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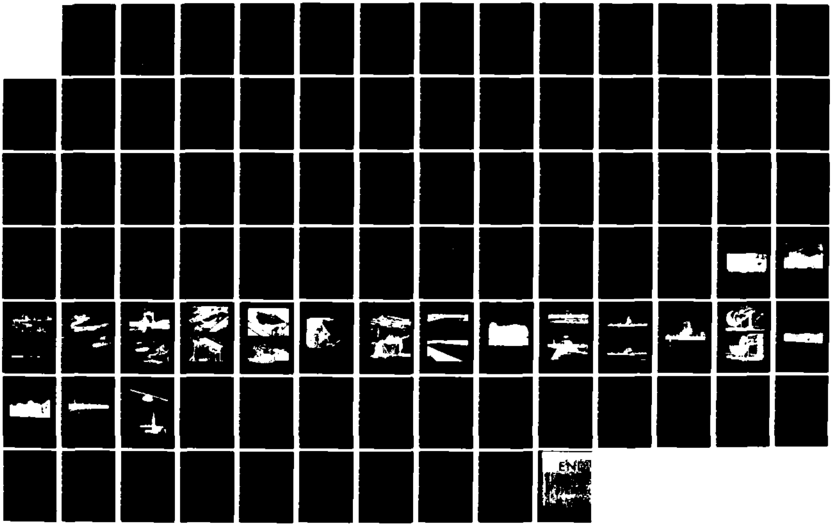

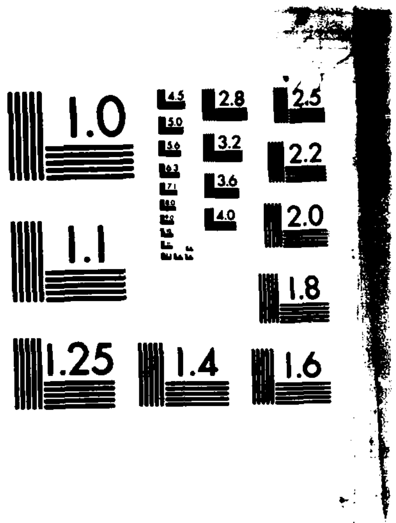

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NATIONAL BUREAU OF STANDARDS-1963-A

FAA/EE-82-11, Volume 2

Office of Environment
and Energy
Washington, D.C. 20591

Study of Noise-Certification Standards for Aircraft Engines

Volume 2: Procedures for Measuring Far Field Sound Pressure Levels Around An Outdoor Jet-Engine Test Stand

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June 1983

Final Report

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It is a pleasure to acknowledge the cooperation of the engine and airplane manufacturers, the NASA Lewis Research Center, and the NASA Ames Research Center in supplying technical information about their engine test stands. The many suggestions and comments from the author's colleagues Robert L. Chapkis and Gary L. Blankenship are also acknowledged.

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16. Abstract

This study, reported in three volumes, had the purpose of considering the feasibility of establishing an FAA requirement for a manufacturer of aircraft engines to demonstrate compliance with an engine noise-level standard in order to obtain an engine-noise type certificate. The objective of engine-noise type certification (if feasible on the basis of economic reasonableness, technological practicality, and appropriateness to the type design) would be to supplement the aircraft-noise type certification requirements in Part 36 of the Federal Aviation Regulations. The scope of the study was limited to aircraft turbofan engines.

Volume 2 describes the general characteristics of 16 outdoor engine test stands used by 11 organizations for measurements of engine noise levels. Instruments and microphone installations are also described. Recommendations are presented for test procedures to measure farfield sound pressure levels around a turbofan engine mounted on an outdoor test stand. After adjusting the measured data to common reference conditions, the test results should be suitable for demonstrating compliance with the requirements for a static-engine noise type certificate.

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METRIC CONVERSION FACTORS

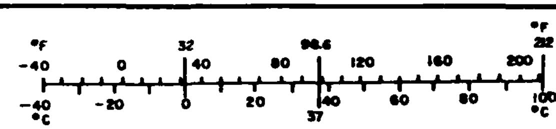
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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STUDY OF NOISE-CERTIFICATION STANDARDS FOR AIRCRAFT ENGINES

VOLUME 2: PROCEDURES FOR MEASURING FARFIELD SOUND PRESSURE LEVELS AROUND AN OUTDOOR JET-ENGINE TEST STAND

INTRODUCTION

This report is the second in a three-volume series that presents results of a study of the feasibility of establishing federal standards to limit the level of noise produced by jet engines. If issued, the standards would be part of a requirement for an engine manufacturer to obtain a noise type certificate for an engine in addition to the basic engine airworthiness type certificate. The Introduction to Volume 1 [1][1] provides additional background information on the study.

To demonstrate compliance with noise-certification standards, the engine manufacturer would conduct tests to measure farfield sound pressure levels produced by an engine of a type for which a certificate is desired. To provide meaningful results, as well as fair and equitable treatment for all manufacturers, the tests should be conducted in accordance with specific test procedures. The subject of this report is the development of recommendations for procedures to measure sound pressure levels around a jet engine designed to provide thrust for airplane propulsion and installed on an outdoor engine test stand.

Organizations in the USA, England, and France that were known to operate outdoor engine test stands were contacted to determine information related to the general characteristics of their test facilities and associated measurement instruments. The purpose of contacting the organizations was to ensure that the recommendations for the test procedures would be generally compatible with existing capabilities. The second and third sections of this report present the results of those surveys.

The fourth section of the report contains a discussion of technical issues involved in developing recommended procedures for measuring farfield engine noise levels. A resolution for each issue is suggested. An Appendix to the report presents the major elements of the recommended procedures for the measurement of farfield sound pressure levels around an outdoor engine test stand.

[1]Bracketed numbers refer to documents listed in the References Section.

SURVEY OF GENERAL CHARACTERISTICS OF OUTDOOR ENGINE TEST STANDS

Eleven organizations were determined to have outdoor engine test stands suitable for the measurement of farfield sound pressure levels under controlled conditions. Each of the eleven organizations had conducted several engine-noise measurement programs, some since the mid 1950s.

The eleven organizations consisted of three categories of manufacturers and two research centers of the National Aeronautics and Space Administration (NASA). The organizations were:

engine manufacturers:

Avco Lycoming Division of the Avco Corporation
Garrett Turbine Engine Company*
General Electric Company
Pratt & Whitney Aircraft Group of United Technologies Corporation
Rolls Royce Limited
SNECMA †

engine nacelle manufacturer:

Rohr Industries Incorporated

airplane manufacturers:

Boeing Commercial Airplane Company
Douglas Aircraft Company of the McDonnell Douglas Corporation

NASA:

Ames Research Center
Lewis Research Center

Each organization was contacted to obtain information about their test stand's general characteristics relevant to engine noise measurements. Recent photographs were also obtained to help document the configuration of the test stand and the surrounding area.

Information obtained from the survey of general characteristics is summarized in Table 1. The data are current as of March 1982 and represent existing or, in the case of Rolls Royce, planned capabilities for sixteen engine-noise test facilities.

From left to right, the first five of the twelve items listed on each sheet of Table 1 are for identification or general interest. The thrust capacity in the fifth column is the limit on the maximum thrust that can be measured.

The height of the engine centerline above the ground plane and whether a device was available and usually installed around the engine's inlet duct to control atmospheric turbulence and steady (repetitive) distortion in the airflow into the inlet are considerations in measurement of the noise produced by the fan stage of turbofan engines.

*formerly known as the AiResearch Manufacturing Company of Arizona
†Société Nationale d'Étude et de Construction de Moteurs d'Aviation

The eighth, ninth, and tenth items describe meteorological or climatic conditions and their measurement. Temperature, humidity, wind speed, and wind direction were usually measured.

Test stand elevation above sea level is a consideration during a test because less-dense air at a high elevation may prevent the attainment of sea-level takeoff thrust except at higher values of engine shaft speed. Less-dense air may affect the level of noise generated by many sources of engine noise, a factor that should be accounted for during data analysis. Local climatic conditions can limit the number of available test days per year and have a significant impact on test schedules and costs.

The eleventh and twelfth items provide information relevant to a program for engine noise measurements. The location for the engine, or facility, reference point is often used to specify the locations for the microphones. If the microphones are those designed to have their flattest frequency response at 0° incidence, then the reference point (or its vertical projection) was often used to establish the orientation of the microphones.

In Table 1, the plan view sketches show a few of the major features of the test stands, particularly the shape, type, and extent of the defined ground surface over which sound from the engine propagates to microphones located along various geometric arrays. All sketches were drawn to the same scale. Dimensions are in meters.

For acoustical tests, all test stands, except for the facilities of Avco Lycoming and Rolls Royce, were fixed to a foundation such that the engine inlet was always oriented in the same direction and sound pressure levels were always measured on the same side of the engine. Test engines were mounted on a rotatable support or turntable at the Avco Lycoming test stand and will be so mounted at the new Rolls Royce test stand.

For the fourteen fixed-orientation test stands, the direction of jet-exhaust is to the right in the plan-view sketches as indicated by the arrowhead on the horizontal centerline. The engine reference point, or test-facility reference point, is indicated by a short vertical bar on the centerline.

The Garrett (AiResearch) facility had a concrete pad with asphalt paving around the concrete. Microphones were located over a sloping dirt surface that extended beyond the asphalt, see Fig. 1.

The Avco Lycoming facility had an asphalt surface between the engine and the microphones as shown by the views in Fig. 2.

The T1 stand at Boeing's Tulalip test site and the B150 stand at Rohr's Brown Field test site had trap-rock covering the ground between the engine and the microphones. The concept of using a surface consisting of a layer of small pieces of angular broken rock originated several years ago as an attempt to provide irregular ground reflections. The irregularity of the direction of sound waves reflected from the pieces of broken rock was intended to permit mast-mounted microphones to obtain measurement of the sound produced by an engine with negligible spectral distortion caused by phase differences between direct and reflected sound waves. Figure 3 illustrates a trap-rock surface at Rohr's B150 stand. Trap-rock surfaces are no longer in wide use for engine noise testing.

The most-common surface between the engine and the farfield microphones was smooth concrete. Eleven of the sixteen engine noise test facilities listed in Table 1 had a concrete surface over which sound pressure levels were measured. A concrete surface helps provide repeatable test conditions and reproducible test results. The light color of concrete minimizes solar heating of the surface and the associated temperature inhomogeneities near the surface. The sealed asphalt surface at the new Rolls Royce test bed No. 11 will be painted white. See the sketch in Table 1(d).

Figures 4 to 10 illustrate salient features of some of the engine noise test facilities that had concrete ground surfaces. The facilities include those of Boeing (Figs. 4 and 5), McDonnell Douglas (Fig. 6), General Electric (Figs. 7 and 8), Pratt & Whitney Aircraft [P&WA] (Fig. 9), and Rohr (Fig. 10).

The NASA-Ames test facility, Fig. 11, had a central area with steel plates covering a pit. The steel plates were surrounded by a concrete surface. The region beyond the concrete was asphalt. Microphones were usually placed over the concrete surface.

A variety of designs have been developed for devices to control steady distortion as well as atmospheric turbulence in the airflow into an engine's inlet. Most designs made use of honeycomb material. Some of the devices intended for use around large-diameter engines are large structures as shown by the photographs in Fig. 12 and 13 of an inflow-control device around a P&WA JT9D test engine, and in Figs. 14(a) and 14(b) for an inflow-control device around GE CF6 and CF34 engines.

SURVEY OF INSTRUMENTS AND PROCEDURES

Additional information related to engine noise testing was obtained to supplement the general characteristics presented in Table 1 for outdoor test stands. The additional information was all related to acquisition of acoustical data and was for two major components of a sound-measurement system (micropbones and tape recorders). Comments on test limitations for wind speed or community noise constraints were also sought. The results from the survey of test instruments and test limitations are presented in Table 2 for each of the sixteen test stands covered in Table 1.

Microphone data shown in Table 2 were intended to reveal the basic capability of a test facility to measure farfield sound pressure levels as well as to illustrate current practice as of the date of the survey (revised to March 1982). Data were obtained on (1) the number of microphones that were available to measure sound pressure levels and how they were installed (on masts or near the ground plane), (2) the location of the microphone positions in the acoustic farfield where measurements were typically made and at what height above the ground plane, (3) the type of microphone used for each installation and its orientation, and (4) the angular spacing typically provided between microphones for resolution of sound directivity patterns.

The data in Table 2 illustrate the diversity of the approaches that have been employed to measure farfield engine noise levels. They also indicate some remarkable similarities. The following observations were made:

- all microphones were capacitor-type measurement microphones with air as the dielectric between the diaphragm and backplate
- for the microphones at all facilities except the Douglas QIAETsite facility, the dc voltage required to charge the microphone's capacitance was supplied by an external source
- at the Douglas QIAETsite facility, two types of measurement microphones were used: (1) the same type as used at the fifteen other facilities where the capacitor's charge is provided by an external source of dc voltage, and (2) the newer type where the charge is provided by a polarized electret material on the backplate between the backplate and the diaphragm
- all microphones had a 13-mm nominal diameter [NASA-Ames also had some 6-mm-diameter microphones available to supplement their supply of 13-mm-diameter microphones]
- microphones were either mounted on masts so that they could be at the height of the engine centerline [or higher, or both], or were located near the ground plane
- microphones were either those that have their best frequency response for sound in a free field impinging on the diaphragm at an incidence angle of 0° [i.e., normal incidence], or those that have their best frequency response for sound impinging on the diaphragm at random incidence angles [Since the response in a free field at an incidence angle of 90° (or grazing incidence) is approximately equal to random-incidence response, the random-incidence microphones were usually oriented so that sound from the sources of engine noise would arrive at grazing, or near-grazing, incidence.]
- a polar array with microphones positioned along circular arcs centered on the engine reference point [or its projection onto the ground plane, or a facility reference point in the ground plane] was employed for most measurements of engine noise
- supplemental measurements of engine noise were often made by positioning microphones along a line parallel to the engine centerline, especially for locations in the rear quadrant where effective sources of jet noise are distributed along the jet axis and can extend a long distance downstream from the nozzle exit plane
- a consensus agreement did not appear to exist on how far from a given engine the microphones should be located to be assured that every microphone was in the acoustic far field at each frequency of interest, for either the polar or the sideline array
- some organizations used windscreens around their microphones at all times regardless of self-imposed limits on wind speed; most organizations, however, did not use windscreens and appeared to rely on a limitation of the average test-time wind speed to avoid wind effects on sound pressure level measurements or engine operation
- the typical angular spacing of microphones along the polar or sideline arrays permitted a sound directivity resolution of 10°, though the capability existed at most facilities for a finer resolution; a 5° spacing was routinely used by some organizations in regions of maximum sound pressure levels

The two types of microphone installations (i.e., mast-mounted and ground-plane) and the two types of microphone designs (0° and 90°) provide four choices. Table 3 summarizes how the various organizations had made their choices as of the date of the survey.

For the mast-mounted microphones, the choice was approximately equally divided between 0°-incidence installations (point the microphones at the "source") and 90°-incidence installation (point the microphones up for grazing incidence). Grazing-incidence installations are shown in Figs. 9, 13 and 15; installations of 0°-incidence microphones are shown in Figs. 1, 16, and 17.

For the ground-plane microphones, six out of ten organizations used 90°-incidence installations with a vertical-axis, inverted-microphone arrangement where the microphone is placed at a distance of the order of one-half to one microphone diameter above, and pointing down at, the ground plane, see Figs. 13, 18, and 19. The ground plane was a large concrete or sealed-asphalt surface. The surface immediately under the microphone was either a thin, flat, metal plate or a smooth, hard-finish coating of special paint applied to the ground plane surface. A horizontal-axis, near-ground arrangement has also been used, see Fig. 17 for example.

MEASUREMENT OF FARFIELD ENGINE NOISE LEVELS

This section discusses issues involved with the development of recommendations for a procedure to measure sound pressure levels around an outdoor engine test stand. The Appendix to this report contains specific recommendations for major items that should be included in a program to record, analyze, and report measurements of farfield sound pressure levels.

Test Purpose

For this study, the purpose of a test to measure engine noise levels was to determine if the noise produced by a test engine conforms to noise standards prescribed in the requirements for engine-noise type certification. Those requirements were assumed to apply to the noise produced by the basic engine, without the influence of airplane-type inlet or exhaust ducts, and operating under static conditions. The engines were assumed to be turbofan engines designed for applications on civil, transport-category or general-aviation airplanes having subsonic cruise speeds.

Other test purposes might include the measurement of differences between the farfield sound pressure levels produced by different engines, on the same test stand or different test stands. Such measurements might be useful as a supplement to an airplane flyover-noise type certification test that had been conducted on one member of a family of airplanes having similar aerodynamic characteristics but different engines.

Another test purpose might be the demonstration of the magnitude of the effect on engine noise resulting from some change made to the engine, to the inlet or exhaust ducts, or to the nacelle around the engine in an airplane installation.

Noise-Evaluation Quantity

The specific objective of an engine-noise certification test as well as many test details depend on the nature of the quantity (or noise measure) selected to evaluate the noise. Different test procedures would be required, for example, if the purpose of the test was to support noise-certification flight tests.

As described more fully in Volume 3, the noise-evaluation quantity recommended for use in engine-noise type certification is based on sound pressure levels measured around a stationary engine and not on projections of the measured data to representative equivalent flight conditions. The choice of static instead of equivalent flight conditions eliminated the need to consider forward-motion effects or the separation of the total spectrum of the sound pressure into spectral components from various sources of engine noise. The use of static conditions also emphasizes the essential difference between an engine-noise type certification and an airplane-noise type certification.

Measured sound pressure levels must be adjusted to reference conditions so that test results can all be reported on a common basis. The reference conditions include those of an acoustic free field. Interference effects in the sound pressure spectra measured by microphones above the ground plane must be removed so that valid comparisons can be made of data measured around any test stand. For the purposes of this report, reference conditions include inlet and exhaust ducts having circular, axisymmetric cross sections so that the sound radiation pattern in the acoustic farfield is symmetric about the engine centerline. A rotationally symmetric sound field is needed so that sound pressure level measurements in one plane through the engine centerline may be sufficient to characterize the sound field at all frequencies in the range of interest.

