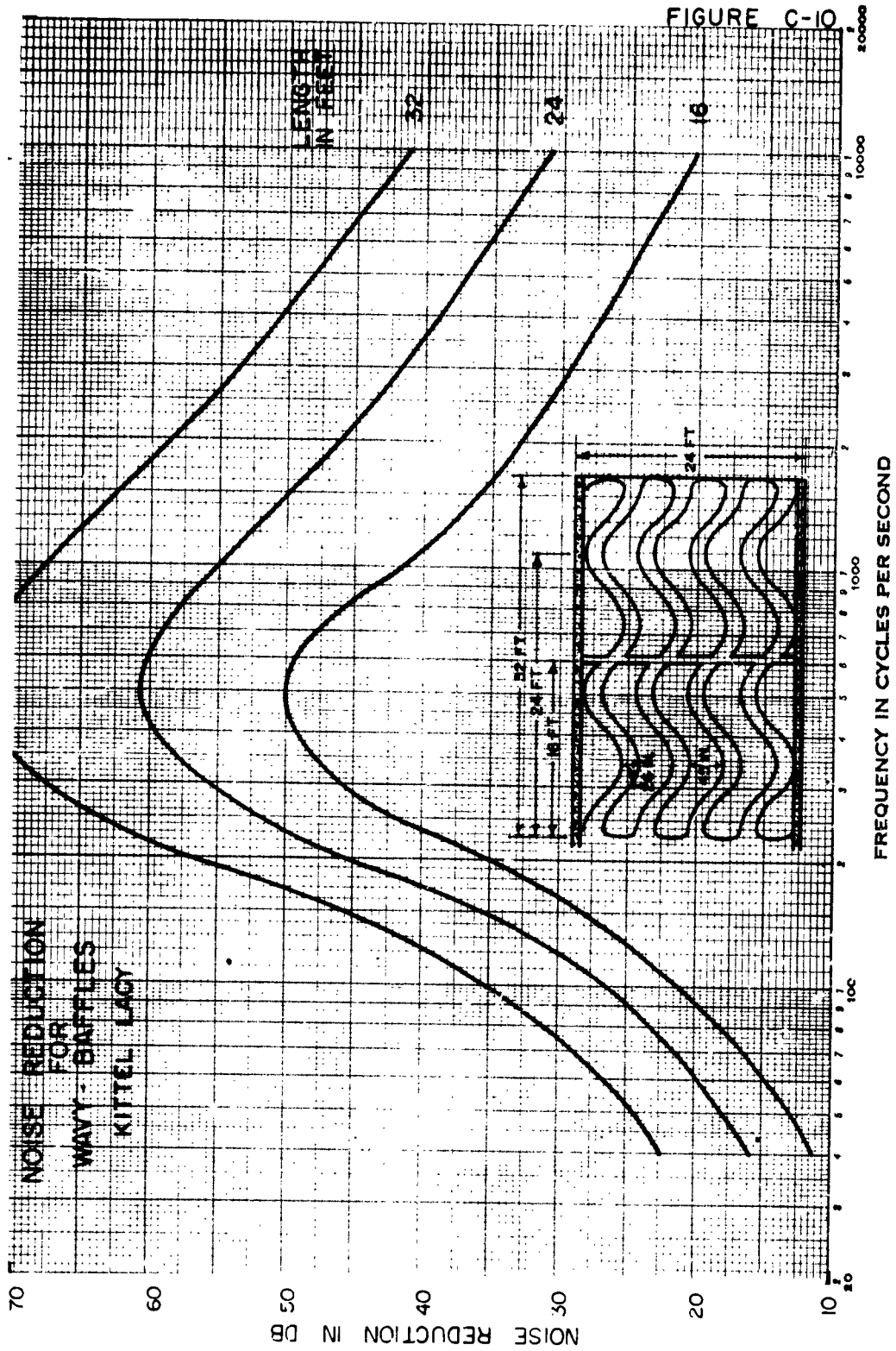


FIGURE C-10

NOISE REDUCTION FOR
MAXIM SILENCER
MAXIM DIVISION
Emhart Manufacturing Co.

Source of Data:

I. Dyer^{17/}

Conditions for Measurement:

Ambient Temperature 60° F; No air flow; Noise source
located around a bend from the silencer.

Effect of Air Flow:

Probably negligible

Effects of Orientation:

High frequency noise reduction may be 5 to 10 db less
if noise source is located on longitudinal axis of
muffler

Construction Details:

See sketch

General Comments:

Available in a wide range of sizes

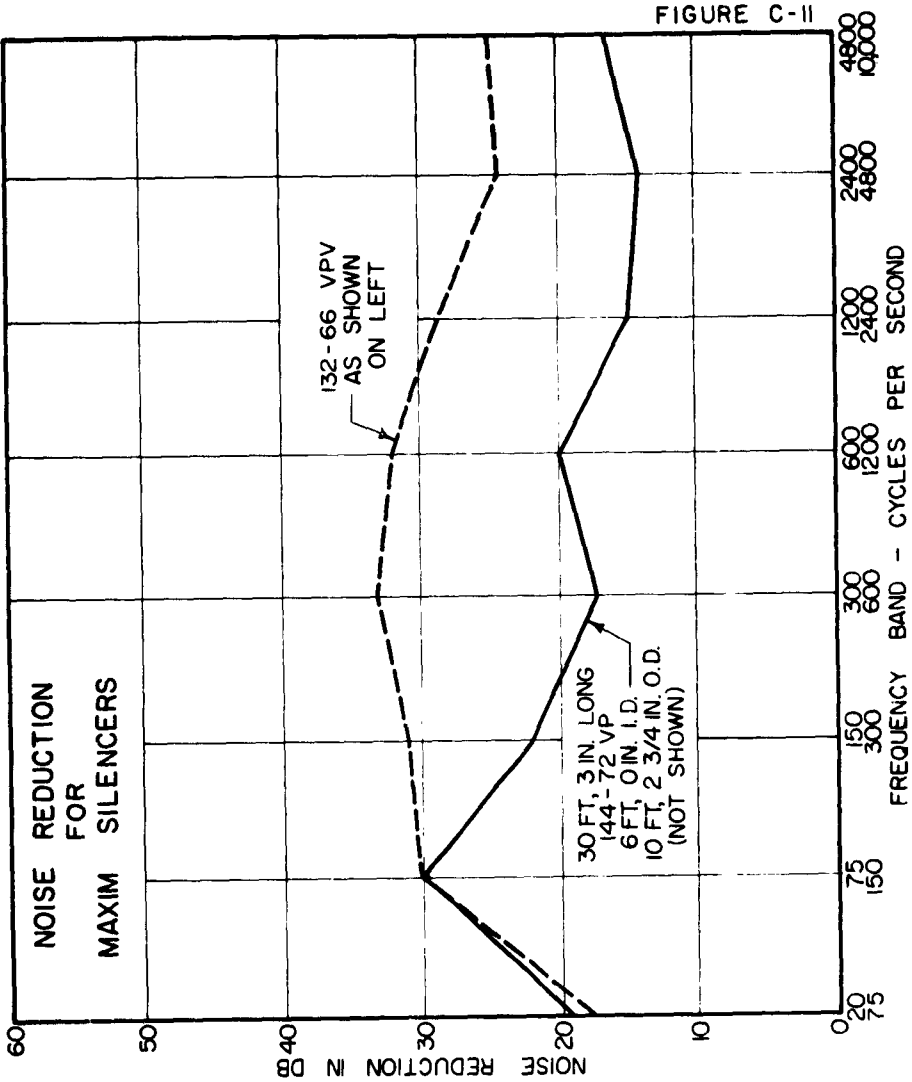
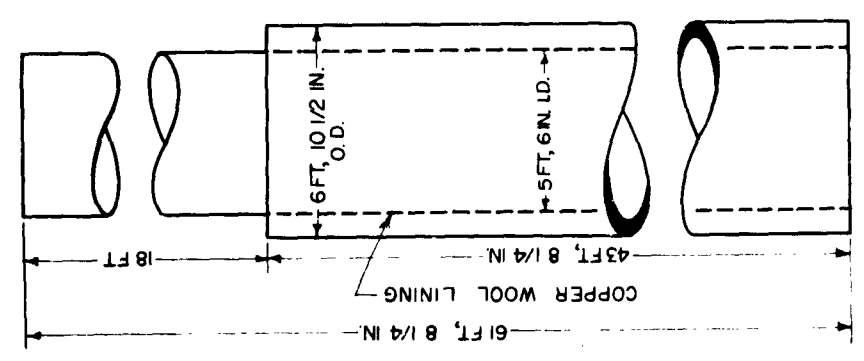
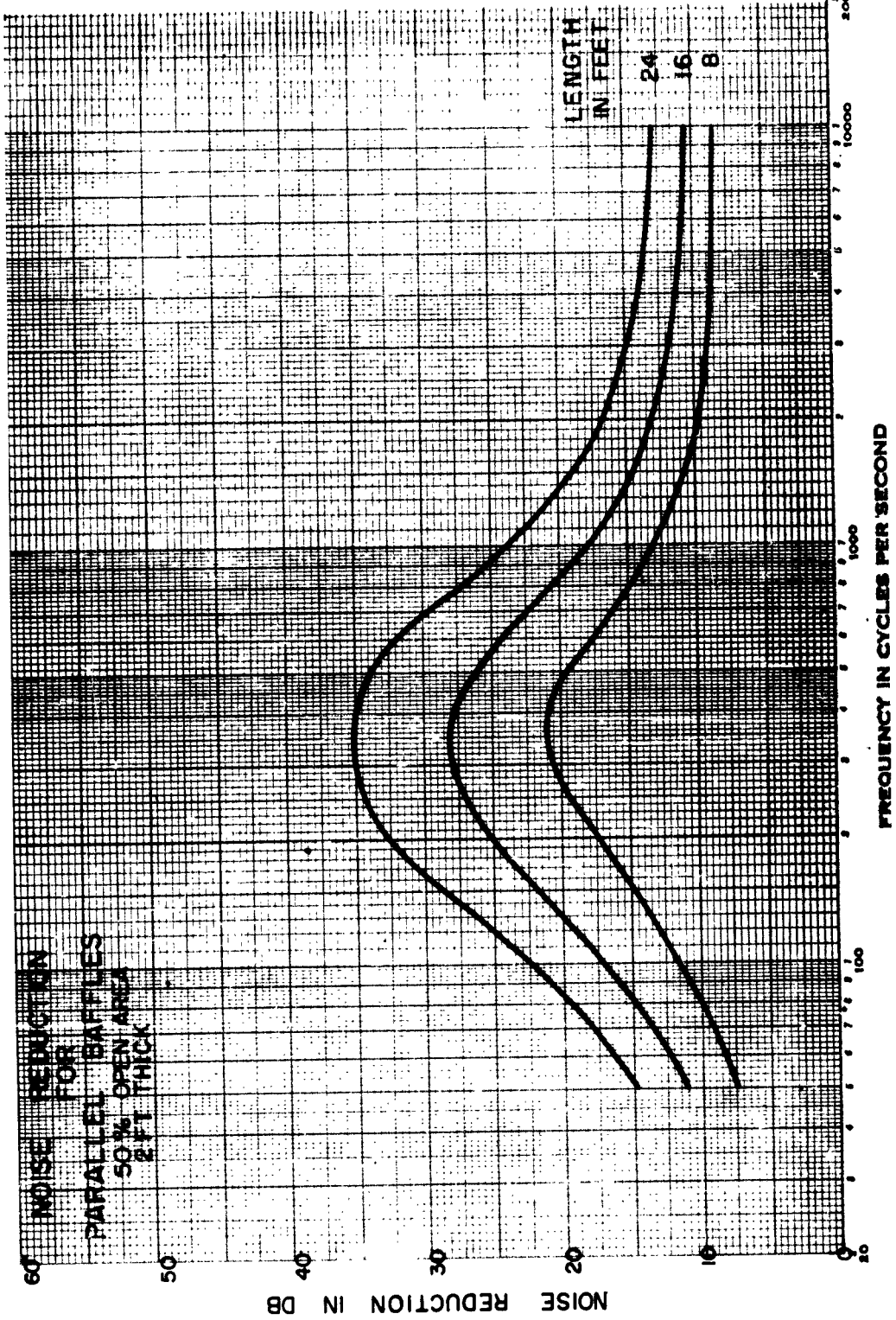


FIGURE C-II



MAXIM MUFFLER
(132-66 MODEL VPV SILENCER)

FIGURE C-12



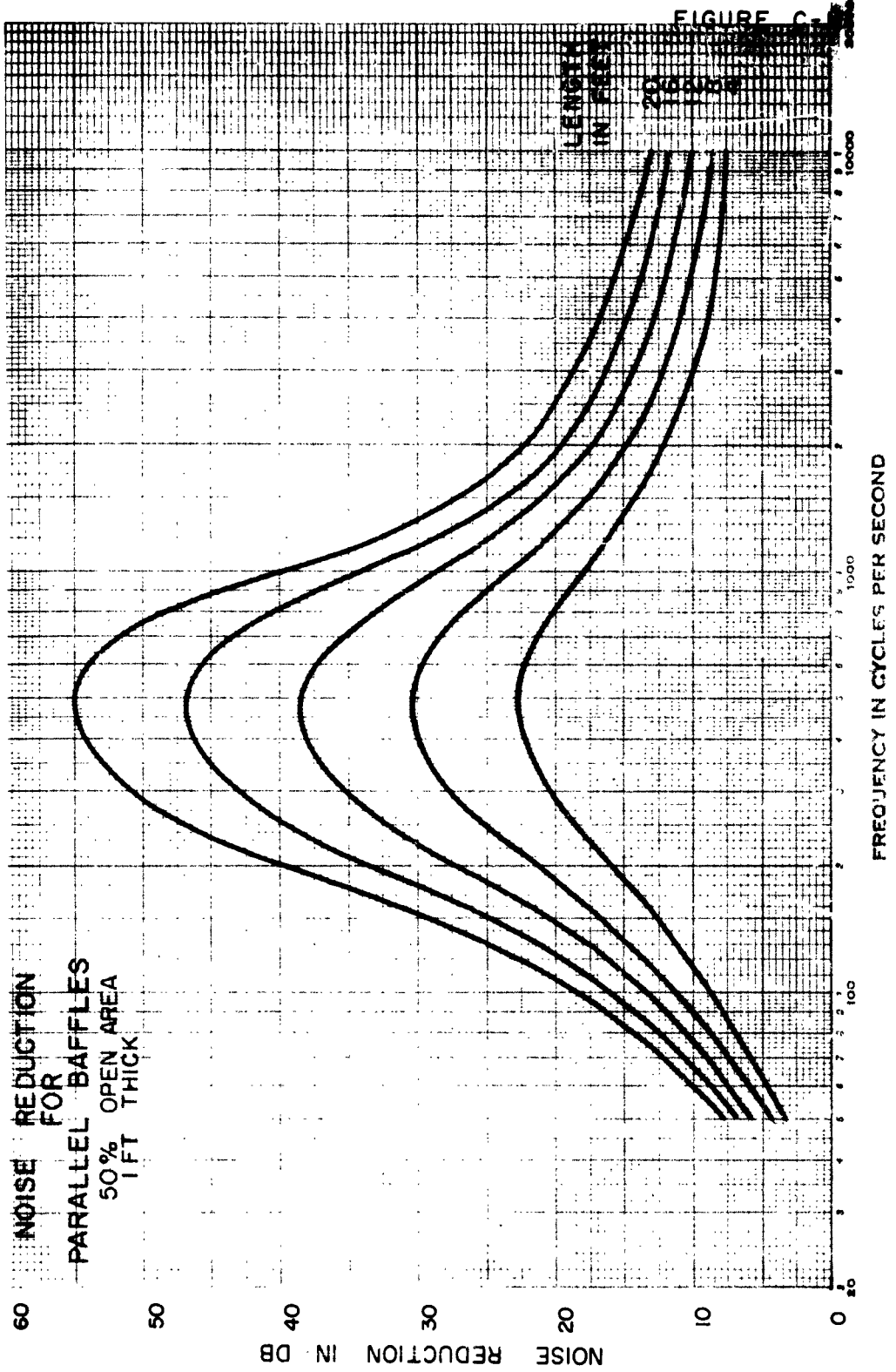
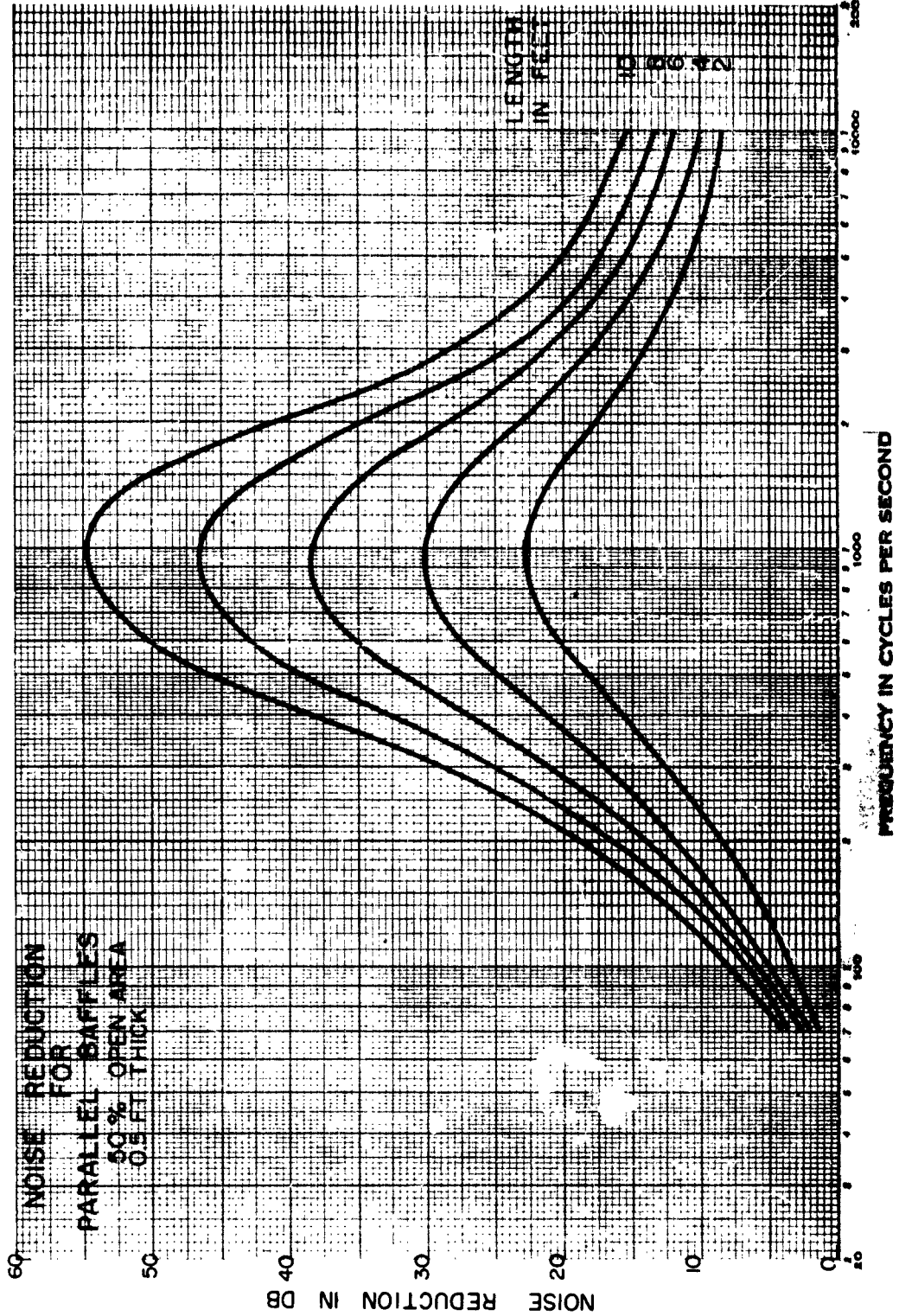
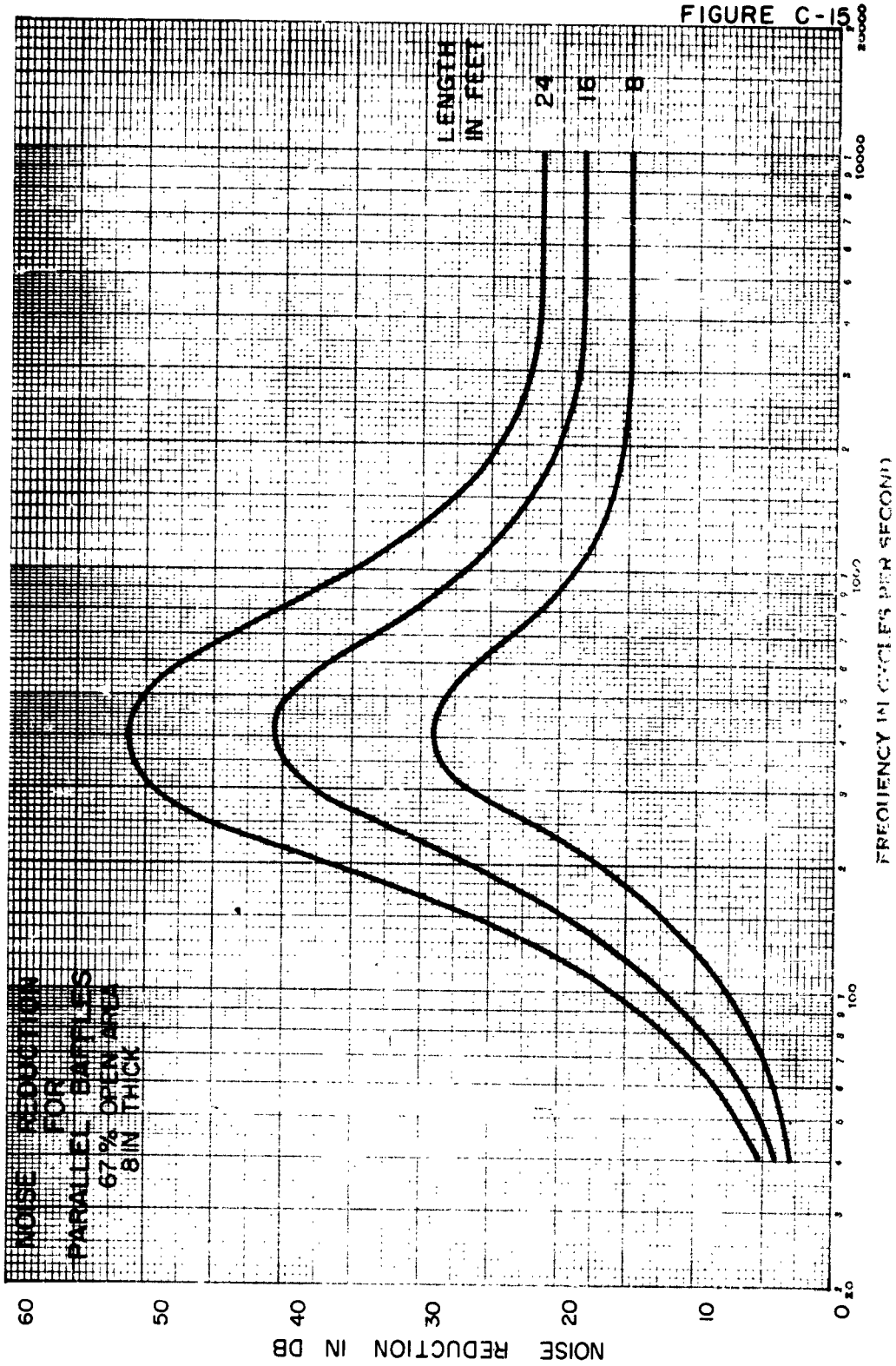