The particular quantity selected to evaluate the noise produced by an engine was the sound power level, specifically the A-frequency-weighted sound power level. To provide a nondimensional quantity suitable for evaluation of the sound produced by engines over a wide range of thrust classes, the nondimensional ratio of A-weighted sound power to engine propulsive power was investigated. Volume 3 presents the results of that investigation.

In order to be able to evaluate noise levels over the engine's operating range, it was considered that compliance with the requirements for an engine-noise type certifcate would be demonstrated at two engine power settings: referred net thrust at takeoff power (at a thrust value defined by the engine manufacturer) and at 25 percent of the defined takeoff referred net thrust.

"Simple" or "Complex" Test Procedure

For small propeller-powered airplanes, noise-certification tests under Appendix F of Part 36 of the Federal Aviation Regulations are conducted by a relatively "simple" test procedure. The noise-evaluation quantity is the maximum A-frequency-weighted slow-exponential-time-averaged sound level. Sound levels have been measured by a sound level meter having a digital display or a dial and pointer type of indicator. The maximum sound level is noted by an observer as the test airplane flies overhead.

Engine-noise certification tests also could be conducted using a "simple" test procedure similar to that used for Appendix F airplane-noise certification tests. The noise-evaluation quantity could be the wideband or FLAT-weighted sound level or the A-weighted sound level. If read by a conventional sound level meter, the sound level would presumably be read with slow exponential time averaging. The sound level could be controlled in terms of the maximum value that was observed while walking along a geometric path in the acoustic farfield while the engine was operated at prescribed power settings.

While it may be technically feasible to conduct a "simple" test to determine whether an engine conformed to the requirements for noise certification, such a test procedure was rejected in favor of a "complex" test. The "simple" test would not provide detailed information on the spectral content of the sound produced by the engine. The results from various "simple" tests would not likely be as repeatable or reproducible as those from various "complex" tests because measurements by an observer reading a sound level meter might be influenced by the presence of the observer as well as by reflections of sound waves from the ground surface. Neither the effects of the presence of the observer, if present, nor the effects caused by interference between direct and reflected sound waves could be removed from the measurements. Furthermore, the readings of maximum sound level around one engine probably could not be easily adjusted to common reference conditions and thus might not be comparable to measurements of sound levels around other engines.

Outdoor Engine Test Stand or Enclosed Test Cell

The sound power level produced by a test engine could be approximated from measurements of diffuse-field sound pressure levels inside an engine test cell. Engine test cells are enclosed structures often used by engine manufacturers for engine-development testing. However, a test cell is rarely large enough for the microphones to be located in the diffuse part of the sound field at the mid and low frequencies of interest. Moreover, it is usually not practical (or often even feasible) to obtain valid measurements inside a test cell of the sound produced by external jet-mixing processes. Furthermore, no sound-field directivity data are available from measurements inside a test cell.

Although it may have weather-related problems, an outdoor engine test stand was preferred. Sound-radiation patterns can be derived from measurements of farfield sound pressure levels at locations around a properly designed engine test stand. Sound pressure level spectra at various angles often provide useful information about the engine's sound generating characteristics. If the sound field is rotationally symmetric, sound power levels may be readily computed from the farfield sound pressure levels measured on one side of the engine in one plane.

Sound Pressure Levels from the Complete Engine or from Separate Sound Sources

If the noise-evaluation quantity were to be based on equivalent flight conditions, then it might be necessary to determine the spectrum, level, and directivity of noise radiated from the inlet duct and from the fan-discharge duct, of turbine noise, and of jet-mixing noise. Although the noise produced by the complete engine would have to be shown to meet the requirements for certification, knowledge of the spectrum, level, and directivity of the sound from separate "sources" would be needed because the effects of forward motion on spectrum, level, and directivity are not the same for all "sources" of engine noise.

At the time of this study, the technical capability to determine the contribution of the separate sound "sources" by analytical or experimental means was not well established. For research purposes, some organizations have conducted tests (e.g., using special screens or special inlets or exhaust ducts) to isolate and define "source" noise levels for specific noise sources on certain engines.

The recommended test procedures in the Appendix apply to a complete engine and do not include a requirement to determine the sound pressure levels from separate "sources" of engine noise. Application to a complete engine is consistent with the concept of engine-noise type certification being based on static rather than an equivalent "flight" operation.

Configuration of the Test Engine

The internal configuration of the test engine and the configuration of the inlet and exhaust ducts have a major influence on the spectrum, level, and directivity of the farfield sound pressure signals. Therefore, the configuration chosen for the test engine must be consistent with the purpose of the test.

For an engine-noise-certification test, the internal configuration of the engine within the engine envelope should be that for which a type certificate is desired. It should include all the noise-control features sold by the engine manufacturer as components of the basic engine for each airplane application (see Ref. 1).

Items of special concern external to the basic engine are (1) the inlet duct, (2) the exhaust duct(s), and (3) an actual or simulated nacelle around the engine and the inlet and exhaust ducts.

Inlet duct. The inlet's cross-sectional shape, its variation along the axis of the inlet, and the length of the inlet all influence the level and directivity of the noise produced by the fan stage.

If an airplane on which the engine is installed uses an inlet duct that contains struts, or blow-in doors or other variable-geometry devices, or any comparable structural or aerodynamic sources of circumferential distortion in the flow of air into the fan, then the noise produced by the fan stage is likely to be greater than it would be if such items were not present in the inlet duct.

For engine-noise-certification purposes, the inlet duct for the test engine should not contain distortion-producing items even if an airplane installation for the engine does have inlet ducts with such items.

Engine performance tests are often conducted with a bellmouth inlet, sometimes with a bellmouth lip on a cylindrical section, e.g., see Figs. 6(b), 7(b), and 8(b). The minimum flow area is at the front face of the fan. For a civil jet transport, a flight-type inlet duct has the minimum flow area some distance ahead of the fan and a diffuser section from the throat to the face of the fan.

A flight inlet is often not rotationally symmetric. Also, the centerline of the inlet duct may not be in line with the engine centerline, but may be canted down a few degrees. The entrance plane to a flight inlet may not be perpendicular to the duct centerline, but may be canted at an angle to provide better inflow characteristics during critical portions of flight.

If a flight-type inlet duct is installed for a static test, the noise generated by the fan stage may be different from that generated when a conventional static-test bellmouth inlet duct is installed because of differences in the turbulent boundary layer on the wall of the inlet at the tips of the fan rotor blades. The boundary layer on the wall of an inlet duct during a static engine test may be thicker, or more turbulent, or less circumferentially symmetric than the boundary layer on the wall of an actual flight inlet during flight. Additional research is required to establish the need to control the boundary layer on the inlet wall during static engine noise testing.

For engine-noise-type-certification testing, it was considered that the test inlet should be one that does not represent a flight inlet, is not airplane specific, and does not add noise-generating mechanisms and hence increase the noise level of the basic engine. A test inlet should also have one basic shape so that all engine manufacturers receive equitable consideration. The recommended shape is that of an axisymmetric bellmouth, with or without a cylindrical section, and symmetrical about the engine centerline.

The shape and length of the test inlet duct should be determined by the engine manufacturer and approved by the certifying authority.

Exhaust ducts. Because of the variety of designs for aircraft turbofan engines (see Ref. 1), it was not feasible to recommend one set of general characteristics for appropriate shapes or lengths for the fan-exhaust duct or the turbine-exhaust duct. However, if the engines were divided into certain classes, some general recommendations could be made that were applicable to all engines in a class. The definition for a class should consider the basic design of the engine as well as its installation on certain airplanes. All models of a given engine type would be included within each class.

One possible set of engine classes is the following four with engines that were described in Ref. 1:

(1) fan stage as the first stage of the low-pressure compressor; single exhaust nozzle discharging a mixture of fan and turbine-exhaust flows; turbine-exhaust flow discharged through separate nozzles within the common-flow exhaust duct (e.g., ATF3-6)
(2) fan stage as part of the low-pressure turbine; separate exhaust nozzles for discharge of fan and turbine exhaust flows (e.g., CF700 and CJ805-23)
(3) fan stage as the first stage of the low-pressure compressor; single exhaust nozzle discharging a confluent mixture of fan and turbine-exhaust flows; turbine-exhaust flow discharged through a round, convergent nozzle or a flow-mixing nozzle (e.g., JT8D)
(4) fan stage as the first stage of the low-pressure compressor; separate exhaust nozzles for discharge of fan and turbine exhaust flows (e.g., JT15D, TFE731, ALF-502, CF34, JT3D, CFM56, RB.211, CF6, JT9D, and PW2037)

In general, it is preferred that the nozzles have a fixed, round, convergent shape, except where prohibited by a requirement to fair around engine accessories [e.g., as on the JT3D] or around the structure that supports the engine from the test stand. Relatively short fan-exhaust ducts are preferred over

mid-length, long, or confluent-flow fan-exhaust ducts for the separate-flow engines in classes 2 and 4. Engines in classes 1 and 3 should be tested with a mixed-flow nozzle on the test exhaust duct.

The test exhaust ducts should not necessarily attempt to simulate the shape or lengths of exhaust ducts for an airplane installation. External plugs in the exhaust nozzle, as an extension of the fairing over the shaft hub, may be included if so installed in every application for the engine. Airplane-specific items such as thrust reversers should not be included within the test exhaust ducts.

The design for the test exhaust ducts should be developed by the engine manufacturer and approved by the certifying authority.

Duct linings. For many turbofan engines intended for installation on civil jet transports, the inlet and exhaust ducts as installed will contain sound-absorbing linings on surfaces within the ducts. The linings may provide a large part of the control for noise generated by the fan and turbine stages.

For some engines, the engine manufacturer may design the linings that are then fabricated and installed in the inlet and exhaust ducts made by another manufacturer [e.g., a nacelle manufacturer]. The engine with ducts and nacelle is then shipped to the airplane manufacturer for installation on the airplane.

However, even though the engine manufacturer may have total responsibility for the design of the sound absorbing duct linings for some airplane installations [including financial responsibility], for engine-noise type certification tests, it is recommended that sound-absorbing linings not be installed within the test inlet and exhaust ducts, except when they are an integral part of the basic engine. The engine-noise type certificate will then pertain to the noise produced by the basic engine and thus provide a means for evaluating the noise-control features included by the engine manufacturer within the engine.

Another reason for not installing sound-absorbing linings within the test inlet or exhaust ducts is that some engines are quiet enough that the airplanes on which they are installed can meet the most-stringent of current aircraft noise standards without sound-absorbing linings in the inlet or exhaust ducts. Engines for business-jet aircraft, for example, have fundamental fan blade-passage frequencies at takeoff power that exceed 4000 Hz, some exceed 7000 Hz. For those airplanes, the engines are usually mounted on the sides of the fuselage and the combination of the shielding provided by the wings and flaps and the attenuation provided by atmospheric absorption at high frequencies is sufficient to permit some newer designs of business jets to achieve low levels of fan and turbine noise without the use of noise-control design features other than those incorporated within the basic engine.

Since the installation of sound-absorbing linings provides noise reduction that would not be present when some engines of a certain thrust class are installed on an airplane, it was considered that an equitable arrangement would be to not permit the installation of sound-absorbing linings in any test inlet or exhaust ducts. Linings that are included by the engine manufacturer within the engine envelope, as basic components of every engine, should be in place during the noise-certification test.

Nacelle. When an engine is installed on an airplane there is a nacelle around the outside of the inlet duct, fan case, fan-exhaust duct, engine case, and turbine-exhaust duct. The nacelle provides a contoured aerodynamic shape to minimize drag and to protect engine accessories.

Some noise may be transmitted through the structure of the inlet duct, fan case, fan-exhaust duct, and engine case. The nacelle attenuates the noise transmitted through the structure of those components, the degree of attenuation depending on the details of the structural configurations.

It was not considered to be practical to specify the design for a standard nacelle that should be installed around an engine during a static noise-certification test. Therefore, it was recommended that engine-noise-certification tests be conducted without simulated nacelle components around the test engine. The structure of an engine nacelle may, however, be simulated and installed downstream of the exit of the nozzle on short fan-exhaust ducts (e.g., on class 4 engines) if necessary to prevent fan-exhaust flow from impinging on engine accessories or components.

Test Site and Engine Test Stand

Ideally, the measurements of sound pressure signals in the farfield should be free of any significant influence caused by reflections or scattering from natural objects or structures at the test site. The structure of the engine test stand should have negligible influence on the generation of sound by the engine or the subsequent radiation of sound to the farfield microphones.

The ground surface between the engine and the farfield microphones is an important consideration in determining the repeatability and reproducibility of the sound pressure level measurements. It is desirable for the acoustic impedance of the ground surface to be uniform and the same at all test stands on every day of the year. A hard-troweled, smooth concrete surface, or equivalent, is recommended. During daytime hours, the light color of the concrete surface also helps to reduce temperature fluctuations and the associated inhomogeneities in the air through which the sound propagates to the microphones. A dirt surface is not recommended but could be suitable providing the acoustic impedance was determined at the time of the tests and the difference between the acoustic impedance of the dirt surface and that of a smooth, hard surface was accounted for, by an approved procedure, during data analysis.

Experience in engine noise testing that was acquired in the 1970s, as documented in Tables 1 to 3 and Figs. 1 to 19, permitted the development of the recommendations in the Appendix for a test site and an engine test stand.

The height of the engine above the ground plane is an important consideration in the generation of fan noise. Wind and solar heating of the ground cause turbulent inhomogeneities in the air near the ground. The inhomogeneities can introduce distortions in the airflow into the engine and increase the noise produced by the fan compared with the noise that would be generated if the inlet airflow were free of distortions.

To minimize the effect of inflow distortions caused by turbulence in the air near the ground surface, the test stand should be tall enough that the height of the engine centerline is at least 1.5 times the estimated diameter of the largest fan stage likely to be tested.

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For some engines, the engine manufacturer may design the linings that are then fabricated and installed in the inlet and exhaust ducts made by another manufacturer [e.g., a nacelle manufacturer]. The engine with ducts and nacelle is then shipped to the airplane manufacturer for installation on the airplane.

However, even though the engine manufacturer may have total responsibility for the design of the sound absorbing duct linings for some airplane installations [including financial responsibility], for engine-noise type certification tests, it is recommended that sound-absorbing linings not be installed within the test inlet and exhaust ducts, except when they are an integral part of the basic engine. The engine-noise type certificate will then pertain to the noise produced by the basic engine and thus provide a means for evaluating the noise-control features included by the engine manufacturer within the engine.

Another reason for not installing sound-absorbing linings within the test inlet or exhaust ducts is that some engines are quiet enough that the airplanes on which they are installed can meet the most-stringent of current aircraft noise standards without sound-absorbing linings in the inlet or exhaust ducts. Engines for business-jet aircraft, for example, have fundamental fan blade-passage frequencies at takeoff power that exceed 4000 Hz, some exceed 7000 Hz. For those airplanes, the engines are usually mounted on the sides of the fuselage and the combination of the shielding provided by the wings and flaps and the attenuation provided by atmospheric absorption at high frequencies is sufficient to permit some newer designs of business jets to achieve low levels of fan and turbine noise without the use of noise-control design features other than those incorporated within the basic engine.

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It was not considered to be practical to specify the design for a standard nacelle that should be installed around an engine during a static noise-certification test. Therefore, it was recommended that engine-noise-certification tests be conducted without simulated nacelle components around the test engine. The structure of an engine nacelle may, however, be simulated and installed downstream of the exit of the nozzle on short fan-exhaust ducts (e.g., on class 4 engines) if necessary to prevent fan-exhaust flow from impinging on engine accessories or components.

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The ground surface between the engine and the farfield microphones is an important consideration in determining the repeatability and reproducibility of the sound pressure level measurements. It is desirable for the acoustic impedance of the ground surface to be uniform and the same at all test stands on every day of the year. A hard-troweled, smooth concrete surface, or equivalent, is recommended. During daytime hours, the light color of the concrete surface also helps to reduce temperature fluctuations and the associated inhomogeneities in the air through which the sound propagates to the microphones. A dirt surface is not recommended but could be suitable providing the acoustic impedance was determined at the time of the tests and the difference between the acoustic impedance of the dirt surface and that of a smooth, hard surface was accounted for, by an approved procedure, during data analysis.

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To minimize the effect of inflow distortions caused by turbulence in the air near the ground surface, the test stand should be tall enough that the height of the engine centerline is at least 1.5 times the estimated diameter of the largest fan stage likely to be tested.

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To minimize the effect of inflow distortions caused by turbulence in the air near the ground surface, the test stand should be tall enough that the height of the engine centerline is at least 1.5 times the estimated diameter of the largest fan stage likely to be tested.

Even though the test stand is designed to have the engine centerline as high above the ground plane as possible, some turbulence will still be present in the air that enters the engine inlet. The inlet airflow may also contain vortices caused by airflow around structural components of the test stand and over the ground. When the engine is operating at a constant power setting, those vortices may remain at essentially one circumferential location and hence act as a source of "steady" distortion unlike the atmospheric turbulence which always varies in circumferential location and axial extent. Sources of steady distortion can cause once-per-revolution disturbances in the pressure field on the fan blades.

For tests of some turbofan engines (particularly those with single-stage fans and a low-noise design), an inflow-control device may be placed around the inlet duct to reduce the influence of atmospheric turbulence and vortices on sound generated by the fan stage. For those engines, use of an inflow-control device should yield more-repeatable and more-reproducible measurements of noise generated by the fan stage. [In the technical literature, inflow-control devices have also been called inflow-control structures and turbulence-control structures.]

Inflow-control devices may be constructed from honeycomb, screens, or similar materials. Information on the design of inflow-control devices is available in Refs. 2 and 3.

Meteorological Conditions

Meteorological conditions prevailing at the time of the tests affect (1) propagation of sound waves from the engine to the microphones, (2) the operation of the acoustical test instruments, and (3) the operation of the engine. The adjustments of the measured sound pressure levels to the atmospheric absorption for an acoustic reference day could be relatively large at high frequencies, even for the relatively short propagation pathlengths, if the test-time conditions are extremely absorptive. Small adjustments to the measured data may also be required if the acoustic impedance of the air is significantly different from that under acoustic reference conditions.

Atmospheric conditions that are extremely absorptive, however, would probably seldom occur in practice during an engine noise test. Therefore, the recommended limitations on allowable test-time meteorological conditions were aimed primarily at minimizing the effects of temperature, humidity, and wind on the instruments used to measure sound pressure signals and at minimizing the effects of winds on stable engine operation.