FIGURE C-14





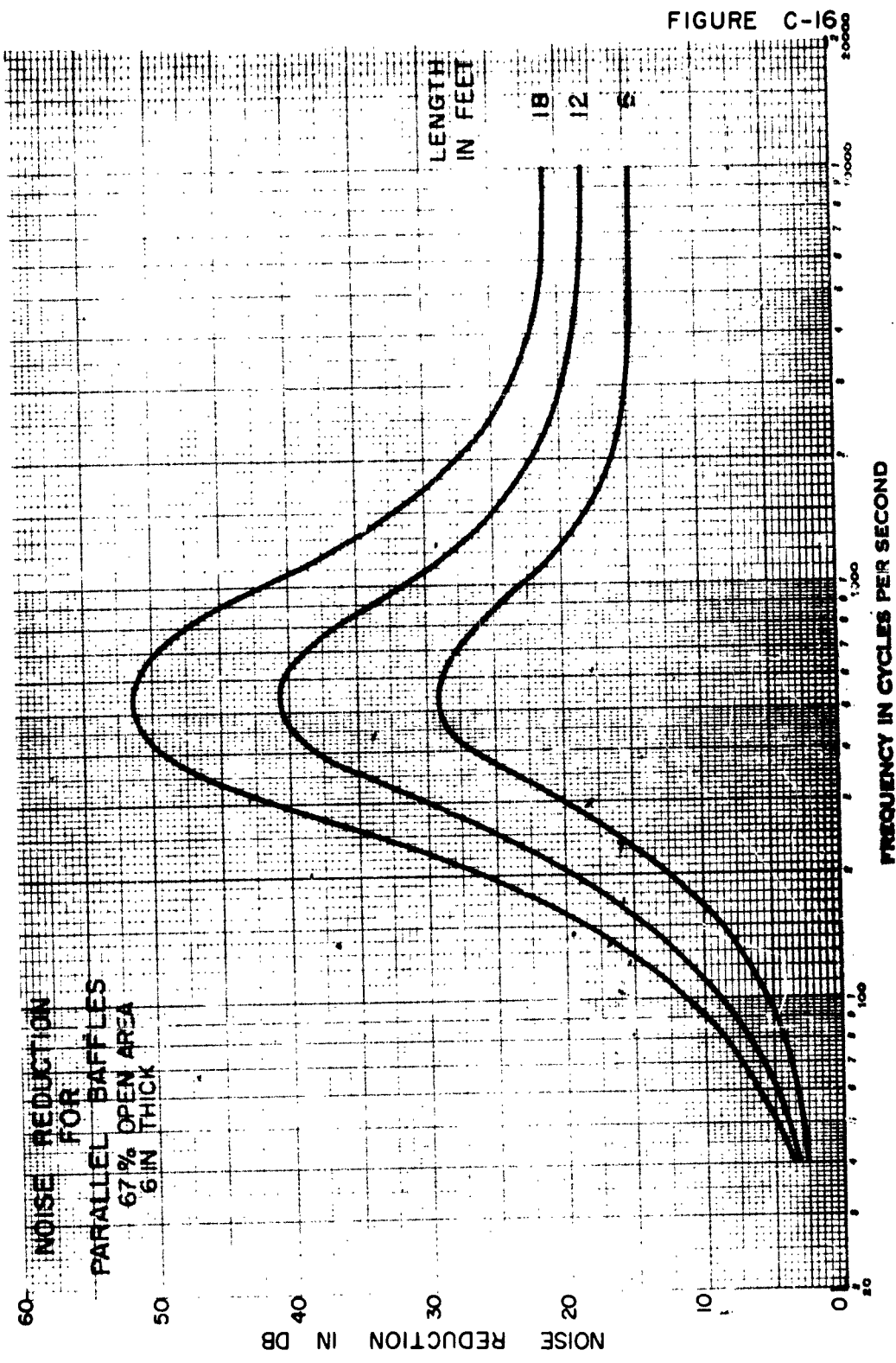


FIGURE C-16

FIGURE C-17

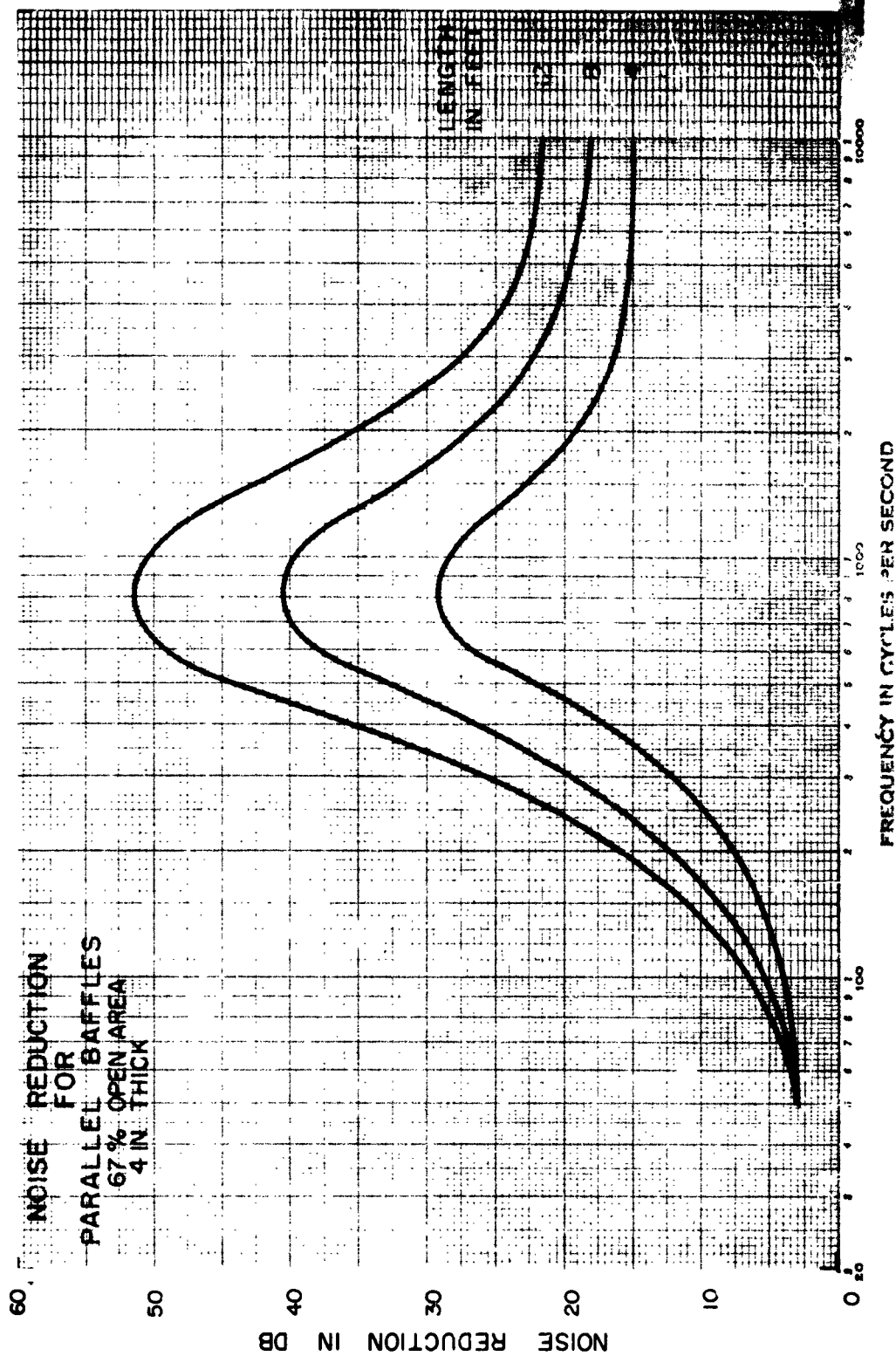


FIGURE C-18

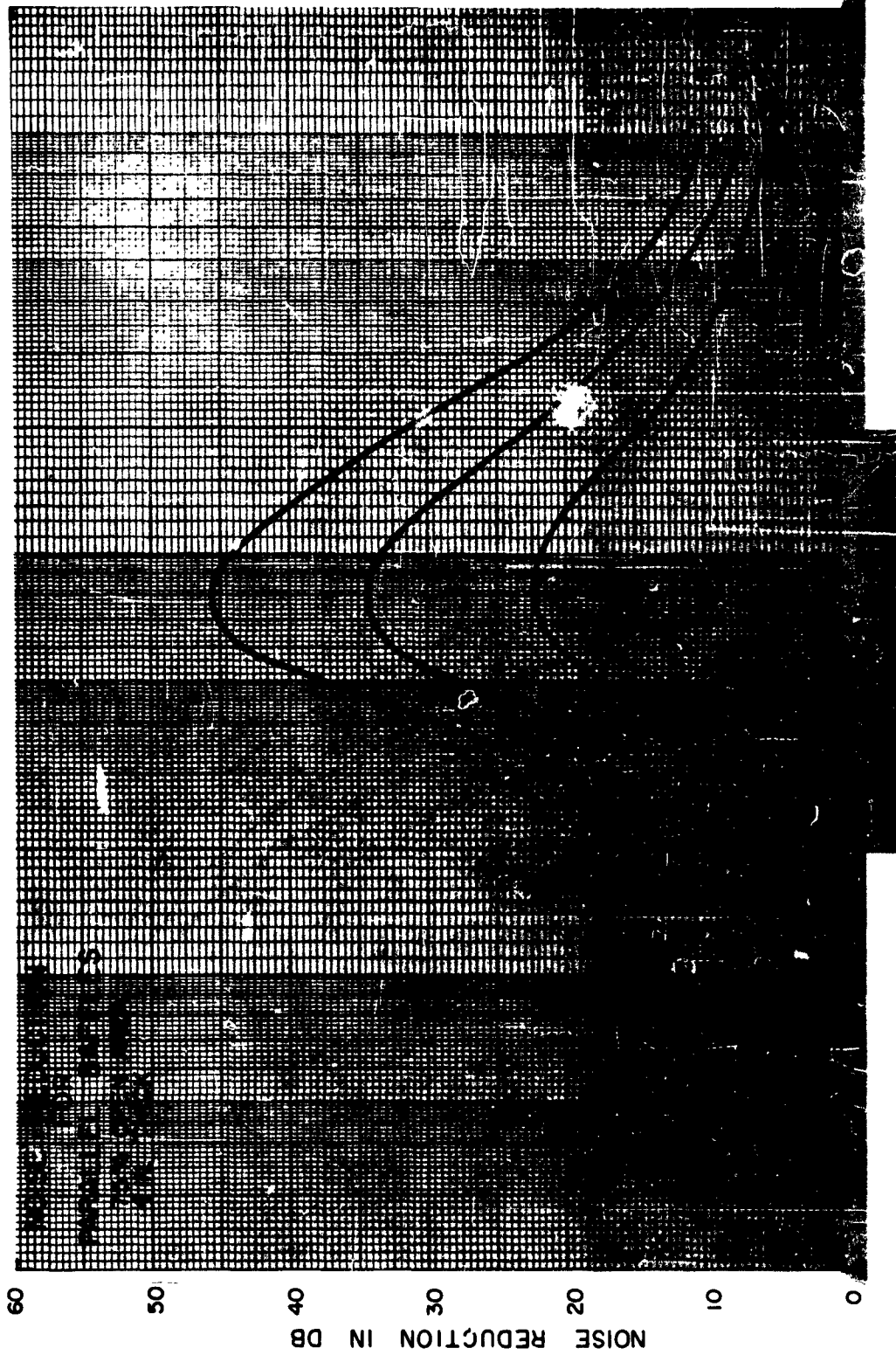
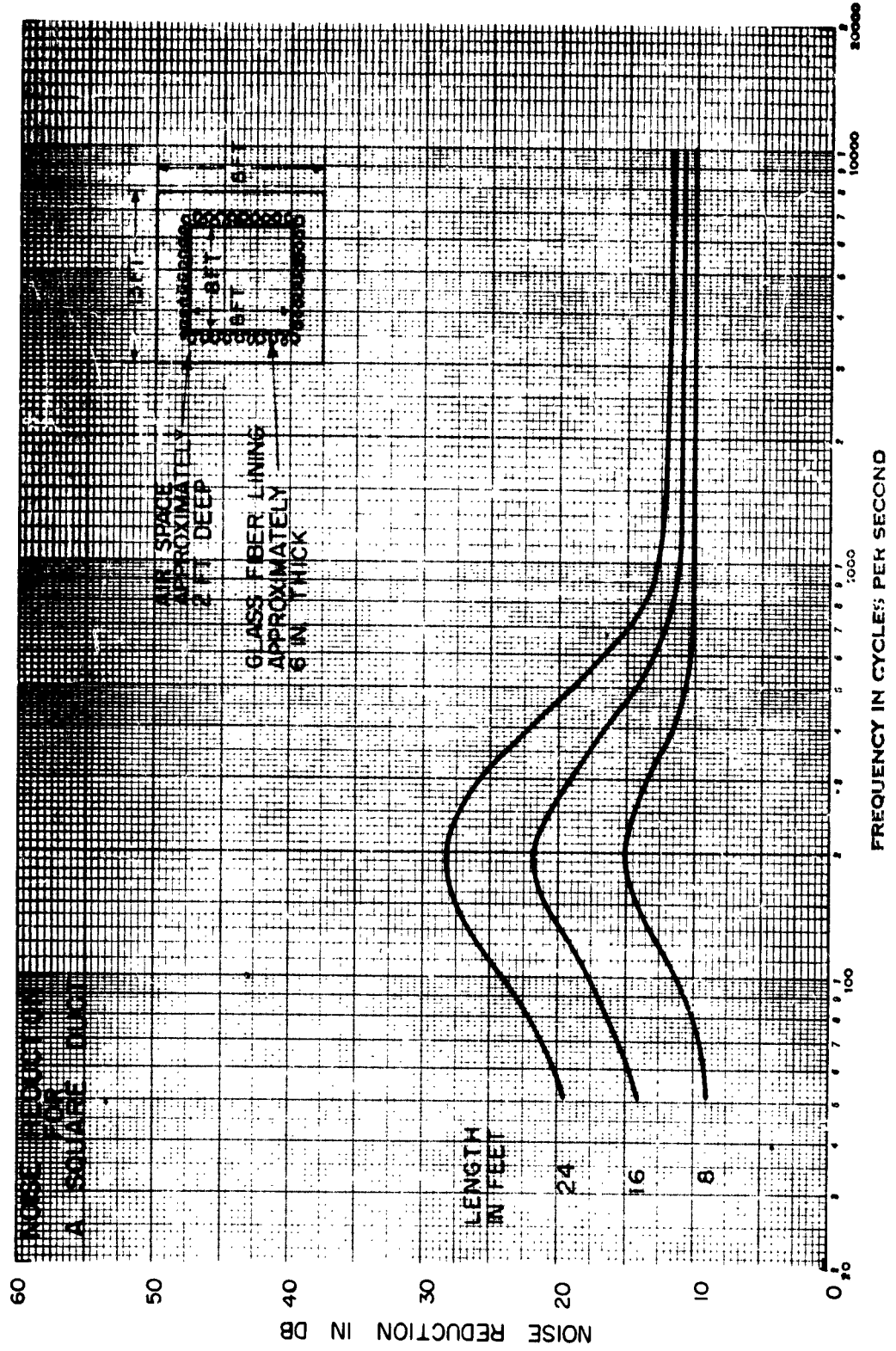


FIGURE C-19



APPENDIX D

NOISE REDUCTION BY IMPERVIOUS BARRIERS

The noise reduction (NR) and transmission loss (TL) of an impervious barrier are defined in Section III of this report. The transmission loss of many different partitions and of many types of building constructions can be found in the literature of the National Bureau of Standards and other publications of independent testing laboratories. The data presented here are intended to supplement such data, as the transmission properties of some structures encountered in engine test cell design are not generally available in the literature. The data obtained from field measurements occasionally conflict with data reported elsewhere. The discrepancies arise mainly because a small wall panel used in a laboratory experiment may not have the identical noise transmission properties as the large panels encountered in engine test cells. Furthermore, the transmission loss depends upon spatial distribution of the noise field in the "source room". The data presented here are more directly applicable to test cell design problems.

A common element in engine test cell construction is a 12 in. thick concrete wall. Such walls are used for the test section and for the air intake and exhaust passages. The transmission loss of a 12 in. thick concrete wall and a 6 in. thick concrete wall for such applications is given in Fig D-1. The transmission loss in the low frequencies is somewhat higher than the value generally given for such walls. The coincidence dip is neither as deep nor as wide (in frequency) as the generally published values. Both of these discrepancies arise from the peculiar character of the space distribution of the noise field in the test section of test cells.