A low-temperature limit of -10° C was recommended to avoid practical problems with instruments and equipment at temperatures well below freezing. No upper limit on test-time air temperature was considered necessary because all high-quality acoustical test instruments should be able to operate satisfactorily at the highest environmental air temperature likely to be encountered at an outdoor engine test stand.

It is noted, however, that the accuracy of atmospheric absorption calculations is not as good at air temperatures less than 0° C as at temperatures above freezing where the moisture content of the air is generally greater. Also, when the air temperature is high (e.g., greater than 30° C), the engine may not be able to produce the desired thrust at the takeoff power setting, especially at high elevations above sea level, because of the lower density of the air. Data recorded under hot-day conditions may need special treatment to determine accurate adjustments to reference conditions.

For test-time relative humidity, it was considered that there was no need to specify any limitations except an upper limit of 95 percent, without condensation, in order to avoid moisture problems with the instruments, especially capacitor microphones and cable connectors. Humidity problems may be more severe for ground-plane than for mast-mounted microphones, especially in the early-morning and nighttime hours.

The speed and direction of the wind affect the propagation and measurement of sound and the operation of the engine. Wind blowing over a microphone may cause a series of short-duration transient signals as well as broadband noise from turbulence in the wind. Wind-induced noise can be reduced by enclosing the microphone within some form of windscreen. The direction of the wind affects the amplitude of the sound pressure signals received at the microphones. Wind-induced turbulence in the air near the ground plane can cause large fluctuations in the amplitude of the signal at a ground-plane microphone because of phase changes associated with refraction of sound waves propagating through the turbulence. Reference 4 recommends a limit on the average wind speed of 3.7 m/s (7 knots) when using ground-plane microphones.

If the wind direction is other than a headwind into the engine inlet (or within some range such as ±45° of a headwind), then the allowable maximum average wind speed may have to be reduced to preserve the stability of engine operation. Some turbofan engines can tolerate only a very small tailwind component. Greater crosswinds may be tolerated if an inflow-control device is placed around the engine's inlet duct (see Ref. 2).

Although each test may have different needs, it is generally recommended that the time-average wind speed (averaged over the duration of the sound pressure recordings) not exceed 5 m/s (10 knots) with short-term wind gusts not greater than 10 m/s (20 knots). At those wind speeds, the preferred wind direction is within ±45° of a headwind directly into the engine inlet. Specific wind limits depend on the choice of acoustical test instruments, whether or not windscreens are used around the microphones, whether or not ground-plane microphones are used, on the sensitivity of the particular test engine to crosswinds or a tailwind, and whether an inflow-control device is installed around the engine.

Frequency Range of Interest

The frequency range of interest is an important element in selection of the noise-evaluation quantity. It is also a major consideration in the selection of acoustical test instruments and data analysis. The frequency range of interest is a factor in determining where to locate the microphones since each microphone should be in the acoustic farfield at all frequencies of interest.

The sound pressure recordings will be analyzed by 1/3-octave-band filters. The recommended frequency range of interest is that covered by 1/3-octave-band frequencies from 50 Hz to 10 000 Hz, i.e., from approximately 45 Hz to 11 000 Hz.

Farfield Conditions

For the purpose of noise-certification testing, sound-measurement positions should always be far enough away from the test engine that the microphones are in the acoustic farfield at all frequencies of interest. When the measurement positions are in the farfield at all frequencies of interest and no significant sound energy from the engine is reflected to the microphones, then the particle velocity of the outward propagating sound waves will be primarily in the direction of propagation and the time-average sound intensity will decrease in proportion to the square of the distance from the effective center of the sources of sound.

The sound pressure level of the signal in a free farfield environment will decrease by 6 dB for every doubling of the distance from the effective source, ignoring atmospheric absorption and other frequency-dependent attenuation mechanisms. In a free farfield environment, the average sound intensity, and hence the sound power, may be calculated with good accuracy from the mean square sound pressure.

Analyses of the radiation of sound from various types of sound sources (see for example chapter 4 of Ref. 5) indicate that a measurement position can be assumed to be in the farfield if the radial distance r from the effective acoustic center of the sound source is large with respect to a typical source dimension b [the geometric criterion] and is also large with respect to the wavelength λ [the acoustical criterion]. Analyses and many experiments have indicated that the criterion for "large" should be at least a factor between three and ten. To provide a conservative estimate, a minimum factor of eight is recommended giving as criteria $r > 8b$ and $r > 8\lambda$. The criteria should be evaluated at the lowest frequency of interest for the sound radiated from the test engine.

The minimum distance needed to satisfy the acoustical criterion is a function of the spectrum of the sound produced by the test engine. If the engine produces significant acoustic power at frequencies as low as those included within the one-third-octave band centered at 50 Hz where the lowest frequency of interest is approximately 40 Hz, then the longest wavelength of interest is approximately 8.6 m when the speed of sound is 343 m/s. The minimum radial distance from the effective source of sound at 40 Hz should then be approximately 69 m. At 60 Hz, the minimum radial distance should be approximately 46 m; at 100 Hz, it should be approximately 27 m, and so on.

The geometric criterion should be evaluated for the source of sound having the largest dimensions. The sources of low-frequency sound will generally have the largest dimensions.

The largest sources of low-frequency sound will usually be those associated with external jet-mixing noise when the engine is operating at its highest engine power setting. The axial extent of the effective source of jet-mixing noise is at least 3 D_e where D_e is the equivalent nozzle diameter associated with the total exit area of the fan and turbine-discharge flows. With that estimate for the low-frequency source dimension, the geometric distance criterion becomes $r > 24\ D_e$ for most frequencies in the range of interest.

For fan noise, the relevant source dimension is the diameter D_f of the fan rotor blades. Depending on bypass ratio, the fan diameter is of the order of 1.5 times the equivalent nozzle exit diameter. Thus, a distance criterion for fan noise that would be comparable to that for jet noise would be $r > 12\ D_f$.

To provide additional assurance that the measurement locations are in the acoustic farfield at most frequencies in the range of interest, the Appendix recommends that the minimum radial distance from an engine reference point be 25 D_e or 15 D_f, whichever is larger.

Microphone Installations and the Determination of Free-Field Sound Pressure Levels

Microphones may be installed on masts, or poles, at some height above the ground plane or they may be installed near the surface of the ground plane.

When a microphone is mounted on a mast, it will receive signals propagated directly from the engine's sound sources and signals that have been reflected to the microphone from the surface of the ground plane. Those two signals will be out of phase because the travel time along the reflected path is longer than along the direct path.

Diffraction effects associated with propagation through turbulent inhomogeneities in the air near the surface of the ground plane may alter the direction and hence the length of sound waves travelling along ground-reflection paths to the mast-mounted microphones. The principal factors, however, that determine the phase differences are (1) the height of the microphone above the ground plane, (2) the height of the engine above the ground plane, and (3) the effective axial location of the presumed source, or sources, of engine noise in each 1/3-octave-band in the frequency range of interest.

Phase differences between the direct and the reflected sound signals at the mast-mounted microphones cause destructive and constructive interference effects. Whether the interference effect is destructive or constructive at a particular frequency depends, primarily, on the ratio of the difference, Δr, between the pathlengths to the wavelength, λ, of the sound.

Increasing the height of a microphone above the ground plane increases the pathlength difference and reduces the frequency of the largest destructive spectral distortion at the frequency associated with $\Delta r/\lambda = f(\Delta r)/c = 1/2$. For mast-mounted microphones, microphone height should be at least that of the engine centerline above the ground plane.

At high frequencies (i.e., frequencies greater than approximately 1000 to 3000 Hz for test stands described in Table 1), spectral interference effects should be of the order of ±1 dB, or less, and the amplitude of the sound pressure signal should be approximately 3 dB greater than the equivalent value in a spherical free field.

To obtain estimates of the equivalent free-field sound pressure levels at all frequencies of interest from measurements made by microphones mounted on masts, the spectral irregularities caused by ground-reflection effects must be removed from the measured data. For the typical engine test stand and with microphones at engine centerline height, the largest spectral irregularities will probably occur at frequencies less than 300 Hz. The procedure used in the analysis of the data to remove the effects of ground reflections may be an empirical procedure developed by the engine manufacturer and specifically applicable to a particular engine test stand. The certifying authority should review and approve the procedure.

When the rotational speed of the fan is such that the rotational speed at the tip of the fan rotor blades is supersonic, the spectrum of the sound from the engine will contain discrete-frequency components at the fundamental and harmonics of the engine rotational speed. Engine rotational speed will probably not exceed 150 rev/sec for moderate-thrust engines or 80 rev/sec for high-thrust engines. Thus, for many engines the discrete low-frequency spectral components (called buzzsaw or multiple pure tones) will occur in the same frequency range as the largest spectral distortions caused by ground-reflection interference effects.

The empirical procedure used to adjust the sound pressure levels measured by mast-mounted microphones to free-field conditions should be able to distinguish between spectral distortions caused by ground-reflection interference effects and actual spectral components of the engine noise signal, particularly the low-frequency buzzsaw components. The information in Refs. 6, 7, and 8 provides guidance that may be useful in developing a procedure to remove spectral distortions caused by ground-reflection effects. The specific procedures described in Refs. 7 and 8 are applicable to sources of broadband sound such as external jet-mixing noise. The procedures would have to be modified to make them applicable to sound spectra that were a combination of broadband and discrete-frequency sounds. If the acoustic impedance of the ground plane is other than that of a smooth and hard surface, then the actual acoustic impedance of the surface at the time of the tests should be included in the adjustments of the measured spectra to free-field conditions.

As an alternative to mounting the microphones on masts, microphones may be located near the surface of the ground plane. If a small microphone were to be installed flush with the surface of an acoustically rigid ground plane, then the measured sound pressure should be twice the pressure that would exist at the same location in a free field in spherical space. The sound pressure level at any frequency should be 6 dB greater than the equivalent free-field sound pressure level. There should be no distortions introduced into the measured spectrum by phase differences between direct and reflected waves since the pathlengths should be identical.

Flush mounting a microphone in the ground plane, however, is not practical for routine engine noise testing. An alternative scheme to approximately achieve the simple pressure doubling provided by flush-mounted microphones has been to position the microphone in a special holder such that the axis of the microphone is vertical. The sensing element is located a distance above the surface which is of the order of one-half to one microphone diameter, see Figs. 18 and 19 and Ref. 4.

While the vertical-axis inverted microphone technique can yield sound pressure level spectra comparable to those which would be measured in an equivalent free field, there are certain precautions that need to be considered.

The height of the microphone above the surface of the ground plane should not be much less than one-half a microphone diameter. Reference 9 reports the results of a study of such microphone installations. At height-to-diameter ratios of less than 1/2, there were radial resonance modes in the gap. The resonances caused relatively large variations in the pressure signal sensed by the microphone. Reference 10 reports the results of a series of experiments in an anechoic chamber. Comparisons were made between the sound pressure levels measured by a microphone flush mounted in a flat plate and the sound pressure levels measured by an inverted microphone at height-to-diameter ratios ranging from 1/8 to 2. For sound incidence angles greater than 40°, the inverted microphone gave sound pressure levels that were within ±1 dB of those measured by a flush-mounted microphone for 1/3-octave-band center frequencies to 10 kHz when the height was one-half the diameter. The good agreement did not extend to as high a frequency when the height was increased to more than one-half the diameter.

Another consideration, which applies to any near-ground type of microphone installation, is that phase fluctuations resulting from the propagation of sound waves at shallow grazing angles through atmospheric turbulence can cause large variations in the amplitude of the signal at the microphone. The sources of atmospheric turbulence are winds and solar heating of the ground surface. Small variations in wind direction can also cause large variations in the amplitude of the signal at the microphone.

However, since the test procedure is aimed at obtaining measurements of sound pressure levels only when the engine is operating at constant and stabilized engine power settings, and since the data sampling time period can be relatively long, then a relatively long time average of the squared pressure signal should yield reliable data. A data-recording time period of at least 30 seconds is recommended.

Another technique for measuring sound pressure levels near the ground plane is to install a microphone with its axis horizontal and a short distance above the ground plane, e.g., Fig. 17. With that arrangement, phase differences between direct and reflected sound waves should only affect measurements of high-frequency sound pressure levels because the pathlength difference will be small. A pathlength difference of 13 mm should mean that the first destructive interference occurs at a frequency greater than 13 kHz. At frequencies less than the frequency for the first destructive interference, the sound pressure should be effectively doubled and hence 6 dB more than would be measured in a free-field environment.

For any installation of a near-ground microphone, care should be taken to ensure that the local surface around the microphone is smooth and hard. The region around the microphones may, for example, be coated with a thin layer of hard, glossy, white paint, or equivalent.

On balance, it would appear that the optimum procedure would be to use a combination of mast-mounted and near-ground microphones. High-frequency free-field sound pressure levels would be determined by subtracting approximately 3 dB from the sound pressure levels measured by the mast-mounted microphones. Low-frequency free-field sound pressure levels would be determined by subtracting 6 dB from the sound pressure levels measured by the near-ground microphones. Mid-frequency free-field sound pressure levels would be determined from an appropriate combination of the sound pressure levels measured by the two microphones.

If a combination of mast-mounted and near-ground microphones is not feasible, then either type of installation may be utilized with due consideration given to the problems discussed above. In all cases, the procedures developed by the engine manufacturer to adjust the measured data to free-field conditions should be approved by the certifying authority.

Microphone Orientations

For each type of microphone installation, the microphone may be oriented to receive the sound pressure signals at either grazing (90°) incidence or perpendicular (0°) incidence, depending on whether random-incidence ("pressure-response") microphones or perpendicular-incidence microphones are available. A microphone designed for flattest response for sounds at perpendicular incidence may be used to receive sounds at grazing incidence although with some loss in sensitivity and frequency response.

For any microphone installation, however, a grazing-incidence orientation is much preferred because that choice means that the same microphone directivity-response corrections will apply for every microphone location and every engine power setting.

For mast-mounted microphones, the preferred microphone orientation is with the plane of the sensing element set to pass through the engine centerline. The microphone should point up to take advantage of the microphone's directional response at incidence angles greater than 90°. The reduced sensitivity at those angles should help to discriminate against sound reflected from the ground surface in favor of sound propagating directly from the noise sources to the microphones.

If a mast-mounted or near-ground microphone is oriented to obtain a nominal 0° sound-incidence angle onto the sensing element, then some determination must be made of where the most important sound source is located. In the inlet quadrant, much, but not all, of the sound will radiate from the inlet duct. In the aft quadrant, much of the sound will radiate from effective sources located several nozzle diameters downstream of the nozzle exit plane(s). The engine reference point, or its vertical projection, or some other engine-associated location may be used as a compromise for the "source" location at which to point the microphones.

Since the actual location of the source(s) of sound varies with frequency, microphone location, and engine power setting (and engine configuration), the engine manufacturer should develop appropriate microphone directivity-response corrections to use when analyzing the data measured by microphones oriented for 0° nominal sound incidence. Several sets of corrections may be required. Procedures used to develop the corrections should be approved by the certifying authority. The procedures should include an appropriate means of identifying the actual "source" of sound for each 1/3-octave band so that actual sound-incidence angles may be determined.

Engine Reference Point

A standard engine reference point provides a common origin for the coordinate system used to report the location of the microphones.

It is desirable that the reference point be somewhere that is relevant to the engine's sources of noise. It is convenient if the reference point can be readily determined in the field when the test engine is mounted to the test stand. The location for the reference point should be applicable to any test engine from any manufacturer.

While, as shown in Table 1, many definitions were in use for a reference point, the recommended location for the reference point, for tests to measure the sound produced by an entire engine, is on the engine centerline at the center of the exit plane of the turbine exhaust nozzle if the engine has separate nozzles for the fan and turbine exhausts, or at the center of the exit plane of the final nozzle if the engine has a confluent-flow or a mixed-flow exhaust system. Other reference points may be used to locate the microphones around the test stand providing the data are reported relative to the recommended reference point.

The recommended location for the engine reference point was deliberately chosen as far aft on the engine as possible. The location is relevant to sources of jet noise, combustion noise, and turbine noise. It is roughly midway between sources of high-frequency jet noise downstream of the nozzle exit plane and sources of high-frequency noise associated with the fan stage. The location is not far from the nozzle on the fan-discharge duct for turbofans having separate-flow exhaust systems.

For microphones located in a polar array along a circular arc, the recommended location for the center of the array places the aft-quadrant microphones farther aft than any alternative engine-related definition for the reference point. The aft-displaced location should be particularly appropriate for tests at high engine power settings when the effective sources of jet-mixing noise are located many nozzle diameters downstream of the nozzle exit plane.

Nonsymmetric Sound Field

Measured values of farfield sound pressure levels should be rotationally symmetric about the engine centerline if the test site and test stand are free, as recommended, of objects or structures that reflect significant amounts of sound to the microphones and if, as also recommended, the inlet duct and the discharge duct(s) are essentially round and axisymmetric.

However, if the inlet and discharge ducts are not essentially round and axisymmetric, the farfield sound pressure levels may not be symmetric about the engine centerline at all frequencies in the range of interest. If the sound field is not symmetric, then measurements in one plane through the engine centerline may not be sufficient, especially for calculations of sound power level.

Therefore, when the inlet and discharge ducts do not have the recommended shapes, an investigation should be made to establish the need to measure farfield sound pressure levels in additional planes through the engine centerline. If feasible, measurements in additional planes may be accomplished by repeating the tests with the ducts rotated about their mounting flanges.

Microphone Locations

The primary recommendation for the array of farfield microphones is a set of fixed locations along a circular arc centered on the engine reference point. Supplemental measurements may be made by microphones located at various positions along a line parallel to the engine centerline, i.e., a sideline. Measurements at locations along the sideline may be appropriate for sources of jet noise.

To provide data needed to calculate the sound power through a closed surface about all the test engine's noise sources, it may be necessary to measure sound pressure levels along a circular arc at the downstream end of the sideline. The Appendix describes a recommended combination of circular arcs and a sideline for use when such arrays are considered necessary.

For consistency, it is recommended that all microphone locations be identified in a polar coordinate system in terms of a radius and an angle. The origin should be the engine reference point. Angles should be measured relative to the engine centerline with 0° in the forward direction. The radial distance should conform with the previously stated minimal requirements for measurements of farfield sound pressure levels.

The angular spacing between microphones should not exceed 10°. A closer spacing may be required to define the location and amplitude of the maximum sound pressure level along an array path for various frequency components of the sound from the engine.

Number of Engine Power Settings Per Run

Values of the noise-evaluation quantity for the engine-noise type certificate will be obtained from a line fitted to a plot of the separate values of the noise-evaluation quantity. Those separate values will be calculated from the data that were measured during each individual test condition (or at each individual power setting) for each test run. Referred net thrust is the recommended dependent variable for the plot from which the mean line for the average value of the noise-evaluation quantity is derived.

Since the engine-noise type certificate will require a determination of the value of the noise-evaluation quantity at a minimum of two engine power settings, acoustical test data should be recorded over the test engine's operating range. The range from 20 percent to 100 percent of maximum available thrust is recommended.

To provide enough data to permit a reliable determination of the mean line through the individual data points, each test run should include several test conditions. The total number of test conditions should be of the order of 10 to 15. While the test conditions should include engine power settings over the recommended operating range in order to be able to properly establish the shape of the line for the variation of the noise-evaluation quantity with referred net thrust, for adequate definition the increment between adjacent values of the power-setting parameter should be relatively small around the values of referred net thrust established by the engine manufacturer for the type certificate.

The recommended number of test conditions per test run is considered to be compatible with approximately the largest number of tests that can be accomplished per run in a practical length of time before the prevailing meteorological conditions change to unacceptable values. Experience indicates that a period of five to ten minutes is needed to allow sufficient time to establish the power setting, stabilize the engine, and record the data at each test condition.

To ensure the inclusion of variations in meteorological conditions, it may be helpful to record data at one set of test conditions as the power is increased to takeoff and then alternating test conditions as the power is reduced.

Windscreens

If data are recorded when the average and the peak wind speeds are less than the recommended maximum wind speeds, then it may not be necessary to place windscreens around the microphones. High-pass electrical filters with a turnover frequency of approximately 15 Hz may be incorporated in the signal circuit before the tape recorder. The filters will attenuate the large-amplitude, low-frequency signals caused by the flow of air over the microphones. The high-pass filters will also attenuate any high-level, low-frequency ambient noise that may be present.

The preferred procedure is to not use any windscreens when recording acoustical data and only to record data when the average wind speed is lower than the recommended maximum values. The amplitude of the engine noise signal will usually be significantly greater than the amplitude of the wind noise. The influence of wind-induced variations in the amplitude of the engine-noise signal at the microphone can be minimized by averaging the signal over a relatively long time period.

However, if windscreens are used, then appropriate windscreen corrections should be determined from laboratory calibration tests and applied during data analsis. Reference 11 provides some relevant laboratory test results on the performance of several commonly used microphone windscreens.

For mast-mounted microphones, a convenient windscreen is a porous sphere made from reticulated open-cell foam. The recommended minimum nominal diameter is 9 cm. A porosity of 1000 to 2000 pores per meter is recommended.

For the near-ground microphones, porous foam hemispheres made by cutting a foam sphere are not recommended because it is rarely feasible to avoid gaps and pockets under the windscreen as it lays on the surface of the ground plane for a vertical-axis or a horizontal-axis microphone installation. The gaps and pockets reduce the effectiveness of the windscreen and influence microphone response. Special windscreens may have to be developed for the near-ground microphones. The laboratory calibration of the special windscreens should carefully simulate the various actual installations.

Test-Time Calibrations

Calibrations recorded at the time of the tests must include, as a minimum, the recording of some form of a reference amplitude-calibration signal, preferably a sinusoidal signal. The purpose of the reference amplitude calibration is to establish the absolute sensitivity of each data channel relative to a known sound pressure level at some frequency. In addition, it is recommended that the test-time calibrations include the recording of electrical signals over the frequency range of interest. The purpose of the second type of calibration is to provide the data to establish relative frequency response corrections for each channel of the entire data-acquisition and data-analysis system exclusive of the microphones.

An acoustical calibrator is required to establish the reference sound pressure level at some calibration frequency. The sound pressure level output of the calibrator should be confirmed as part of the laboratory calibration efforts needed to support the test program. The laboratory calibration should also establish the effect on the calibrator's sound pressure level output resulting from differences between the pressure and temperature of the air at the time of calibration and the pressure and temperature of the ambient air at the time of the test.

Each reel of magnetic recording tape that contains recordings of acoustical data should contain at least one recording of a reference amplitude-calibration signal, ideally from a calibrated acoustical calibrator. However, the process of recording calibration signals from an acoustical calibrator through each data channel requires substantial time when there are many microphones, several of which may be mounted on masts that have to be lowered and then raised.

Therefore, in practice, recording of the signal from an acoustical calibrator is often accomplished only as part of the pre-test and post-test calibration activities. Amplitude-calibration signals, required for the various reels of magnetic recording tape used during a test, are then established by alternative procedures. Two alternative procedures have been determined to produce acceptable results.

One alternative procedure is to insert a sinusoidal electrical signal into the microphone preamplifier, either through a dummy microphone or through a special built-in insert-voltage resistor in the preamplifier. This procedure provides both an end-to-end calibration of each data channel (except, of course, for the microphone itself) and a check of the electrical continuity of the signal path.

From the pre-test acoustical calibration, a relationship is established, for each data channel, between the rms voltage at the input to the tape recorder and the sound pressure level incident on the microphone in the cavity of the acoustical calibrator. That relationship is then used to establish the rms voltage of the electrical signal into the microphone preamplifier.

The second alternative procedure is to simply insert a sinusoidal electrical signal at the inputs to the multi-channel tape recorder and record the signal simultaneously on all data channels. Like the first alternative procedure, the second alternative procedure also makes use of the relationship, from the pre-test acoustical calibration, between the sound pressure level in the cavity of the acoustical calibrator and the rms voltage of the signal at the input to the tape recorder.

The second alternative procedure requires much less time to record a reference amplitude-calibration signal than does the first alternative procedure. The second alternative procedure yields acceptable results if the sensitivity of the microphone preamplifiers, cables, and other circuit elements between the microphones and the tape recorder does not change significantly throughout the duration of any given test.

For each alternative procedure, the frequency of the electrical signal should be the same as the nominal frequency of the acoustical calibration signal. The amplitude of the electrical amplitude-calibration signal should be chosen to be within the tape recorder's linear operating range.

For each alternative procedure, the relationship between the rms voltage of the reference electrical amplitude-calibration signal and the sound pressure level in the cavity of the acoustical calibrator should be checked again as part of the post-test activities.

Significant differences between the pre-test and post-test checks of the relationship between the two forms of amplitude-calibration signals indicate that something occurred during the test period to change the sensitivity of the microphone or some other components of the data-acquisition system. Data should not be considered valid that were recorded on a channel for which there was a significant difference between pre-test and post-test amplitude-calibration checks.

Differences between the acoustical sensitivity of each data channel may be accounted for by noting the root-mean-square voltage at the tape recorder input when the acoustical calibrator is applied sequentially to each microphone. Differences between the sensitivity of the various data channels may also be accounted for by use of variable resistors (potentiometers), or other approved methods.

The procedure to establish the reference amplitude-calibration signals should be approved by the certifying authority.

The generator that provides the electrical signal for establishing the system frequency-response corrections may produce random or discrete-frequency signals. A random-noise signal with a pink-noise spectrum is preferred because the spectrum-level slope of a -1 dB per 1/3-octave-band (or -10 dB per decade) yields a set of equivalent 1/3-octave-band sound pressure levels all having the same nominal value. Relative frequency-response corrections may then be determined readily by subtracting the equivalent sound pressure level in any frequency band from the equivalent sound pressure level in the band containing the acoustical calibration frequency.

Comparable system frequency-response corrections may also be obtained from recordings of constant-amplitude sinusoidal signals at the nominal geometric mean frequency of each 1/3-octave band in the frequency range of interest. Since the frequencies would have to be generated sequentially and since the time to record each sinusoidal calibration signal should be the same as the time to record the pink-noise calibration signals, the total time to record a series of sinusoidal calibration signals, for the frequency range covered by 1/3-octave-band center frequencies from 50 Hz to 10 000 Hz, could be as much as 24 times the recording duration of the pink-noise signal.

The system frequency-response signals should be inserted into the data-acquisition chain at the microphone preamplifier. In that way, the resulting frequency-response corrections will apply to the complete acquisition and analysis system except for the microphone and any windscreen. Corrections for windscreen and microphone frequency response should be determined from separate laboratory calibrations.

Laboratory Calibrations

All instruments used to measure and record acoustical, meteorological, and engine-performance data should be calibrated in a laboratory within three months before the scheduled start of a series of tests. The calibrations should include all the tests required to assess the performance of an instrument by the latest edition of the applicable performance standard.

Laboratory calibrations of the acoustical test instruments should include calibration of the acoustical calibrator, the pink-noise or sinusoidal signal generator, the microphones (and their associated preamplifiers), the magnetic tape recorder(s), and the 1/3-octave-band filters.

Two other special laboratory calibrations are required: for windscreens and for the near-ground microphone installations. The special calibrations do not necessarily have to be performed within three months before the beginning of a test series because the purpose is to determine representative effects for typical (not specific) installations.

If windscreens are used around mast-mounted or near-ground microphones, the effect of each typical windscreen on microphone response should be determined as a function of the frequency of a free-field sound signal, sound-incidence angle, the speed of a steady wind, and the incidence angle of the wind. Details of the actual installation of a windscreen around the near-ground microphones should be carefully simulated. The calibration tests should cover the range of frequencies, sound-incidence angles, wind speeds, and wind-incidence angles likely to be encountered during an engine-noise test.

The laboratory calibrations should also determine the effect of such important, or potentially important, variables as deformation caused by handling, the presence of various amounts of dust in the pores of the windscreen, the presence of moisture on the surface and in the interior of the windscreen, and the deterioration of the material from which the windscreen is made as a result of exposure to sunshine and usage.

The effect of the ground plane on microphone response for any near-ground microphone installation is not likely to be available from the microphone manufacturer's literature or other sources. Laboratory calibrations are requi[illegible] to evaluate the directional response of the near-ground microphone installations. The directional response should be determined for several frequencies including 250, 500, and 1000 Hz and all the 1/3-octave-band center frequencies from 1250 to 10 000 Hz.

For a vertical-axis inverted-microphone installation, directional response measurements need be made only in one plane through the microphone axis and should include sound-incidence angles from 90° to at least 150°. A range of microphone height-to-diameter ratios should be included in the investigation.

For a horizontal-axis near-ground microphone installation, directional-response measurements should be made in at least three planes of symmetry through the microphone axis. In each plane, sound-incidence angles should range from 0° to at least 120°. A range of microphone height-to-diameter ratios should be included.

Analysis of the Recorded Data

When this report was prepared, procedures to analyze the recorded acoustical, meteorological, and engine-performance data were well established and relatively straightforward for those organizations that operate engine test stands. There appeared to be only two technical issues potentially involved in determining test-time 1/3-octave-band sound pressure levels.

One potential issue was the possible use of exponential time averaging in the determination of time-mean-square sound pressures. Some data-analysis systems may include exponential time averaging to simulate, for example, the standard slow response of a sound level meter. The use of exponential time averaging is not recommended.

The second potential issue involved the question of what to do about high levels of ambient noise (or of background electrical instrument noise), if present, and the resulting contamination of the measurements of engine-noise signals.

The recommended test procedure includes a measurement of ambient noise before and after the recordings of engine noise signals. The indicated sound pressure levels of those ambient noise recordings should be averaged on a mean-square-pressure basis and the results compared with the indicated sound pressure levels of the engine noise signals.

If the difference between the indicated sound pressure level of engine noise and the sound pressure level of ambient noise is 5 dB, or more, then it is considered that a valid ambient-noise correction can be determined from the difference in mean squared pressures. The correction will be negligible if the difference between the sound pressure levels is 15 dB, or more.

However, if the difference between the sound pressure levels is less than 5 dB, then a valid ambient-noise correction probably cannot be determined and the contaminated sound pressure levels should not be considered valid.

To avoid the need to reject acoustical data because of contamination by high levels of ambient noise, it is recommended that preliminary tests be performed to establish maximum tolerable levels of ambient noise. If, as expected, high-quality acoustical test instruments are used, the level of background electrical noise should be well below the level of the engine noise signal at the quietest engine power setting.

If some of the indicated 1/3-octave-band sound pressure levels for the engine-noise signal are rejected because the level of ambient noise was less than 5 dB below the indicated sound pressure level, then the effect of the loss of those sound pressure levels should be assessed in terms of the associated changes in the magnitude of the noise-evaluation quantity for that particular engine power setting. The recommended procedure is to calculate the noise-evaluation quantity twice, once without including the sound pressure levels that were rejected because of contamination by high-level ambient noise and then again with the contaminated sound pressure levels replaced by estimates of the maximum likely value of the true sound pressure level. The procedure for determining maximum likely values for the contaminated sound pressure levels should be approved by the certifying authority.

If there is no significant difference between the two calculated values for the noise-evaluation quantity (for example, a difference of less than 0.2 dB), then the data for that engine power setting should be acceptable even though some 1/3-octave-band sound pressure levels are missing. If the difference between the two calculated values for the noise-evaluation quantity is significant, then the data for that power setting should be rejected. If the data from several power settings are rejected because of contamination by ambient noise, then it may be necessary to re-run the test when ambient noise levels are lower.

Adjustments to Reference Conditions

Before applying any adjustments to the measured sound pressure levels to account for differences between test-time and reference conditions, the time-averaged sound pressure levels for each test condition should be corrected for non-uniformities in frequency response and, if necessary, for contamination by ambient noise. The purpose of applying the adjustments to reference conditions is to provide sets of 1/3-octave-band sound pressure levels that are as free as possible of the influence of a particular test site and test-time atmospheric conditions.

The resulting values for the noise-evaluation quantity should then provide an equitable basis for comparison of the results obtained by one manufacturer with those obtained by another manufacturer. The requirement to adjust the measured sound pressure levels to common reference conditions also provides an equitable basis for assessing the values of the noise-evaluation quantity, at the specified values of the engine-power-setting parameter, against the requirements for engine-noise type certification.

Adjustments to reference conditions include: (1) removal, if necessary, of spectral distortions caused by interference between sound waves radiated directly from a source of engine noise and those reflected from the ground plane to a microphone, (2) subtraction of a suitable constant (e.g., 3 dB from sound pressure levels measured by mast-mounted microphones and 6 dB from sound pressure levels measured by near-ground microphones) to yield 1/3-octave-band sound pressure levels equivalent to those that would have been measured in an acoustic free field in spherical space, and (3) addition of factors to account for differences between the atmospheric absorption along the sound propagation paths under test-time and reference meteorological conditions.

Procedures to adjust the measured sound pressure levels to reference atmospheric absorption should utilize published specifications for atmospheric-absorption coefficients as a function of frequency and the temperature, moisture content, and pressure of the air.

An appropriate empirical definition should be developed for the length of the sound-propagation path to each microphone from the effective location of a source of sound applicable to each 1/3-octave frequency band. Applicable values of test-time meteorological conditions along the sound propagation paths should be determined from the measured meteorological data.

Adjustments for differences in atmospheric absorption will be largest for the highest frequencies. At mid and low frequencies, the adjustments should range from small to negligible.

Except for measurements made under certain conditions, standard procedures were not available to remove ground-reflection interference effects from the spectra measured by a microphone. Some information is available for guidance from SAE publications referenced in the Appendix. The engine manufacturer should develop appropriate empirical procedures for removing ground-reflection interference effects and submit the procedures for approval to the certifying authority. The procedures should be able to distinguish between spectral irregularities caused by ground reflections and spectral irregularities related to discrete-frequency components of the engine-noise signal. Those discrete-frequency components include the low-frequency multiple-pure-tone or buzzsaw sounds at harmonics of the fan rotational speed when the Mach number at the tip of the fan rotor blades is supersonic.

Number of Test Runs

Data from one test run are not likely to be sufficient to establish with accuracy the mean line that will define the average variation of the noise-evaluation quantity as a function of referred net thrust.

To provide enough independent data points to establish the mean line with a high degree of confidence, it is recommended that the test be repeated at least once. Since variations in atmospheric conditions are a principal cause for variations in the test-time sound pressure levels at a given engine power setting, the prevailing meteorological conditions should be somewhat different during each test run, although always within the recommended ranges. The actual number of test runs required will depend, as described in the next section, on the scatter in the individual values of the noise-evaluation quantity.

With two test runs and 10 to 15 test conditions per test run, there will be 20 to 30 separate data points to determine the mean variation of the noise-evaluation quantity with referred net thrust.

Determination of the Noise-Evaluation Quantity

The recommended procedure to determine the final values for the noise-evaluation quantity is contained in the steps described in this section. The procedure is based on the premise that, after applying corrections for nonuniform frequency response and ambient noise and applying the adjustments to acoustic free-field and reference meteorological conditions, all 1/3-octave-band sound pressure levels represent valid data. Consequently, all individual values for the noise-evaluation quantity derived from the sets of sound pressure levels for each test condition are regarded as representing valid data and must be included in the determination of the mean line through the data points unless there is a technical reason not to include one or more data points. Exclusion of any data from the determination of the mean line through the individual data points should be approved by the certifying authority.

To make the discussion in this section more specific, the general expression "noise-evaluation quantity" is here replaced by "A-weighted sound power level" because, as stated earlier, that quantity is recommended in Volume 3 for use in engine-noise type certification. However, any other single-valued quantity could be determined by the recommended method.

1. The first step is to determine the A-weighted sound power levels from the 1/3-octave-band sound pressure levels for each test condition and each test run. The preferred procedure is to first calculate the sound power level in each 1/3-octave band. Then combine the standard A-frequency weighting with the 1/3-octave-band sound power levels to form the A-weighted sound power levels. A sound field that is rotationally symmetric about the engine centerline permits the measurements of farfield sound pressure levels in one plane to be used to calculate the acoustic power that passes through certain definable surface areas such as the sector of a sphere or a cylinder about the engine's internal and external noise sources.

2. The second step is to plot all the individual values of A-weighted sound power level at the associated value of test-time referred net thrust for the engine configuration that was tested.