TRANSMISSION LOSS
FOR
TYPICAL CONCRETE WALL
USED IN TEST CELLS

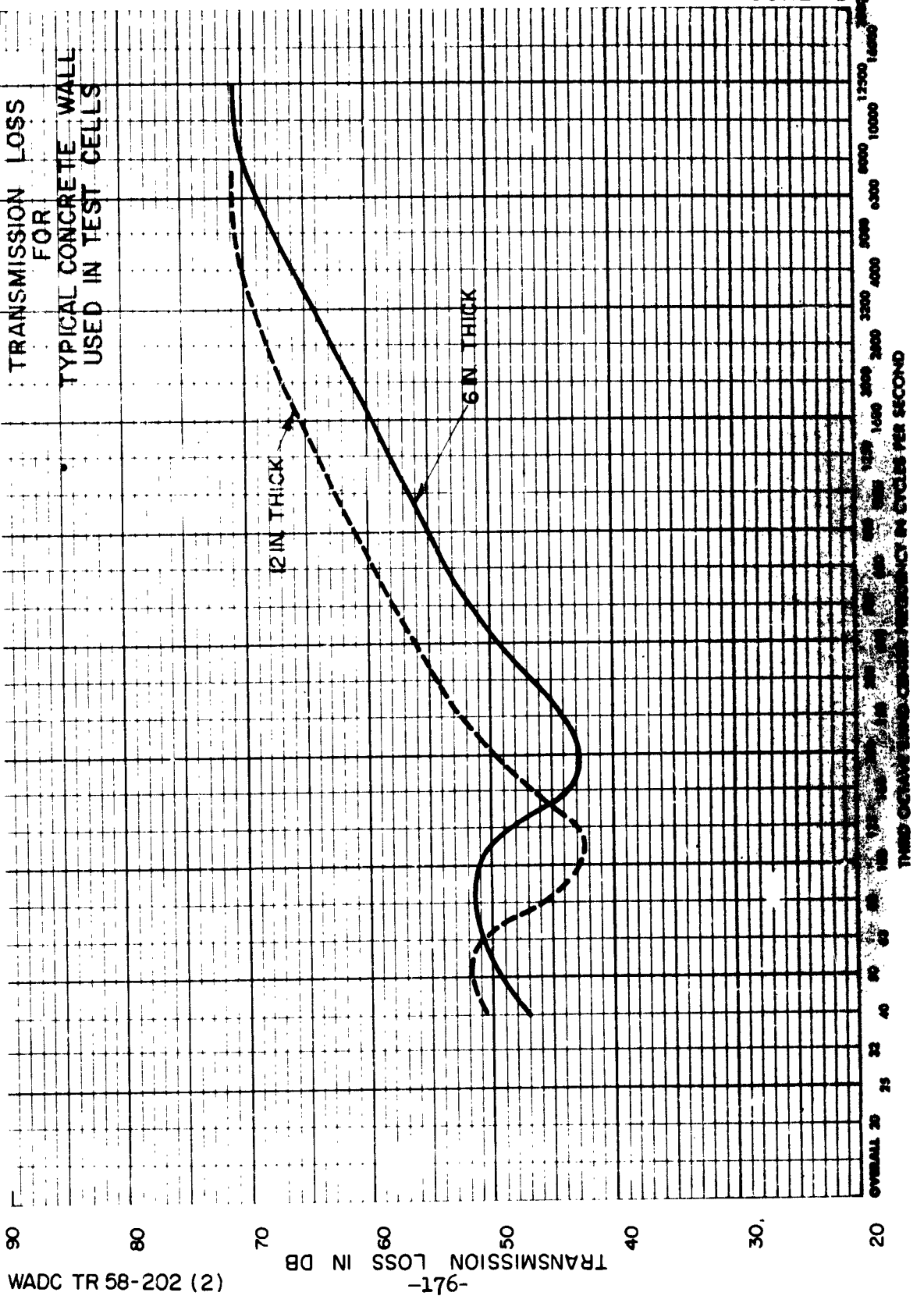


FIGURE D

As explained in Section III of this report, double wall constructions are frequently required between the test section of the test cell and the control room of the test cell. The data presented in Fig D-2 show the order of magnitude of transmission loss obtained from such structures under field conditions. The data here are taken from Volume Three. The transmission loss values shown here are influenced by flanking paths which carry sound energy around the walls to the receiving room. If flanking paths are eliminated, the transmission loss values might be from 10 to 15 db greater than the values shown.

The noise transmission properties of multiple pane windows are not well understood. Only a meager amount of experimental data are available and a comprehensive theory has not yet been developed. The transmission loss of two types of multiple pane windows is given in Figs D-3 and D-4. These data indicate a minimum value for the transmission loss of these structures. It is generally not possible to discriminate between sound energy which was transmitted through the window structure and sound energy which was transmitted over flanking paths. Thus, the transmission loss in each case may actually be higher than the value shown.

MEASURED TRANSMISSION LOSS OF THREE DOUBLE WALLS

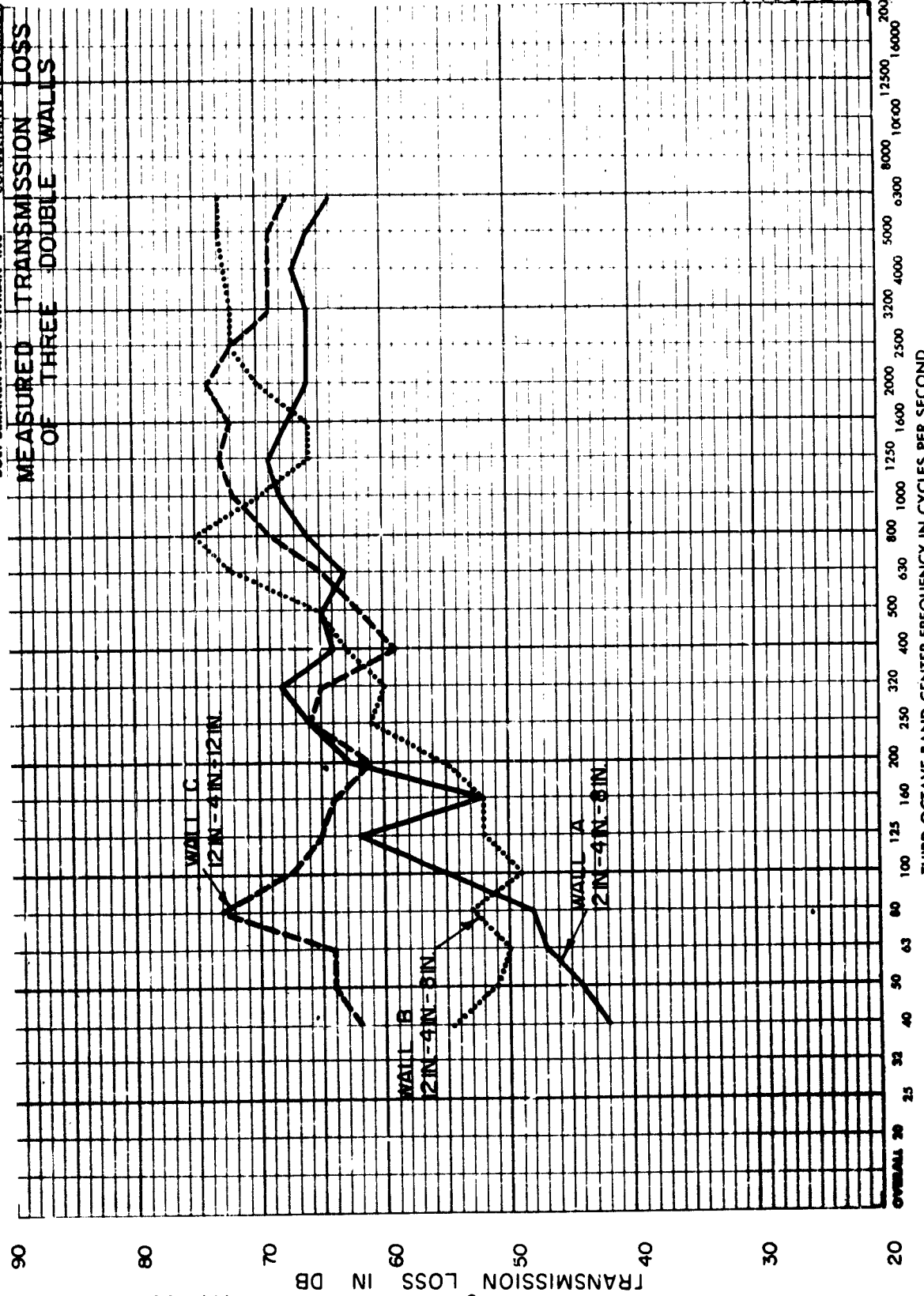


FIGURE D

80

70

60

TRANSMISSION LOSS IN DB

179-1

WADC TR 58-202 (2)