3. The third step is to use a regression technique, or an approved engineering method, to fit a mean line through the data points. The line is likely to be a curve and may have some relatively sharp changes in slope in the vicinity of certain engine power settings. It should, however, be repeatable.

4. The fourth step is to determine if the variations of the individual data points about the mean line are within acceptable bounds. The recommended criterion for determining acceptability of the data scatter is that 90 percent of the data points should lie within ±1 dB of the mean line. If more than 10 percent of the data points do not lie within ±1 dB of the mean line, then another test run should be conducted to obtain additional data.

5. For Step 5, at the values of referred net thrust specified for the engine-noise type certificate, determine the corresponding values of A-weighted sound power level from the mean line derived in Step 3. Extrapolation, if necessary, beyond the limit of the data should be by a method approved by the certifying authority.

Reporting

An engineering report should be prepared to document the tests that were performed, the analyses that were made, and the results that were obtained. It is not considered necessary to report all the test-time sound pressure levels from each test run. It should be sufficient to tabulate only the values of the noise-evaluation quantity at the values of referred net thrust defined by the engine manufacturer as applicable to the engine for which a noise type certificate is sought.

The Appendix includes a detailed list of the information which it is recommended be included in the report.

CONCLUDING REMARKS

General characteristics were determined for sixteen outdoor engine-noise test facilities operated by eleven organizations. The organizations included six manufacturers of turbofan engines, two airplane manufacturers, one engine-nacelle manufacturer, and two NASA research centers. Facilities operated by the nine manufacturers should be suitable for conducting engine-noise type-certification tests, although some facilities may need to be modified to satisfy recommended test-site requirements.

The survey of outdoor engine-noise test facilities also included a review of the instruments and equipment available to measure acoustical and meteorological data. Instruments and test procedures used by most organizations were consistent with the instruments and procedures recommended for engine-noise type-certification tests.

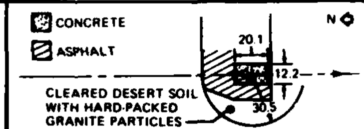
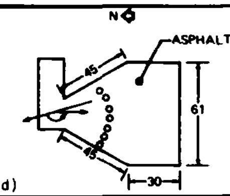
Recommendations were developed for procedures to conduct engine-noise type-certification tests, and to analyze and report the results. The desired results are time-averaged 1/3-octave-band sound pressure levels at several positions in the acoustic farfield around a test engine. The measured test-time sound pressure levels should be adjusted during data analysis so as to be equivalent to those that would have been measured in an acoustic free field. The sound pressure levels should also be adjusted for differences between atmospheric-absorption losses under test-time and reference meteorological conditions.

The inlet and exhaust ducts to be installed on the test engine should be designed to ensure the acquisition of meaningful and consistent test results, and to permit evaluation of the noise produced by a test engine without reference to airplane-specific components. The test inlet and exhaust ducts should not contain sound-absorbing surfaces except if provided by the engine manufacturer for all airplane installations. Sound-absorbing surfaces included by the engine manufacturer within the engine's envelope, for every engine of a given type or model, should be in place during engine-noise type-certification tests.

Specific recommendations were developed and are included in an Appendix for conducting a test to measure sound pressure levels around a test engine installed on an outdoor engine test stand and equipped with test inlet and exhaust ducts. The Appendix includes recommendations for (1) the test site and test stand, (2) location and installation of microphones in the acoustic farfield, (3) reference meteorological conditions, (4) minimum instrument performance requirements for major components of the systems for measuring acoustical, engine-performance, and meteorological data, (5) noise test procedures, (6) data analysis, and (7) reporting of the test results.

Table 1. General characteristics of jet-engine test stands used for far-field outdoor noise measurements (March 1982).

(a) AiRESEARCH AND AVCO LYCOMING

Organization	Name and location of engine test stand (nearest city)	Identification code for test stand	Year first noise tests performed	Maximum thrust capacity, kN	Nominal height of engine centerline above ground plane, m	Structure used to control atmospheric turbulence in inlet airflow	Elevation of ground plane above mean sea level, m	Typical climatic conditions	Location and capabilities of meteorological instruments (see Note a)	Type and extent of ground surface over which noise measurements are made (see Note b)	Nominal engine reference point for noise measurements
AiResearch Manufacturing Company*	San Tan Test Site (Phoenix, AZ)	Stand 5	1965	25	2.29	no	335	arid area, cold and dry to hot and dry, wind generally calm when testing	at engine control station; T_d, T_w, WS, WD		on engine centerline midway between inlet and exhaust flanges
Avco Lycoming Division	Free Field Test Stand (Stratford, CT)	FFTS	1970	45[c]	2.44	no	3	moist, near Long Island Sound, temp. varies from cold to hot, prevailing winds from NE to SE	30 m from engine and microphone array; T_d, T_w, WS, WD	 (see Note d)	on engine centerline midway between inlet and exhaust flanges

Notes:

(a) T_d = dry bulb temperature; T_w = wet bulb temperature; DP = dew point; WS = wind speed; WD = wind direction.

(b) Dimensions in meters.

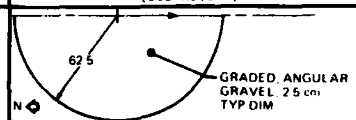
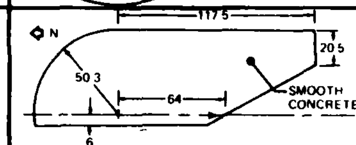
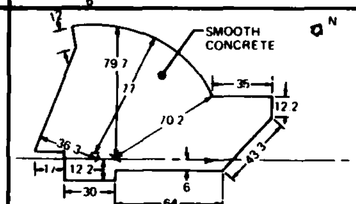
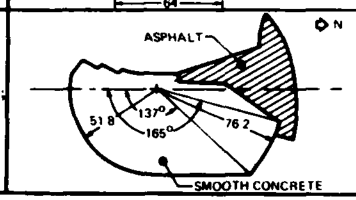
(c) Thrust is not measured on the test stand, but is calculated from an engine calibration curve and measured values of internal engine parameters (shaft speeds, temperatures, and pressures) plus ambient temperature and pressure.

(d) Engine is mounted on a test stand that can be rotated to obtain sound directivity data from the array of microphones.

*Name changed in January 1981 to the Garrett Turbine Engine Company.

Table 1. Continued.

(b) BOEING AND DOUGLAS

Organization	Name and location of engine test stand (nearest city)	Identification code for test stand	Year first noise tests performed	Maximum thrust capacity, kN	Nominal height of engine centerline above ground plane, m	Structure used to control atmospheric turbulence in inlet airflow	Elevation of ground plane above mean sea level, m	Typical climatic conditions	Location and capabilities of meteorological instruments (see Note a)	Type and extent of ground surface over which noise measurements are made (see Note b)	Nominal engine reference point for noise measurements
Boeing Commercial Airplane Company	Tulalip (Everett, WA)	T1	1965	222	adj. to max. of 5.8	yes	9	cool and moist, near Puget Sound, not much wind from the south or the north, some winds from the east or west	4-m mast at 45° and 80 m west of engine inlet; T_d, DP, WS[e], WD		on engine centerline at exit plane of fan-exhaust nozzle[f]
		T2	1966	334	4.88	yes	9		4-m mast at 60° and 150 m east of engine inlet; T_d, DP, WS[e], WD		on engine centerline at exit plane of fan-exhaust nozzle[f]
	Boardman (Pendleton, OR)	B2	1963	111	3.96	yes	212	arid area in the Columbia River valley, cold and dry to warm and dry, winds mainly from the west to southwest	4-m mast at 40° and 37 m from engine inlet; T_d, DP, WS, WD		on engine centerline at exit plane of core-engine or primary-exhaust nozzle[f]
Douglas Aircraft Company	QIAETsite (Quartzsite, AZ; Blythe, CA)	Site 1 at C10	1978 at QIAETsite (1957 at EAFB)	334	4.88	no	272	arid area, cold and dry to hot and dry, prevailing winds from the south	on portable 4.9-m mast at location to suit test requirements; T_d, DP, WS, WD		as required[f]; engine position on test stand may be varied longitudinally by 5.6 m

(e) Wind speed can be measured down to 0.1 m/s.

(f) Microphones can be moved longitudinally to accomodate any desired engine reference point.

Table 1. Continued.

(c) GENERAL ELECTRIC, PRATT & WHITNEY AIRCRAFT, AND ROHR

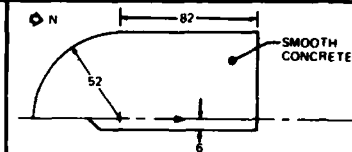
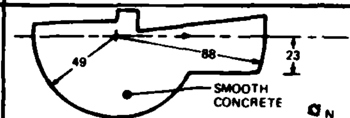
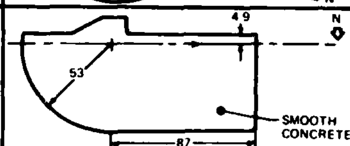
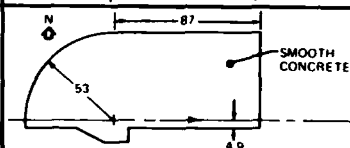
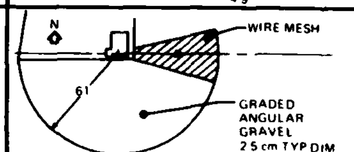
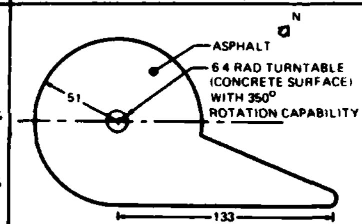
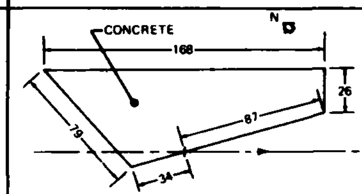
Organization	Name and location of engine test stand (nearest city)	Identification code for test stand	Year first noise tests performed	Maximum thrust capacity, kN	Nominal height of engine centerline above ground plane, m	Structure used to control atmospheric turbulence in inlet airflow	Elevation of ground plane above mean sea level, m	Typical climatic conditions	Location and capabilities of meteorological instruments (see Note a)	Type and extent of ground surface over which noise measurements are made (see Note b)	Nominal engine reference point for noise measurements
General Electric Company	Peebles Test Site (Peebles, OH; Cincinnati, OH)	Site IVD	1956 for first tests, 1978 with configuration shown	445	3.96	no	327	relatively moist location in southern Ohio in Ohio River Valley, temp. varies from cold to hot, winds from SW	4-m mast at 45° and 49 m from engine inlet; T_d, T_w, WS, WD		on engine centerline at exit plane of fan-exhaust nozzle[f]
	EAFB Test Site Edwards AFB (Lancaster, CA)	North Site	1965 for first tests, 1978 with configuration shown	445	3.96	yes, 7.3-m dia	693	arid area in Antelope Valley, cold and dry to hot and dry, winds from SW	4-m mast at 315° and 30 m from engine inlet near control room; T_d, T_w, WS, WD		on engine centerline at exit plane of fan-exhaust nozzle[f]
Pratt & Whitney Aircraft Group of United Technologies Corporation	P&WA Government Products Division Engine Test Stand (West Palm Beach, FL)	C11	1952 in E. Hrtfd, CT, 1980 for config. shown for W.P.B., FL	445	4.88	yes, 7.6-m dia	9	humid location on eastern side of Florida, temp. varies from cool to hot, prevailing winds from NE except when running	4.9-m tower at 53 m and 90° from engine inlet; T_d, DP, WS, WD		on engine centerline at exit plane of fan-exhaust nozzle for JT9D-7A with 747-200B nacelle
Rohr Industries Incorporated	Brown Field Test Facility (Chula Vista, CA; San Diego, CA)	B60	1980	334	4.88	yes, 7.6-m dia	160	moderate coastal climate, generally dry, cool to warm, low winds generally from W to SW	4.9-m tower at 45° and 47 m from engine inlet; T_d, DP, WS, WD		on engine centerline at exit plane of fan-exhaust nozzle for JT9D-7A with 747-200B nacelle
		B150	1975	267	4.88	yes, 7.6-m dia			4.9-m tower at 40° and 47 m from engine inlet; T_d, DP, WS, WD		on engine centerline at exit plane of fan-exhaust nozzle for JT9D-7A with 747-200B nacelle

Table 1. Continued.
(d) ROLLS ROYCE

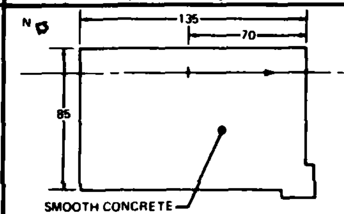
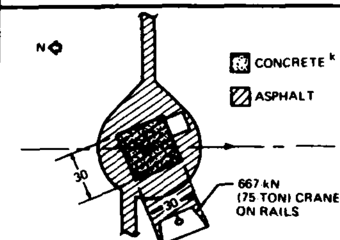
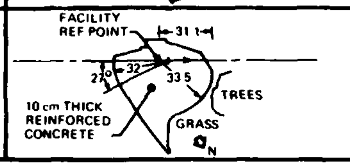
Organization	Name and location of engine test stand (nearest city)	Identification code for test stand	Year first noise tests performed	Maximum thrust capacity, kN	Nominal height of engine centerline above ground plane, m	Structure used to control atmospheric turbulence in inlet airflow	Elevation of ground plane above mean sea level, m	Typical climatic conditions	Location and capabilities of meteorological instruments (see Note a)	Type and extent of ground surface over which noise measurements are made (see Note b)	Nominal engine reference point for noise measurements
Rolls Royce Ltd.	Hucknall Test Facility (near Nottingham and Derby, England)	No. 11 Bed	1955 for first tests at bed No. 7, 1968 at bed No. 9, and 1983 at bed No. 11 shown here	356	6.4	yes, 7.3-m dia	90	cool and moist, prevailing winds from WSW	one movable tower that can be positioned anywhere in test area; WS and WD at 6.4 m or 3 m; high T_d at 5.9 m or 2.6 m; low T_d variable between 13 mm to 30 cm; DP at 3.2 m or 1.5 m		at center of rotation of the turntable
	Aston Down Test Facility (near Stroud and Bristol, England)	Main Site	1960 for first tests, 1968 with configuration shown here	222	3.05 to 3.66[g]	(see note h)	175	cool and moist, prevailing wind from SW	3.6-m tower at 90° and 53 m from engine centerline; WS and WD at 3.6 m; RH from hand held hygrometer to measure T_d, T_w.		normally on engine centerline at exit plane of hot primary-flow exhaust nozzle

(g) No fixed engine test stand at Aston Down; engines are prerigged onto transportable beds which are then bolted to the concrete pad for acoustical tests.

(h) Turbulence control structure used in front of inlet for small engines (i.e., for fan diameters to C.76 m), but not for larger engines.

Table 1. Concluded.

(e) SNECMA, NASA-AMES, AND NASA-LEWIS

Organization	Name and location of engine test stand (nearest city)	Identification code for test stand	Year first noise tests performed	Maximum thrust capacity, kN	Nominal height of engine centerline above ground plane, m	Structure used to control atmospheric turbulence in inlet airflow	Elevation of ground plane above mean sea level, m	Typical climatic conditions	Location and capabilities of meteorological instruments (see Note a)	Type and extent of ground surface over which noise measurements are made (see Note b)	Nominal engine reference point for noise measurements
SNECMA	Istres Test Facility (southern France)	RM3	1967	300	4.00	no	23	coastal climate, generally dry, cool to warm, prevailing winds from NNW	4-m tower at 0° and 70 m from reference point; T_d, DP, WS, WD		on engine centerline at exit plane of reference exhaust nozzle of Olympus OL593 turbojet engine
NASA Ames Research Center	Outdoor Aerodynamic Research Facility (Moffett Field, CA)	OARF	1975	71[i]	(see note j)	no	1	mild coastal climate, warm and dry in summer, cool and moist in winter, temp. usually between 10° C and 25° C, low winds usually from N	10-m tower at 60° and 20 m from center of pad; T_d, DP, WS, WD		variable, depends on test setup and test objectives
NASA Lewis Research Center	Lewis Vertical-Lift-Fan Test Facility (Cleveland, OH)	VLF	1955 for first tests, 1973 at VLF with configuration shown	133	2.9	yes[ℓ]	229	temperature varies from cold in winter (with snow) to warm in summer, prevailing winds from W to SW	6-m tower for wind speed and wind direction, temperature and relative humidity from weather station at nearby Cleveland Hopkins International Airport		on engine centerline at plane of entrance to engine inlet for forward-radiated fan noise, at exit plane of fan-exhaust nozzle for aft-radiated fan noise, and at exit plane of primary nozzle for jet noise[f]

(i) Facility has no permanent engine test stand but can accomodate various engines up to a rated thrust of 71 kN.

(j) Height of engine centerline can be varied to suit engine being tested and test objectives.

(k) An open-pit structure to support the various engine test stands is located at the center of the concrete pad. The openings to the pit are usually covered by steel plates when sound pressure levels are measured.

(ℓ) Several structures, of a variety of sizes and constructions, are available to reduce the turbulence in the air entering the engine's inlet duct.

Table 2. Instruments and procedures used to sense and record far-field sound pressure levels around jet-engine test stands (March 1982).

(a) AIRESEARCH, AVCO LYCOMING, AND BOEING

Organization	Name and location of engine test stand (nearest city)	Microphones: Number and Locations	Microphones: Typical position and height above ground plane[a]	Microphones: Type[b], installation, and orientation	Microphones: Angular resolution capability for sound directivity	Tape recording	Remarks
AiResearch Manufacturing Company*	San Tan Test Site (Phoenix, AZ)	16 on masts	on arc of circle, 30.5-m radius, 1.5 m above ground plane, from 10° to 160°	B&K type 4133 on masts and pointing toward eng. ref. pt. for 0° incidence, no windscreens	nominal 10° from 10° to 160°	two 14-channel FM tape recorders; 60 in/s for data to 20 kHz	3 m/s wind speed limit for noise data
Avco Lycoming Division	Free Field Test Stand (Stratford, CT)	7 on masts, or 7 on ground plane, or both	on arc of circle, 30.5-m radius, 2.4 m above, or on, ground plane at 10° intervals; generally, only ground-plane microphones are used	B&K type 4133 on masts and pointing toward engine ref. point for 0° incidence; B&K type 4134 on ground plane for grazing incidence, all with windscreens	nominal 10° from 0° to 180° by rotating test stand between test runs	14-channel FM tape recorder; 30 in/s for data to 20 kHz; sound level meters for gain control and mic. polarizing voltage	test stand can be rotated 360°
Boeing Commercial Airplane Company	T1 Site at Tulalip (Everett, WA)	17 on masts	on arc of circle, 45.7-m radius, 4 m above gravel ground plane, from 0° to 160°	B&K type 4134 on masts and pointing up for grazing incidence, with windscreens	nominal 10° from 0° to 160°	14-channel FM tape recorder; 30 in/s for data to 10 kHz	test operations limited by community noise requirement
	T2 Site at Tulalip (Everett, WA)	36 avail., mostly ground plane[c]	on arc of circle, 30.5-m radius, or along 30.5-m (or 45.7-m) sideline, or both, at 13 mm above metal plate pointing down + max. of four mics. on masts	B&K type 4134 for ground plane and mast mics.; mics. on masts point up for grazing incidence; windscreens only used around mics. on masts at engine centerline height	nominal 5°, may be less than 5° if desired	14-channel FM tape recorder; 30 in/s for data to 10 kHz	
	B2 Site (Boardman, OR)	48 avail., ground plane and masts[c]	on arc of circle, 30.5-m radius, or along 30.5-m sideline, or both, at 13 mm above metal plate pointing down + max. of fifteen mics. on masts	B&K type 4134 for ground plane and mast mics.; mics. on masts point up for grazing incidence; windscreens only used around mics. on masts at engine centerline height	nominal 5°, may be less than 5° if desired	14-channel FM tape recorder; 30 in/s for data to 10 kHz	remote test site permits 24-hr, 7-day a week test schedules

Notes:

(a) Microphone position angles are measured from the engine reference point on the engine centerline with 0° in the upstream direction and 180° in the direction of jet exhaust. Microphone positions on polar or sideline arrays are not permanently fixed (for most test stands) and are normally varied to suit specific test requirements. Typical positions are described here.

(b) B&K type 4133 microphones have their flattest response over the widest frequency range for sound that is incident on the diaphragm at 0° (or perpendicular incidence) in an acoustic free field. B&K type 4134 microphones have their flattest response over the widest frequency range for sound that is incident on the diaphragm at 90° (or grazing incidence) in an acoustic free field. Both the type 4133 and type 4134 are capacitor microphones with a nominal diameter of 13 mm and with air as the dielectric between the diaphragm and the backplate; both require an external source of dc voltage to charge the capacitor. [B&K = Brüel and Kjaer.]

(c) Number of microphones indicated represents the number of locations where sound pressure levels could be recorded during a test, although not necessarily all simultaneously.

*Name changed in January 1981 to the Garrett Turbine Engine Company.

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Table 2. Continued.

(b) DOUGLAS, GENERAL ELECTRIC, PRATT & WHITNEY AIRCRAFT, AND ROHR

Organization	Name and location of engine test stand (nearest city)	Microphones: Number and Locations	Microphones: Typical position and height above ground plane[a]	Microphones: Type[b], installation, and orientation	Microphones: Angular resolution capability for sound directivity	Tape recording	Remarks
Douglas Aircraft Company	Site 1 at QIAETsite (Quartzsite, AZ; Blythe, CA)	24 avail., on masts, ground plane, or comb.[c]	on arc of circle from 10° to 160°, radius of arc variable to 45.7 m; 45.7-m sideline from 90° to 137° plus 69.7-m-radius circular arc from 137° to 165°; strip of white epoxy paint on concrete for 45.7-m polar arc, 45.7-m sideline, and 69.7-m aft polar arc; mast mics. 4.9 m above concrete at engine centerline height	B&K type 4134 or GenRad 1962-9610 mics. for mast and ground plane; mics. on masts point up for grazing incidence; inverted ground-plane mics. within one-half mic. dia above and pointing down at epoxy paint strip for grazing incid. (see Note d)	nominal 10° from 10° to 160°, may be less than 10° if desired	two 14-channel tape recorders, FM or direct mode, tape speeds to 120 in/s, data to 10 kHz at 15 in/s in FM wideband group 1	remote test site
General Electric Company	Site IV D at Peebles Test Site (Peebles, OH; Cincinnati, OH)	21 on masts, or 21 on ground plane, or comb.[c]	on arc of circle, 45.7-m radius, 4 m above ground plane and on ground plane, from 10° to 170°; also along 45.7-m sideline in aft quadrant	B&K type 4133 on masts pointing toward eng. ref. pt. for 0° incidence, no windscreens; B&K type 4134 for ground plane for grazing incidence (inverted)	10° from 10° to 80° and from 130° to 170°; 5° from 85° to 125°	28-channel FM tape recorder; 30 in/s for data to 20 kHz	
	North Site at Edwards AFB Test Site (Lancaster, CA)	21 on masts, or 21 on ground plane, or comb.[c]	on arc of circle, 45.7-m radius, 4 m above ground plane and on ground plane, from 10° to 160°; also along 20-m sideline in aft quadrant	B&K type 4133 on masts pointing toward eng. ref. pt. for 0° incidence, no windscreens; B&K type 4134 for ground plane for grazing incidence (inverted)	10° from 10° to 80° and from 130° to 160°; 5° from 85° to 125°	28-channel FM tape recorder; 30 in/s for data to 20 kHz	
Pratt & Whitney Aircraft Group of United Technologies Corporation	Site C11 at P&WA Gov't. Products Div. Engine Test Stand (West Palm Bch, FL)	44 for ground plane, 16 on masts, or comb.[c]	ground plane: on arc of circle, 45.7-m radius, from 5° to 160°. masts: on arc of circle, 45.7-m radius, 4.9 m above ground plane, from 10° to 90° and then along 45.7-m sideline from 100° to 150° plus 155° at 87.5 m and 160° at 84.1 m	B&K type 4134 on masts pointing up and, for ground-plane mics, 13 mm above smooth, hard surface painted on concrete and pointing down for grazing incidence, no windscreens	5° for ground-plane mics.; 10° for mics. on masts	two 28-channel FM tape recorders; 30 in/s for data to 10 kHz	
Rohr Industries Incorporated	B60 and B150 test stands at Brown Field Test Facility (Chula Vista, CA)	B60: same as P&WA B150: 20 on perm. masts + 12 movable masts	B60: same as P&WA B150: on arc of circle, 45.7-m radius, 4.9 m above ground surface, from 10° to 150°	same as P&WA at B60 and B150 except only mast-mounted mics. at B150	B60: same as P&WA B150: 10° from 10° to 150° plus 85°, 95°, 105°, 115°, and 125° plus 12 movable	B60 and B150: two 28-channel tape recorders; 30 in/s for data to 10 kHz	

(d) GenRad type 1962-9610 microphones have their flattest response over the widest frequency range for sound that has random incidence onto the diaphragm. The free-field response at grazing incidence is nearly equal to the random-incidence response. The microphone is a capacitor type with a nominal diameter of 13 mm; air is the dielectric in the gap between the diaphragm and the backplate. An electret material on the backplate acts as an internal source to permanently charge the capacitor.

Table 2. Concluded.

(c) ROLLS-ROYCE, SNECMA, NASA-AMES, AND NASA-LEWIS

Organization	Name and location of engine test stand (nearest city)	Microphones: Number and Locations	Microphones: Typical position and height above ground plane[a]	Microphones: Type[b], installation, and orientation	Microphones: Angular resolution capability for sound directivity	Tape recording	Remarks
Rolls Royce Ltd.	No. 11 bed at Hucknall Test Facility (near Nottingham and Derby, England)	24 on masts, 24 near ground plane (36 max.)	1) polar-arc measurements for any test-bed heading: 6.4 m and 2.5 cm above ground plane, 45.7-m radius, 10° increments from 10° to 160° plus eight mics for 5° increments 2) for fixed test-bed heading of 260° (magnetic): 6.4 m and 2.5 cm above ground plane, on arc of circle 45.7-m radius from 10° to 90° in 10° increments (plus four locations at 5° increments); then along 45.7-m sideline from 95° to 160° in 10° increments (plus four locations at 5° increments)	B&K type 4134, on masts, point up for grazing incidence, no windscreens B&K type 4133, for ground plane, are horizontal with axis pointing at vertical axis of test bed, no windscreens [all microphone preamplifiers have a built-in voltage-insert calibration system]	nominal 10° with 5° in regions of max. forward and max aft noise	60-channel, 14-track digital, for data to 12.8 kHz	5 m/s normal wind-speed limit for noise data
	Main Site at Aston Down Test Facility (near Stroud and Bristol, England)	13 on masts, 11 near ground plane (24 max. w/two recorders)	mast mics.: at engine centerline height ground plane mics.: 5.1 cm above ground plane All microphones located along 30.5-m sideline from 30° to 150° [sideline distance can be increased to as much as 45.7 m]	B&K type 4133 oriented to point at the engine, no windscreens	10°	two 14-channel direct-recording tape recorders; 15 in/s for data to 75 kHz	6 m/s normal wind-speed limit for noise data
SNECMA	RM3 Site at Istres Test Facility (southern France)	26 total for mast and ground plane; 8 on moving trolleys	mast-mounted and ground-plane microphones along arc of circle, 61.5-m radius, from 0° to 165°, mast mics. at 4 m above ground plane; plus mics. on moving trolleys: four mics. along a 60-m radius arc, two mics. along a 10-m radius arc, and two mics. along a sideline path	B&K type 4133 oriented to point at the engine, no windscreens	5° and 10° for mast and ground-plane microphones, continuous for microphones on trolleys	one 14-channel direct-recording tape recorder; 7.5 in/s for data to 37 kHz; one 14-channel FM tape recorder; 15 in/s for data to 20 kHz	5 m/s normal wind-speed limit for noise data, 3 m/s for crosswinds
NASA Ames Research Center	Outdoor Aerodynamic Research Facility (Moffett Field, CA)	max. of fifty 13-mm-dia mics. available; max. of twenty 7-mm-dia mics. available	Microphone positions and heights are selected to meet specific test requirements. Ground-plane and mast-mounted mics. are used. Max radius is 30 m.	for 13-mm-dia mics.: B&K type 4133 pointed at the engine and B&K type 4134 pointed up for grazing incidence; B&K type 4136 for 7-mm-dia mics. pointed up for grazing incidence; windscreens are available	variable, to suit test requirements	four 14-channel FM tape recorders available; 30 in/s for data to 20 kHz. Also, one 32-channel FM tape recorder; 30 in/s for data to 20 kHz	
NASA Lewis Research Center	Lewis Vertical-Lift-Fan Test Facility (Cleveland, OH)	max. of 20 on masts or 20 on ground plane	Microphone positions and heights are selected to meet specific test requirements. Mast-mounted and ground-plane microphones usually along arc of circle from 0° to 160°; height of mast mics. usually 2.9 m, but can be as much as 4.6 m.	B&K type 4133 oriented to point at the engine, with windscreens	typically 10° but can be varied to suit specific requirements	14-channel FM tape recorder; 60 in/s for data to 20 kHz	4.5 m/s wind-speed limit for noise data

Table 3. Summary of microphone installations (March 1982).

Microphone installations and orientations used at engine test stands by organizations listed in Tables 1 and 2	
Microphone's sound-incidence angle for flattest frequency response in a free field	
0°	90°
(a) mast-mounted microphones	
Avco Lycoming	Boeing
Garrett (AiResearch)	Douglas
General Electric	P&WA
Rolls Royce (Main Site)	Rohr
SNECMA	Rolls Royce (No. 11)
NASA-Ames (most locations)	NASA-Ames (few locations)
NASA-Lewis	
(b) ground-plane microphones	
Rolls Royce (No. 11)	Avco Lycoming (inverted)
SNECMA	Boeing (inverted)
NASA-Ames	Douglas (inverted)
NASA-Lewis	General Electric (inverted)
	P&WA (inverted)
	Rohr (inverted)

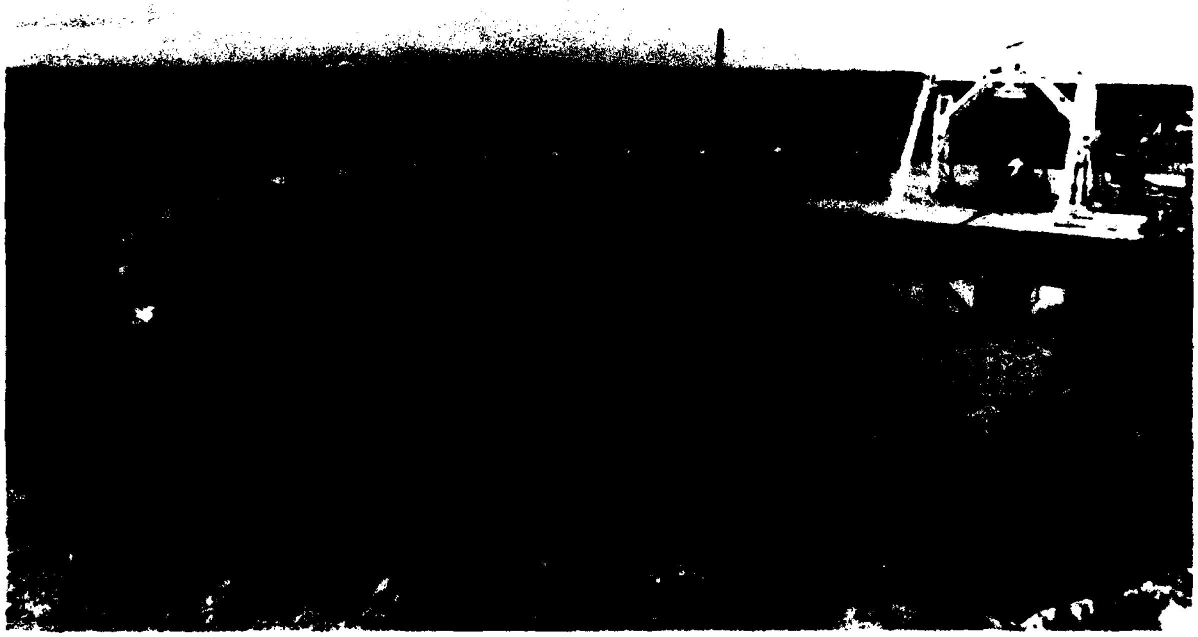


Figure 1. San Tan test site, Garrett Turbine Engine Company.

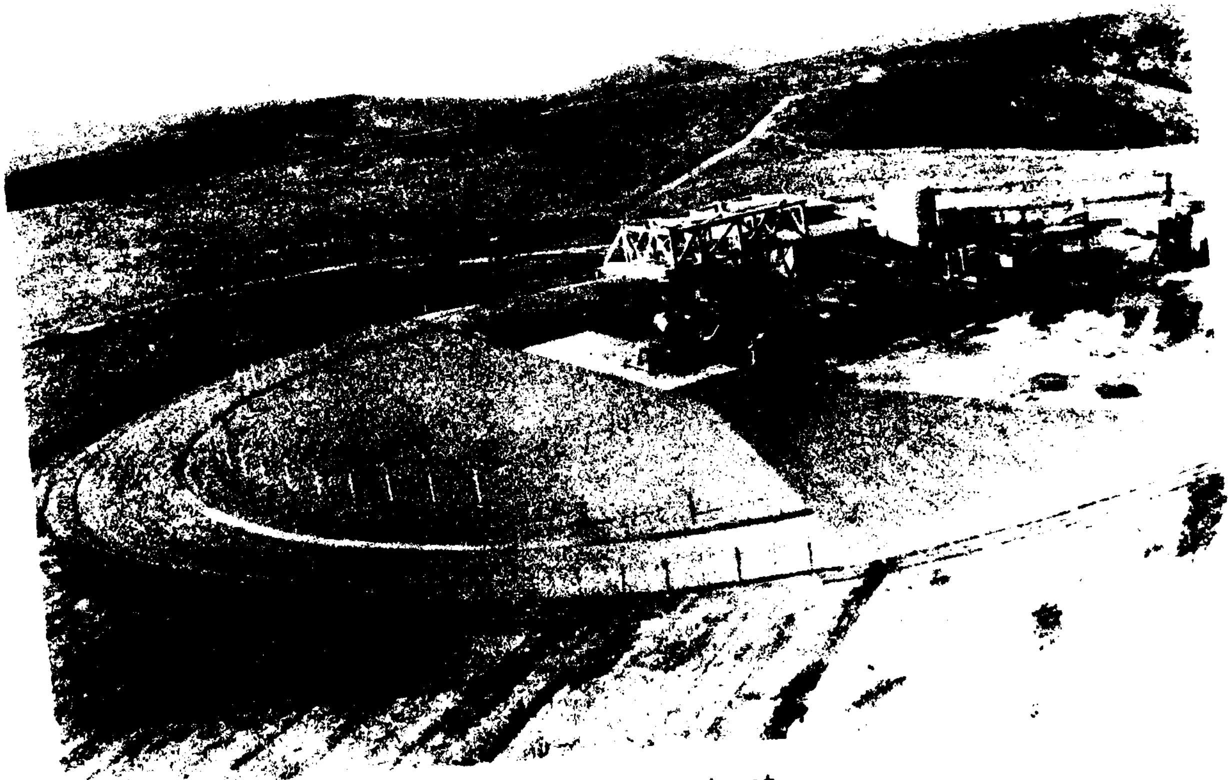
(a) view to southeast

Figure 2. Free-Field Test Stand, Avco Lycoming.

(b) view to north

Figure 2. Concluded.

(a) forward quadrant



(b) rear quadrant

Figure 3. B150 test stand, Rohr.

Figure 4. Tulalip test stand, Boeing.