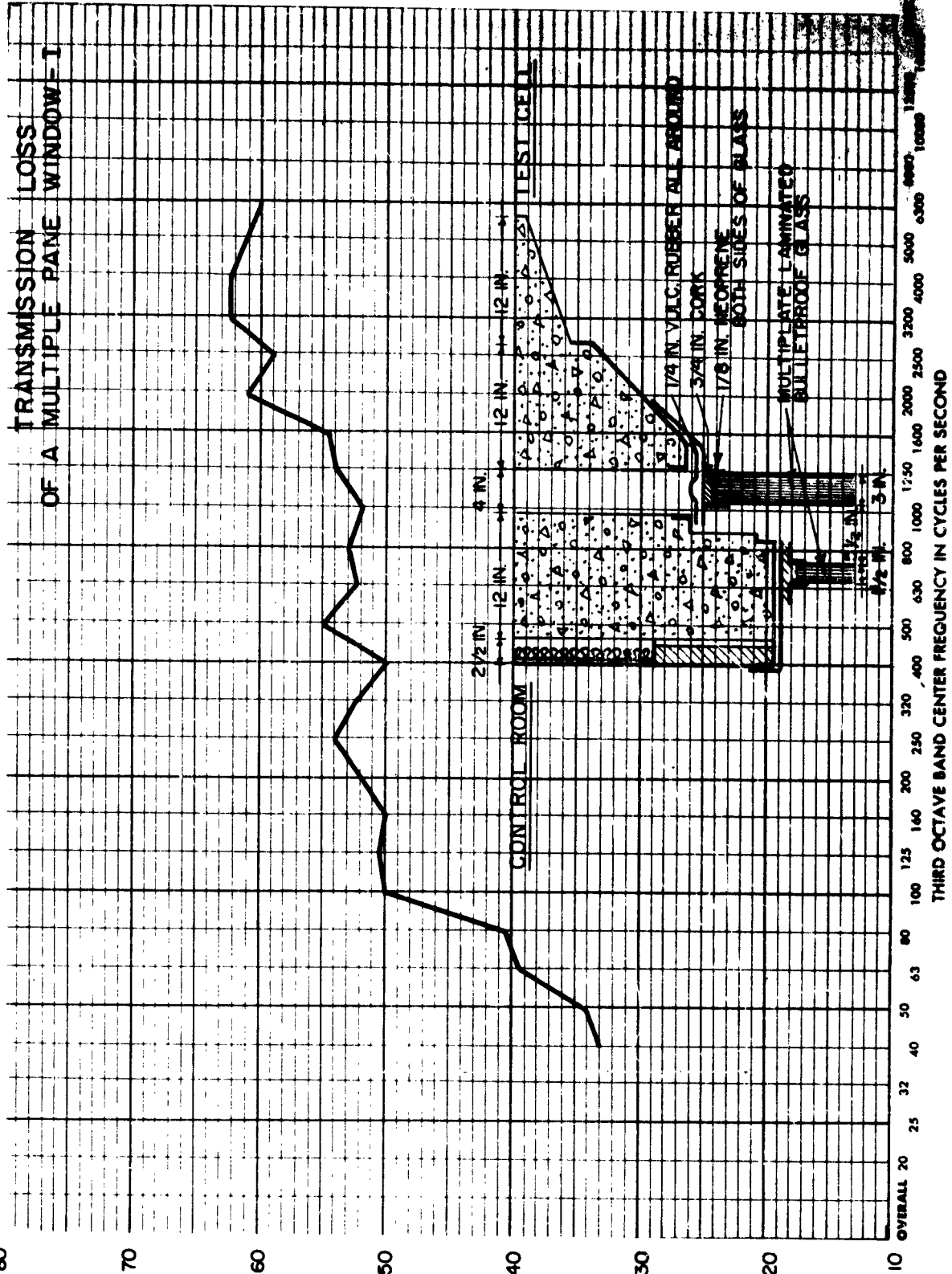
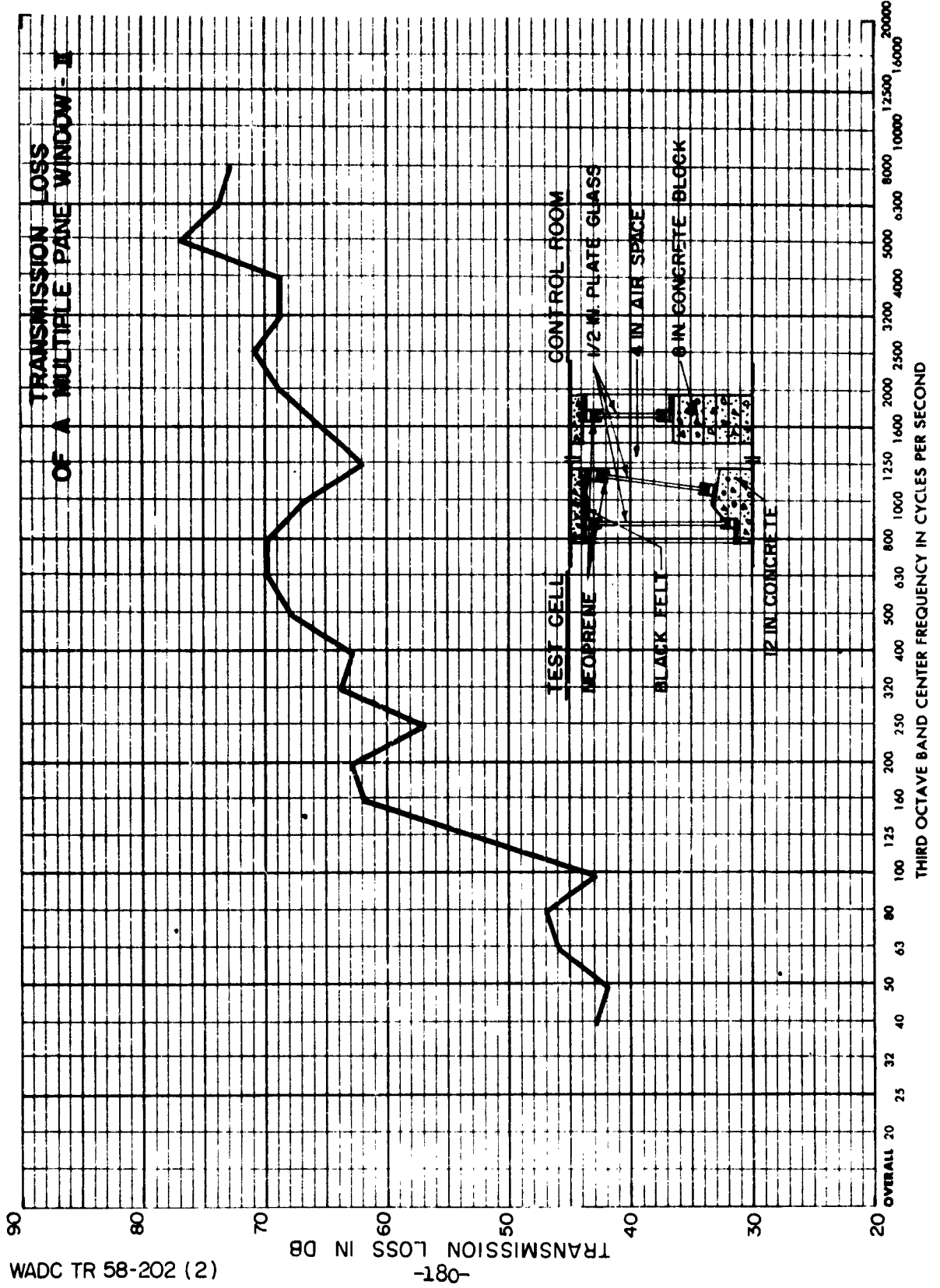


FIGURE D-3

FIGURE D-4



APPENDIX E
JET EXHAUST DIFFUSERS

A most promising recent development in the control of jet engine noise is the use of jet exhaust diffusers to reduce the total acoustic power radiated by the jet engine. A jet exhaust diffuser is a device which modifies the interaction of the jet stream with the surrounding air. The modifications may be brought about by reshaping the jet nozzle, by inducing air flow around the nozzle, or by "spreading" the jet stream. Some typical diffusers and the power level changes afforded by them are shown in Figs E-1 through E-4.

While the physical mechanisms underlying the reduction of noise by diffusers are qualitatively understood, quantitative procedures do not exist for predicting the noise reduction as a function of frequency for all types of diffusers. The noise reduction obtained from a jet diffuser depends on the engine it is used with and its precise location with respect to the engine. Therefore, field measurements may be required to determine the power level changes (See Volume One).

As shown in Figs E-1 through E-4, jet stream modifiers achieve large power level reductions primarily in the frequency range below 1000 cps. In this frequency range, noise reduction through air passages and through walls is obtained only by the use of large and extensive structures. Large noise reduction requirements in this frequency range frequently necessitate double-wall, double-door and even triple- and quadruple-window constructions. Large noise reduction requirements in air passages in this frequency range

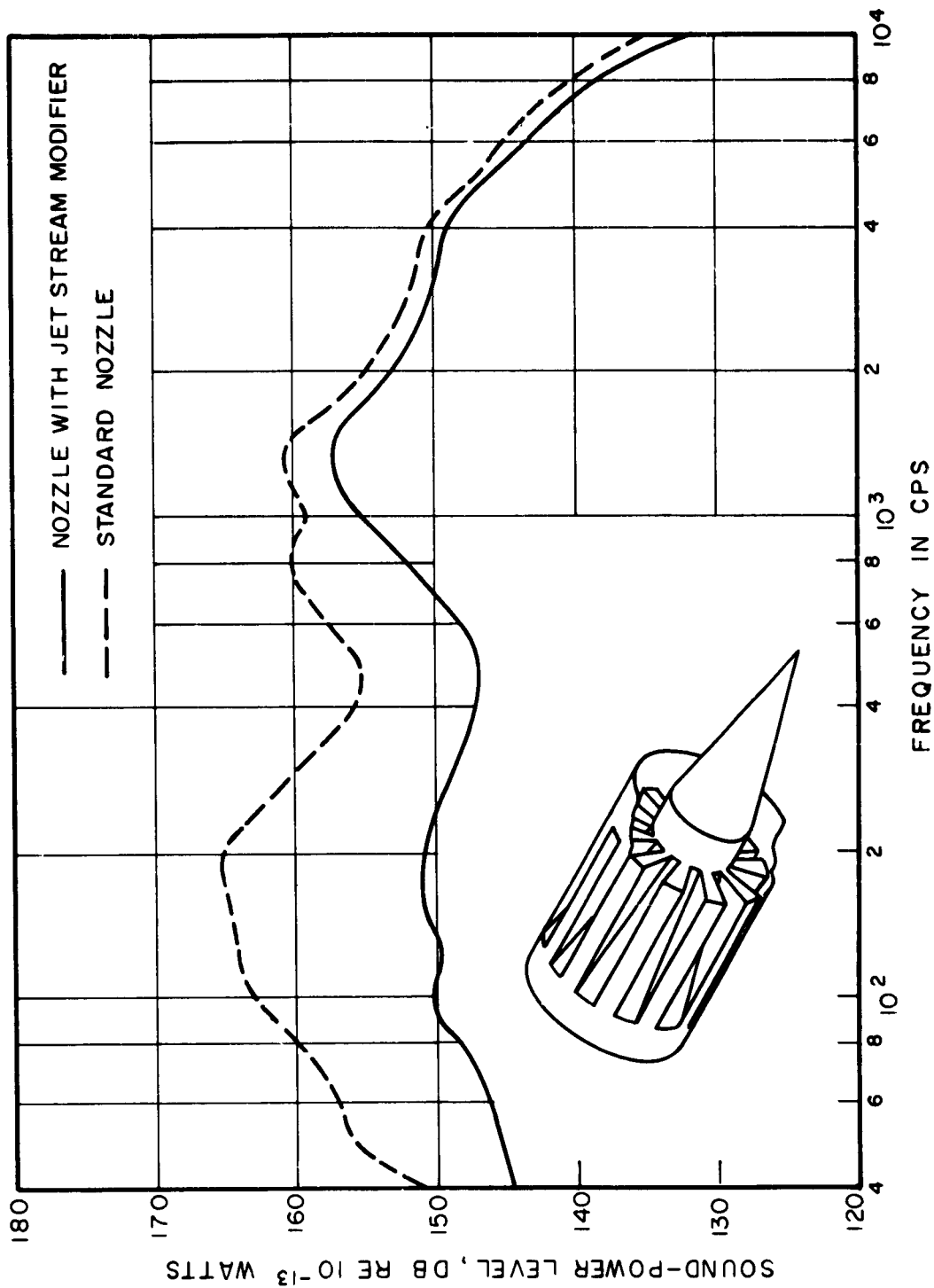


FIG. E-1 THE EFFECT OF A JET STREAM MODIFIER ON SOUND-POWER LEVEL - I

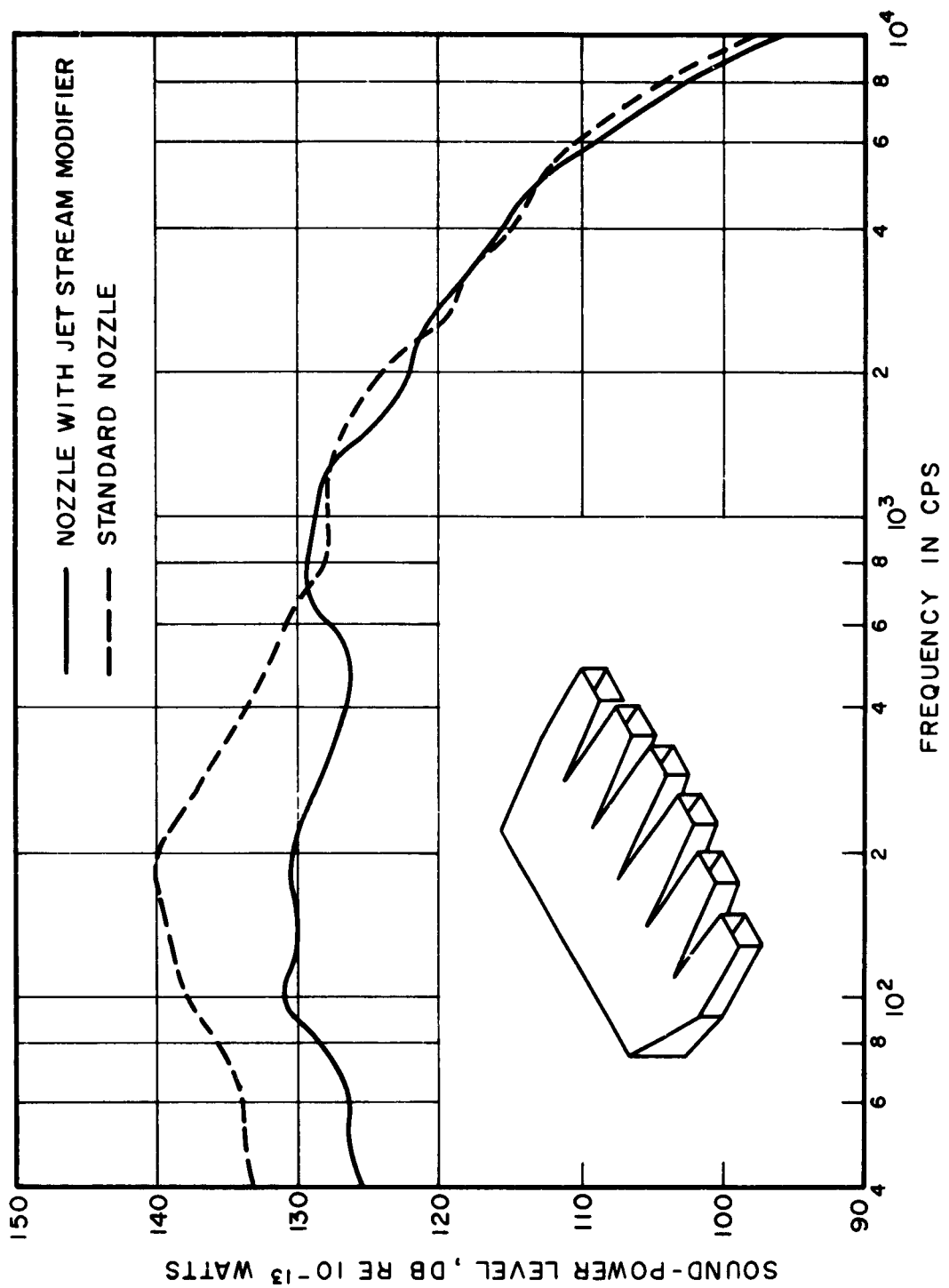


FIG. E-2 THE EFFECT OF A JET STREAM MODIFIER ON SOUND-POWER LEVEL - I

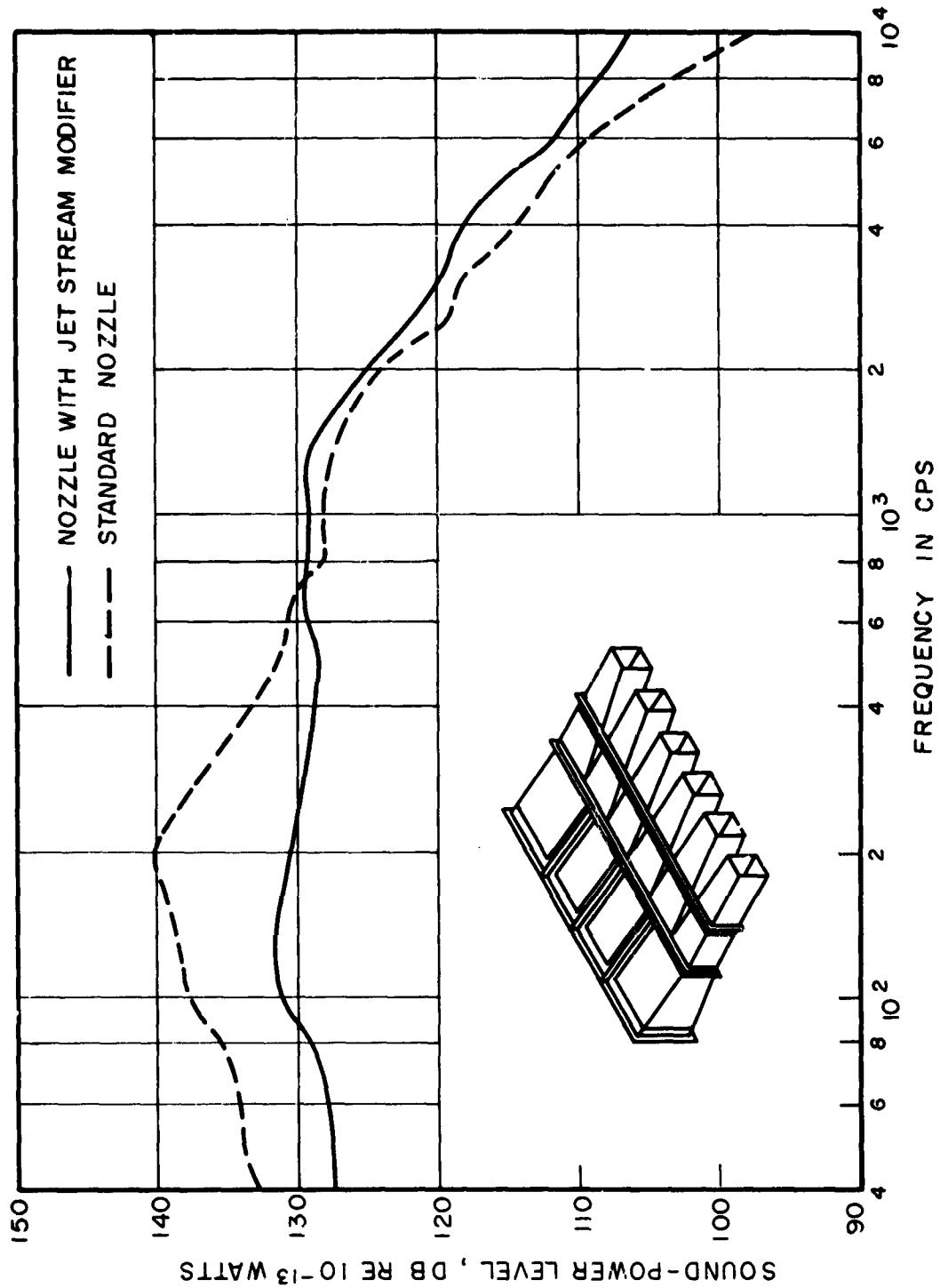


FIG. E-3 THE EFFECT OF A JET STREAM MODIFIER ON SOUND-POWER LEVEL - III

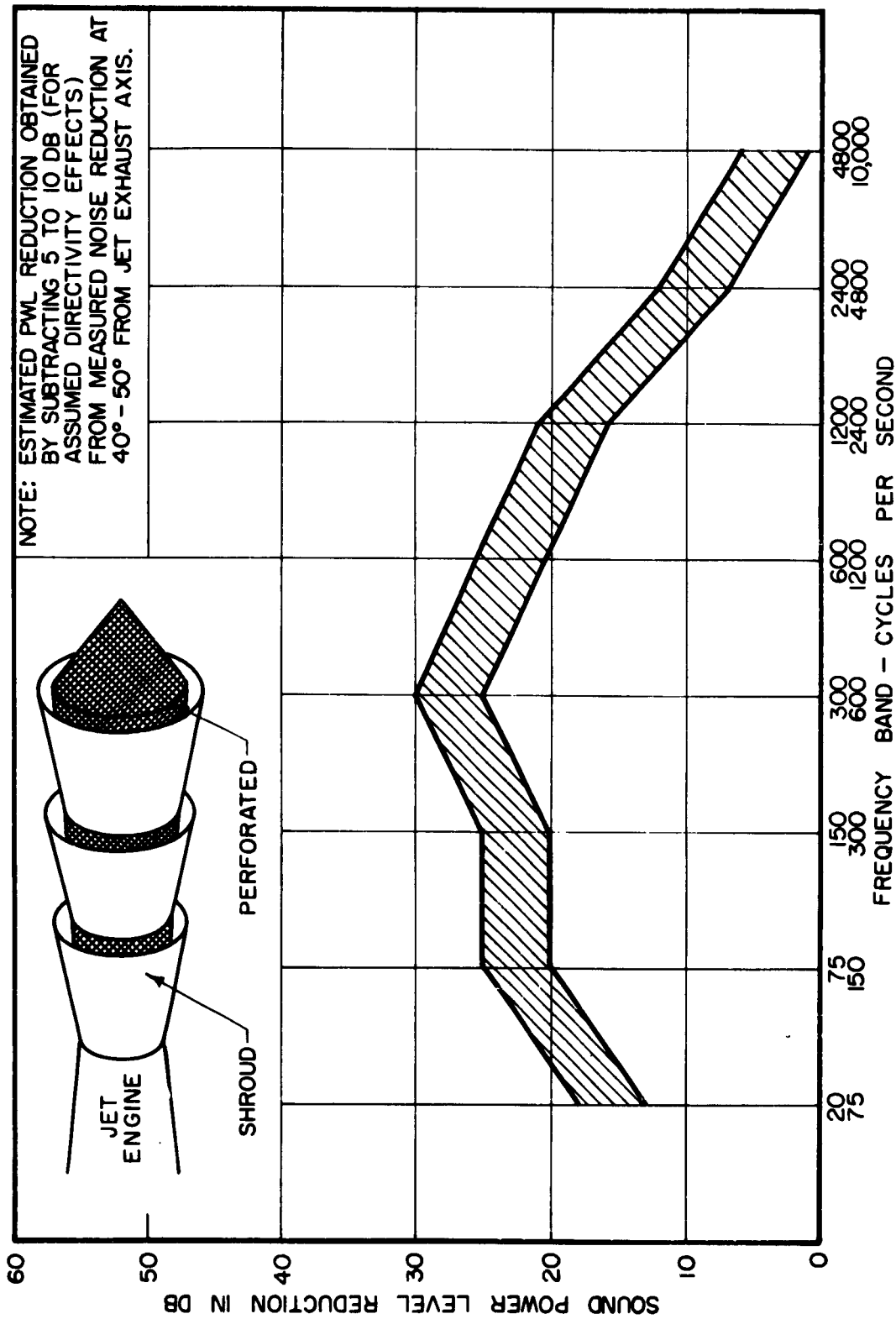


FIG. E-4 ESTIMATED POWER LEVEL REDUCTION IN OCTAVE BANDS FOR TYLER EXHAUST DIFFUSER.

necessitate long structures and relatively small open areas. Thus to obtain a given noise reduction, consistent with a given linear velocity requirement, requires that the gross cross-sectional area of the air passages be very large.

If a diffuser is used to reduce the low frequency noise reduction requirements by decreasing the total acoustic power radiated, the cross-sectional area and the length of a test cell may be reduced by a factor of two. Complex multiple wall structures may, in some cases, be avoided. For these reasons, a test cell or suppressor that incorporates a diffuser will inevitably be less expensive than a test cell without a diffuser which has the same noise reduction requirements.

Diffusers may affect the operation of the jet engine. Thrust, mass flow, temperature, and exhaust pressure ratio may all change when a diffuser is attached to a jet engine. Generalized thermodynamic and aerodynamic analyses are available that may be used to calculate the changes in these parameters provided that the jet stream conditions at the nozzle can be specified. Unfortunately, generalized procedures for the determination of nozzle conditions from physical properties of the diffuser are not yet available. The changes in engine operating conditions may not be important in Air Training Command Facilities. However, they may be extremely important in Air Materiel Command overhaul facilities and in production test facilities. The effects of the jet stream modifier on the engine operating conditions should be studied carefully before selecting a specific type of jet stream modifier (see Ref 7).

The important acoustical characteristic which should be investigated is the change in acoustic power level afforded

by the modifier. Frequently, only the noise reduction at 40° - 50° from the jet stream axis is reported for these devices. This noise reduction will almost inevitably be greater than the reduction in power level. For most exhaust diffusers, the noise reduction at 40° - 50° from the jet stream axis will be about 5 to 10 db more than the power level reduction. If the noise field around the engine-diffuser combination is essentially non-directive, then the power level reduction will be about 7 db less than the noise reduction at 40° - 50° .

APPENDIX F
 PROCEDURES FOR CALCULATING THE REQUIRED CROSS-
 SECTIONAL AREA FOR AN ENGINE TEST FACILITY

The weight flow of air required to cool the exhaust gases of a jet engine from some initial temperature T_j to a final temperature T_f can be found from the conservation of heat energy. The heat energy absorbed by the cooling air must equal the heat energy lost from the jet gases. The appropriate relation is then:

$$c_{pj}m_j (T_j - T_f) = c_{pc}m_c (T_f - T_c) \quad (F-1)$$

in which c_{pj} is the specific heat at constant pressure for the exhaust gases of the jet engine
 m_j is the weight flow through the jet engine
 T_j is the temperature of the exhaust gases of the jet engine
 T_f is the final temperature of the mixture of the cooling air and the exhaust gases
 c_{pc} is the specific heat at constant pressure for the cooling air
 m_c is the weight flow of cooling air
 T_c is the temperature of the cooling air to the test cell.

Solving for m_c yields:

$$m_c = m_j \frac{c_{pj}}{c_{pc}} \left[\frac{T_j - T_f}{T_f - T_c} \right] \quad (F-2)$$

The total mass flow m_t is

$$= m_j \left[1 + \left(\frac{c_{pj}}{c_{pc}} \right) \left(\frac{T_j - T_f}{T_f - T_c} \right) \right] \quad (F-3)$$

The specific heat of the exhaust gases of the jet engine depends upon the specific heat of air, the specific heat of the fuel, usually JP-4, and the fuel-air ratio. Reference 22 shows the appropriate relation to be:

$$c_{pj} = \frac{c_{pa} + f c_{pf}}{1 + f} \quad (F-4)$$

in which c_{pj} is the specific heat of the exhaust gases of the jet engine

c_{pf} is the specific heat of the burned fuel, and

f is the fuel-air ratio