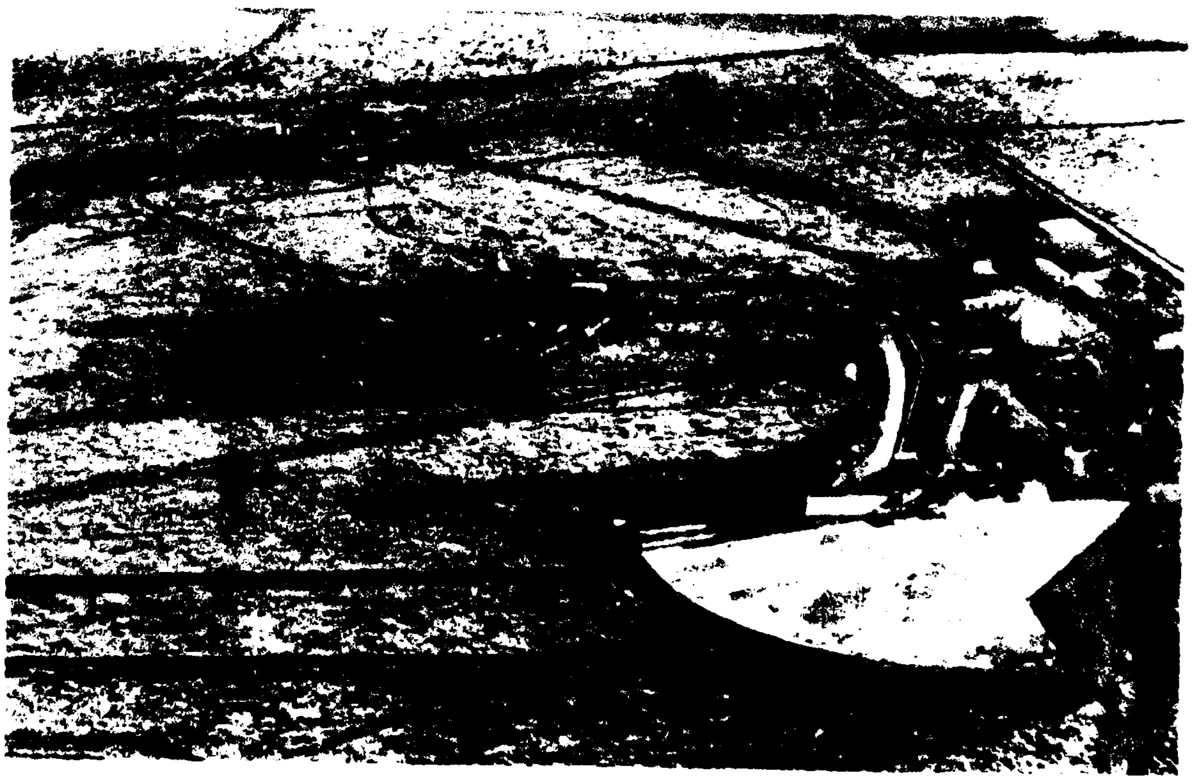
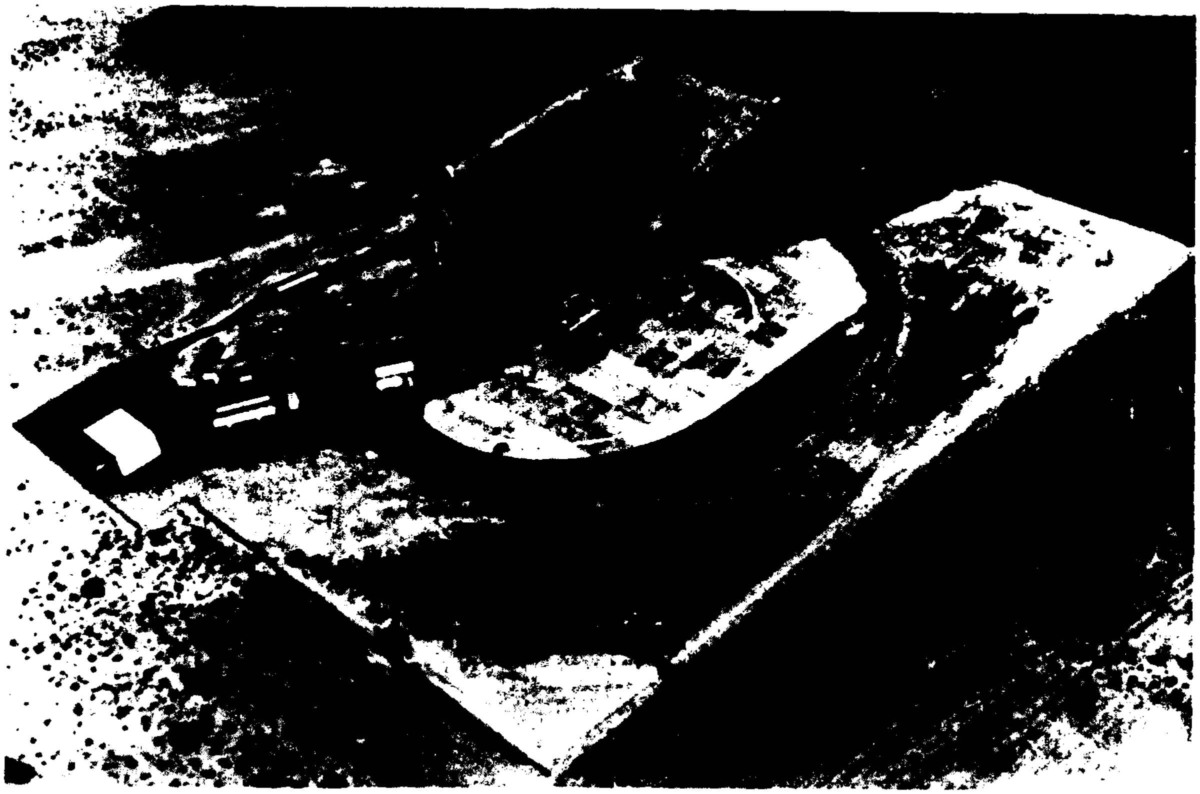
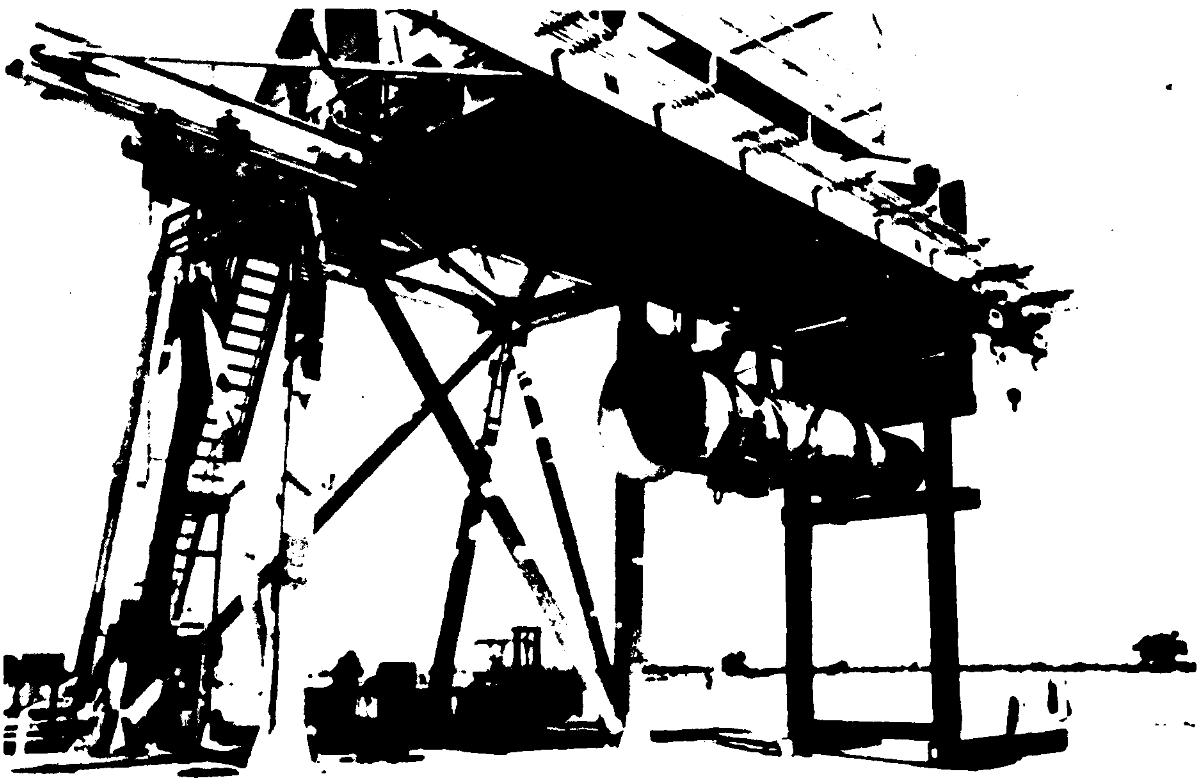


Figure 5. Boardman B2 test site, Boeing.

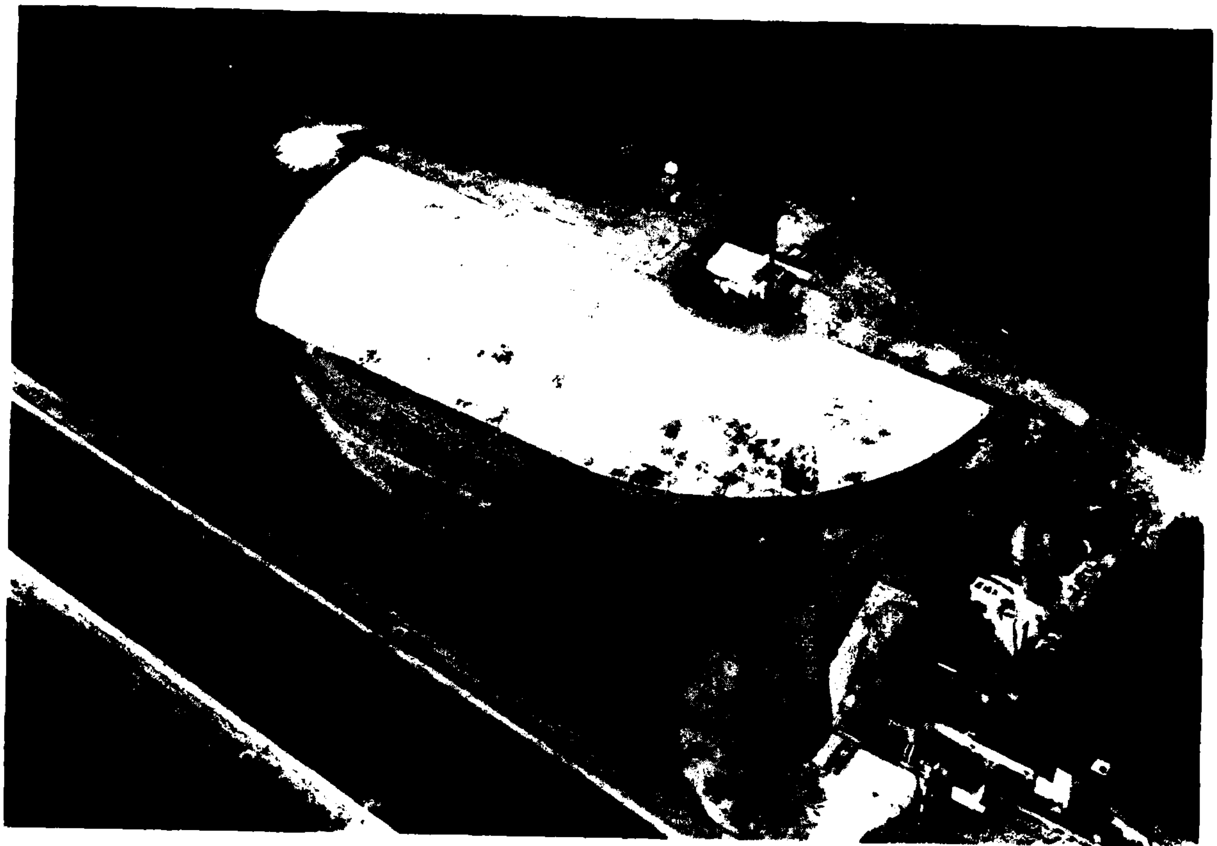


(a) aerial view

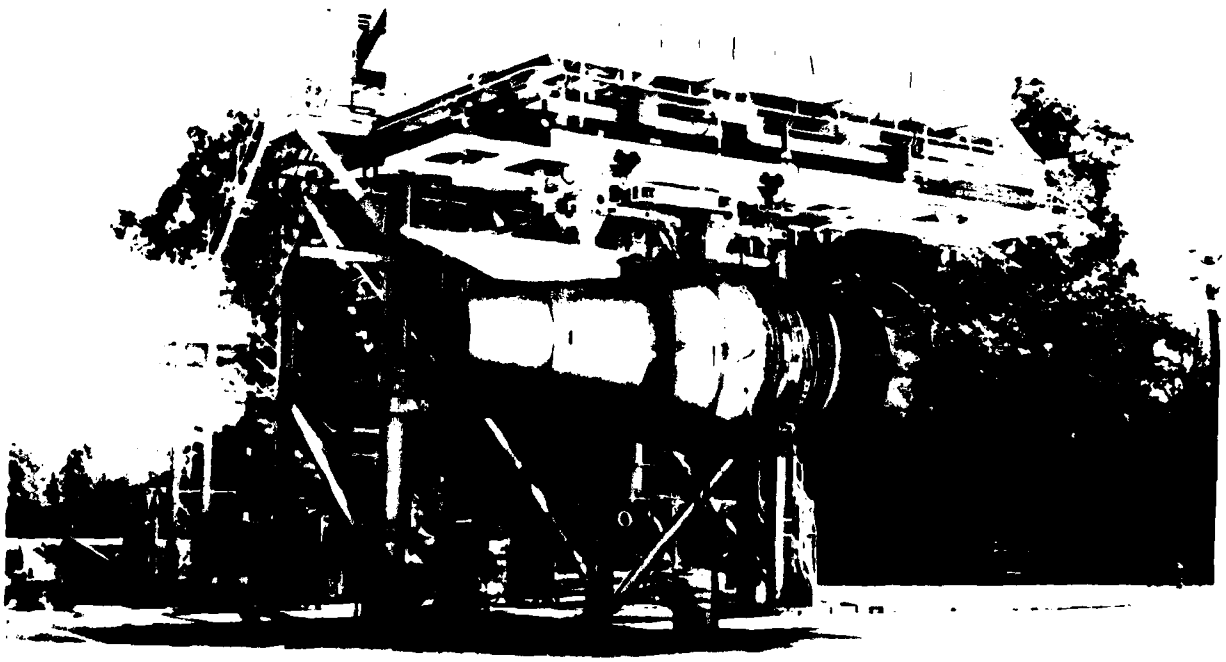


(b) engine on test stand (thrust-reverser test mechanism aft of nozzle)

Figure 6. QIAETsite, McDonnell Douglas.