Reference 21 shows that the c_{pf} is about 0.697 at 1600°R (the appropriate exhaust gas temperature) and about 0.560 at 900°R. The average value of c_{pf} through the mixing process is taken to be the average of these two values or 0.628. The exhaust air which passes through the jet engine has a specific heat capacity, c_{pa} , of about 0.267 and 0.246 at 1600°R and 900°R, respectively. Thus the average specific heat of the exhaust air in the cooling process is about 0.256. Assuming a specific fuel consumption of 0.8 lbs per hour per lb of thrust for a typical 10,000 lb J57, and a mass flow of 170 lbs/sec, one finds the fuel-air ratio to be about 1.2×10^{-2} . Using these values in Eq F-4 one finds c_{pj} to be 0.261. The specific heat of the cooling air c_{pc} is about 0.24 at an ambient temperature of 70°F (530°R) and increases to 0.246 at 910°R at the end of the mixing process. The average value of the specific heat of the

cooling air is taken to be the average value of these two numbers or 0.243. The ratio c_{pj}/c_{pc} is therefore 1.07. Thus the cooling air required is 7% larger than the value which would be obtained if one neglected the difference between the specific heat of air and the specific heat of the exhaust gas mixture and in addition neglected the variation of specific heat with temperature. For the reference test facility, the assumed initial temperature is 1150°F. The assumed final temperature of the mixture of cooling air and exhaust gases is 450°F and the ambient temperature of the cooling air is 70°F. Equation F-2 now becomes:

$$\begin{aligned} m_c &= m_j \times 1.07 (1150 - 450) / (450 - 70) \\ &= m_j \times 1.97 \end{aligned} \quad (F-5)$$

thus

$$\begin{aligned} m_t &= m_j + m_c \\ &= 2.97 m_j \end{aligned} \quad (F-6)$$

The required open area is

$$S_o = m_t / \rho v \quad (F-7)$$

in which m_t is the total air mass flow through the test cell

ρ is the density of the gases flowing through the intake, and

v is the linear velocity of the gases through the open area S_o .

For a standard NACA sea level day, ρ is approximately 7.64×10^{-2} lb/ft³ in the intake treatment. The maximum allowable velocity in the intake treatment has been set at 50 ft/sec, so that:

$$S_o = 2.97 m_j / (7.64 \times 10^{-2}) \quad (50)$$

\doteq 0.775 sq ft of open area for each pound of
mass flow through the jet engine (F-8)

Thus, the total cross section is about one and one-half sq ft for each pound of mass flow through the engine (assuming the treatment occupies one half of the total cross section).

<p>Aeronautical Systems Division Aerospace Medical Laboratory Wright-Patterson AFB, Ohio, Rpt. No. WADC-TR-58-202 (2). NOISE CONTROL FOR AIR-CRAFT ENGINE TEST CELLS AND GROUND RUN-UP SUPPRESSORS. Vol. 2. Design and Planning for Noise Control. Final report, Nov. 1961, xiii + 192 pp, incl. illus., tables, 22 refs. This is part 2 of 3 parts. Unclassified report</p> <p>This volume is the second in a series of three volumes on the physical aspects of noise control in aircraft engine test cells and ground run-up suppressors. This volume provides methods for planning and designing engine test cell facilities. Procedures are presented for determining noise reduction requirements of an aircraft engine test cell from the noise source characteristics, the acoustic criteria and the location. The reference test cell concept is used. Procedures for designing a facility to meet these noise reduction requirements are presented. The analysis and design of ground run-up noise suppressors are similarly treated, but in less detail.</p>	<p>Aeronautical Systems Division Aerospace Medical Laboratory Wright-Patterson AFB, Ohio, Rpt. No. WADC-TR-58-202 (2). NOISE CONTROL FOR AIR-CRAFT ENGINE TEST CELLS AND GROUND RUN-UP SUPPRESSORS. Vol. 2. Design and Planning for Noise Control. Final report, Nov. 1961, xiii + 192 pp, incl. illus., tables, 22 refs. This is part 2 of 3 parts. Unclassified report</p> <p>This volume is the second in a series of three volumes on the physical aspects of noise control in aircraft engine test cells and ground run-up suppressors. This volume provides methods for planning and designing engine test cell facilities. Procedures are presented for determining noise reduction requirements of an aircraft engine test cell from the noise source characteristics, the acoustic criteria and the location. The reference test cell concept is used. Procedures for designing a facility to meet these noise reduction requirements are presented. The analysis and design of ground run-up noise suppressors are similarly treated, but in less detail.</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Acoustics 2. Jet Engine Noise 3. Damping 4. Ground Support Equipment <ol style="list-style-type: none"> I. ARDC Project 7210 Task 71708 II. Biomedical Laboratory III. Contract AF 33 (616)-3335 Contract AF 33(616)-3938 <p>UNCLASSIFIED</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Acoustics 2. Jet Engine Noise 3. Damping 4. Ground Support Equipment <ol style="list-style-type: none"> I. ARDC Project 7210 Task 71708 II. Biomedical Laboratory III. Contract AF 33 (616)-3335 Contract AF 33(616)-3938 <p>UNCLASSIFIED</p>
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