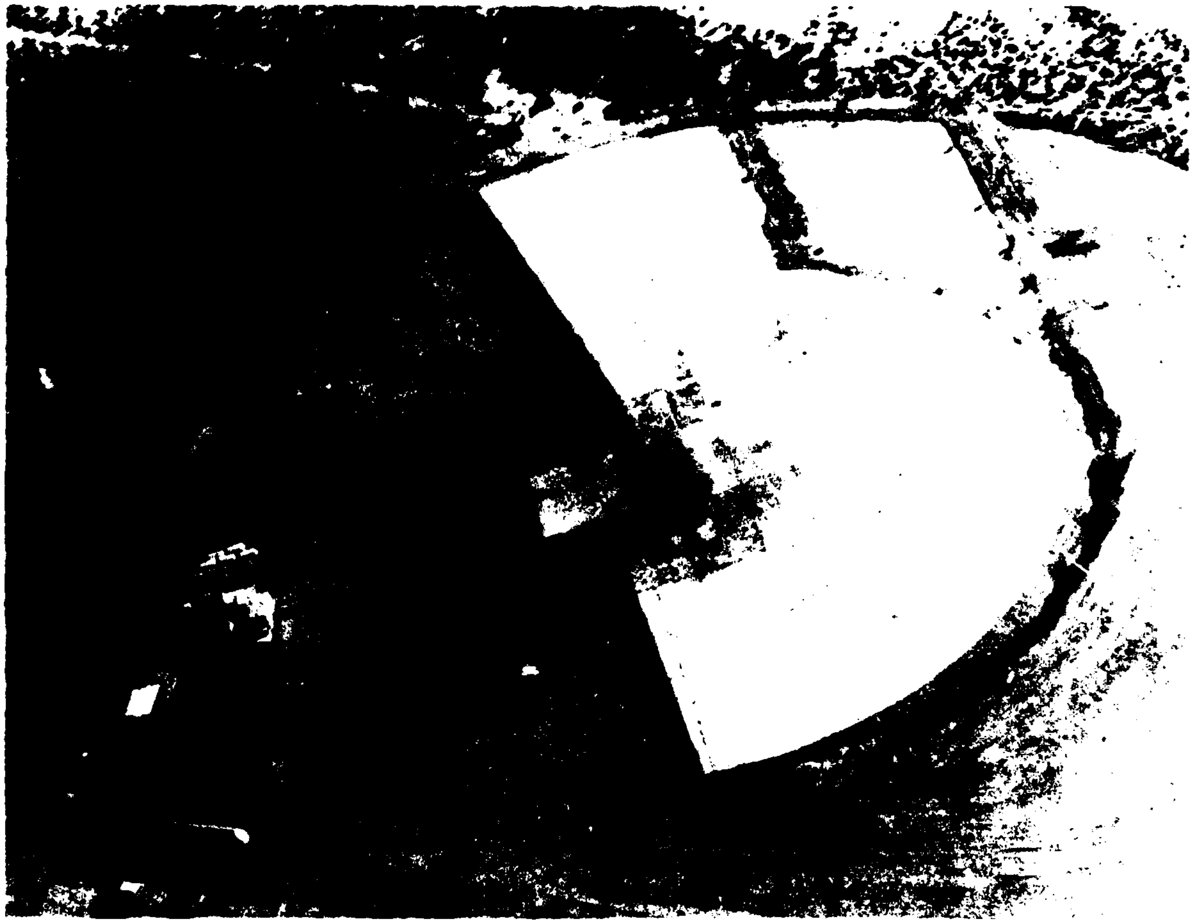


(a) aerial view



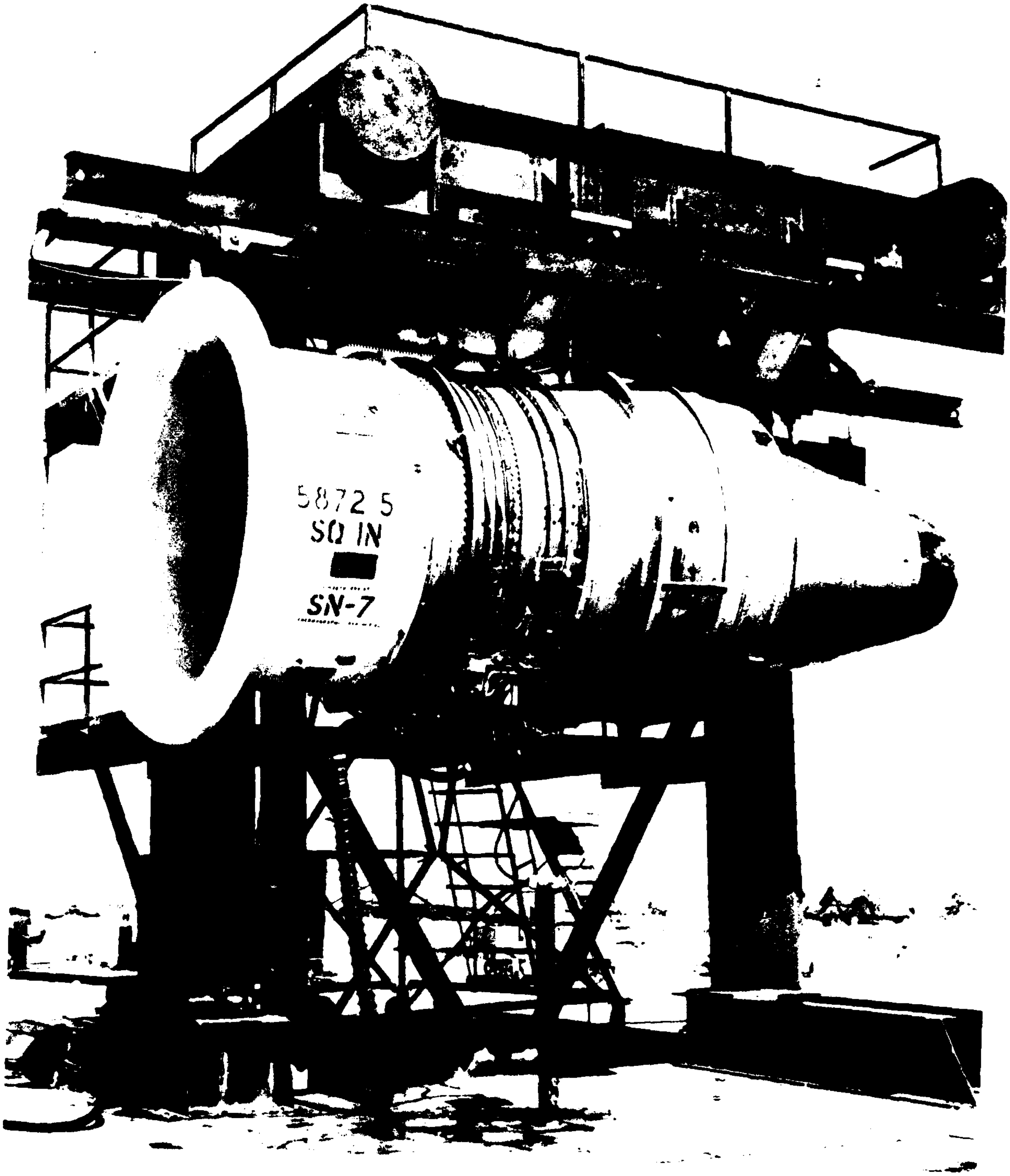
(b) engine on test stand

Figure 7. Peebles test site, General Electric.



(a) aerial view

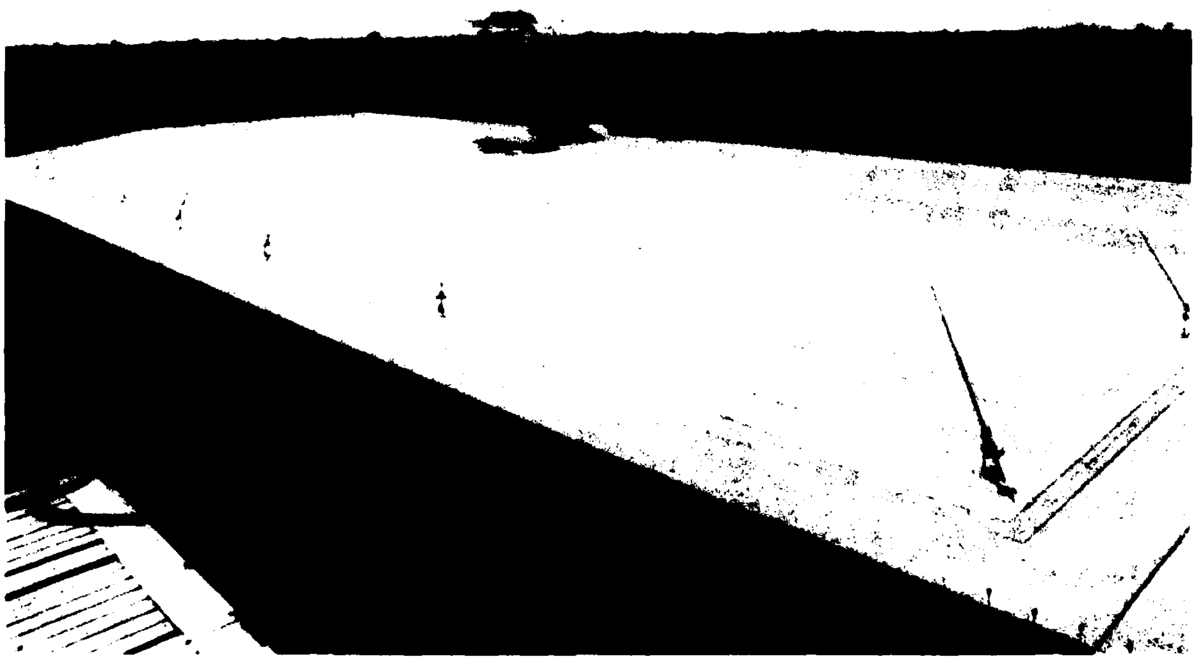
Figure 8. EAFB test site, General Electric.



(b) engine on test stand

Figure 8. Concluded.

(a) view looking forward



(b) rear quarter view

Figure 9. C11 test site, West Palm Beach, P&WA.

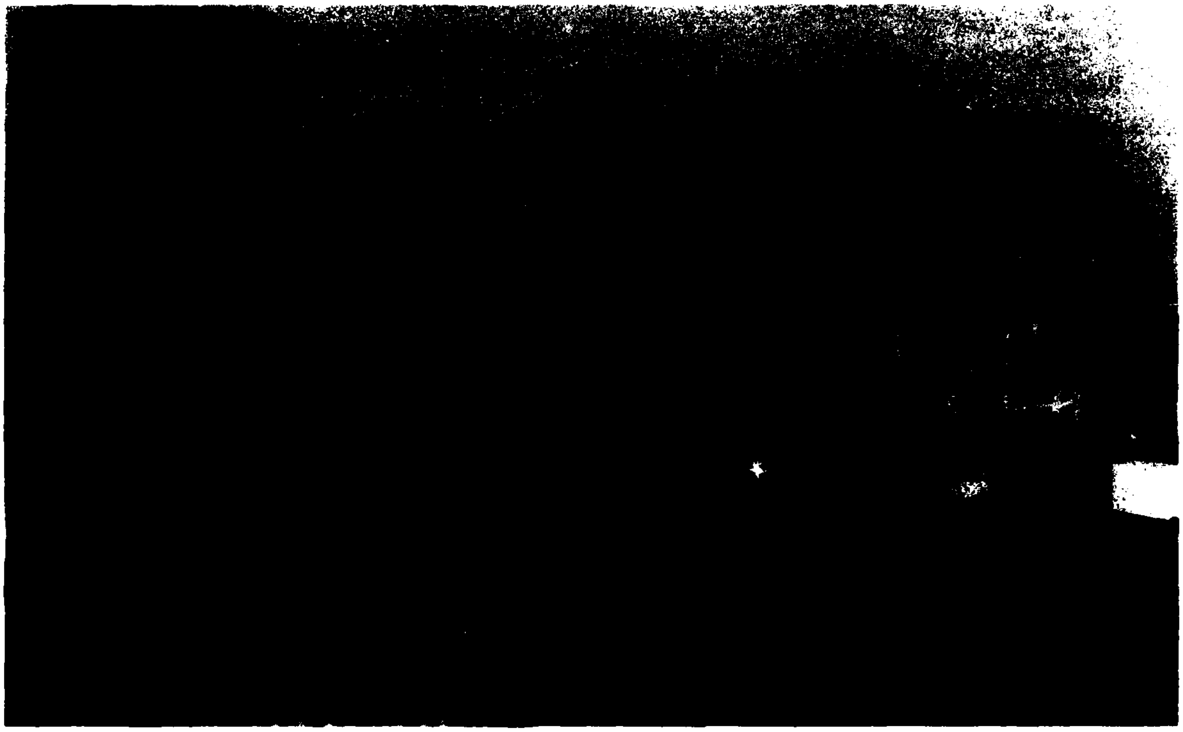
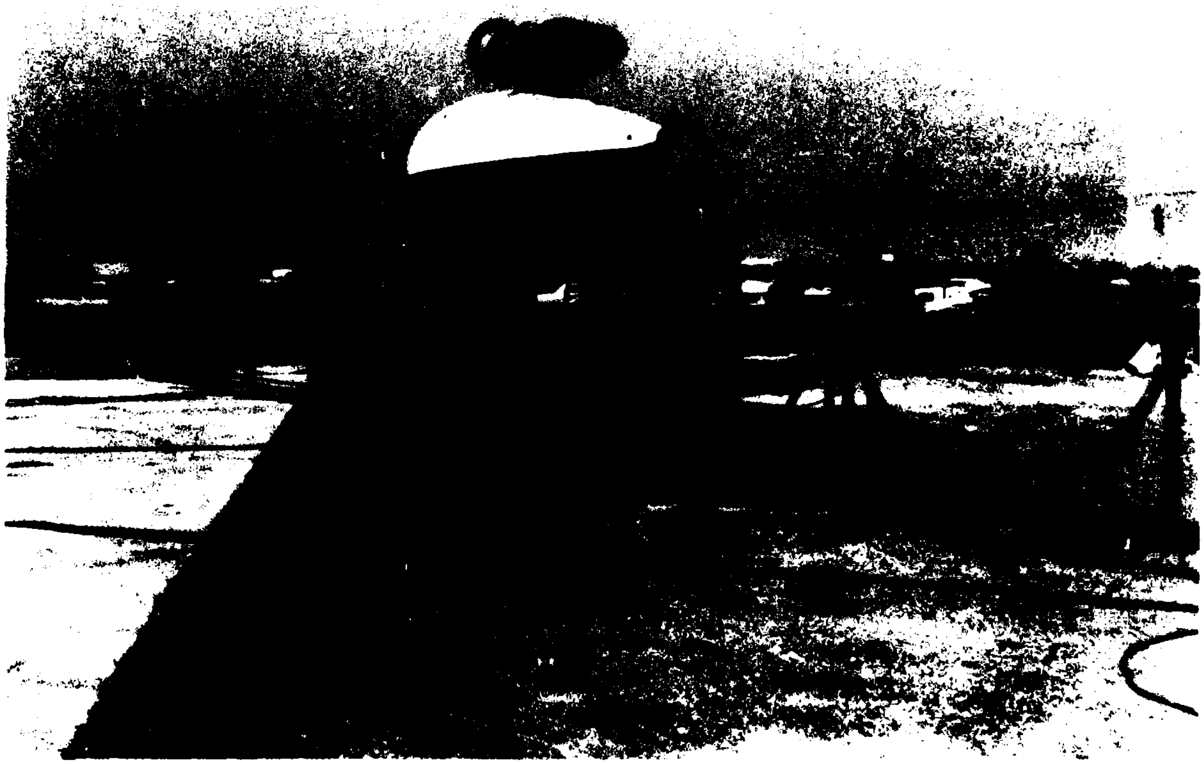


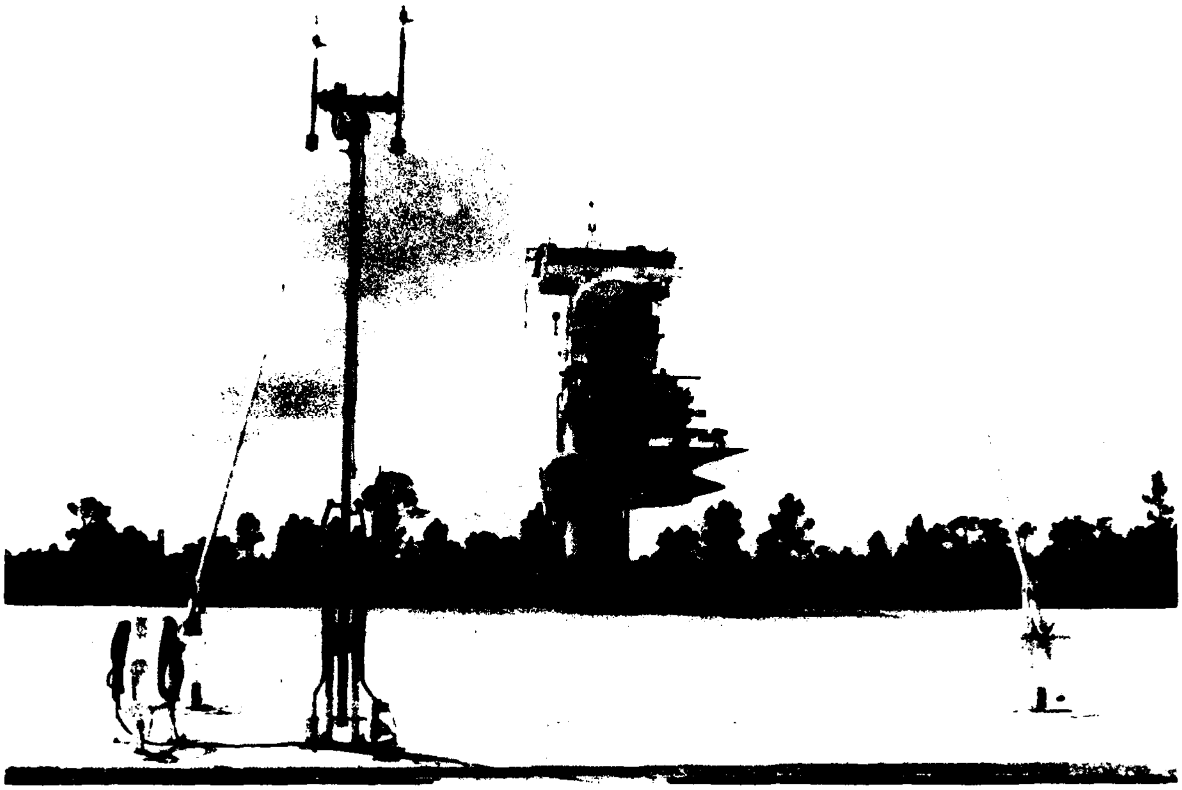
Figure 10. B60 test stand, Rohr.

(a) side view showing farfield microphones
and nearfield microphone on trolley

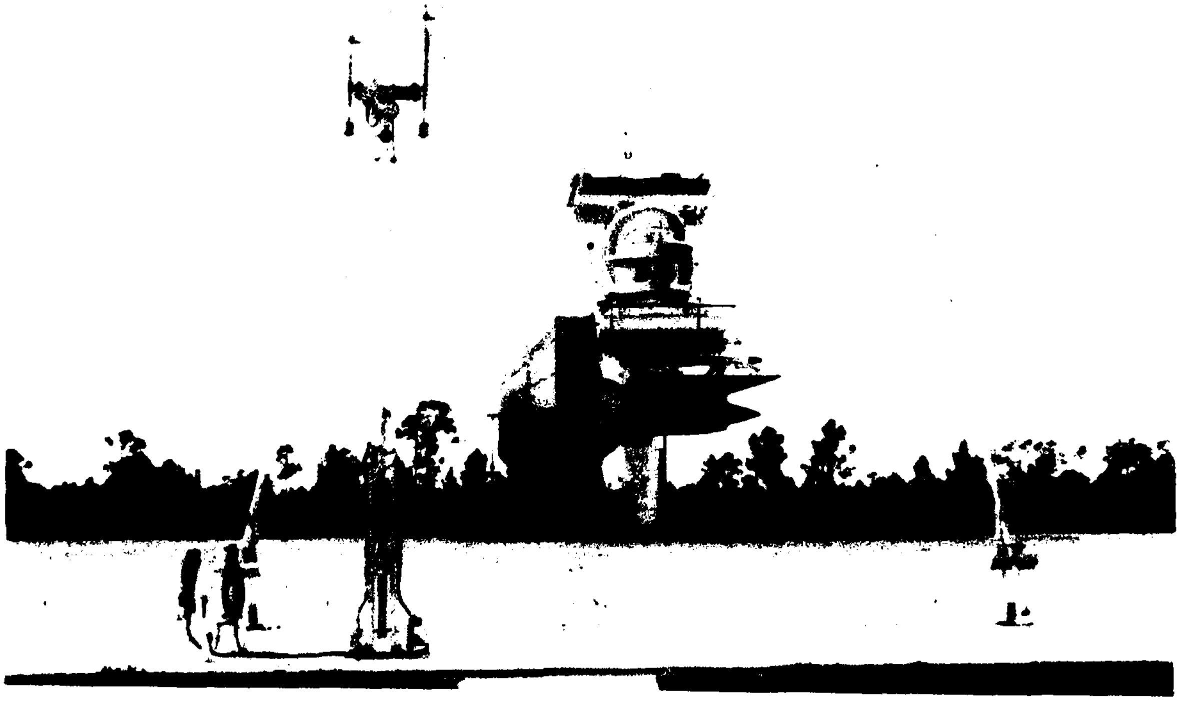


(b) rear quarter view

Figure 11. Test engine on top of aerodynamic fairing on test stand at NASA-Ames test site.



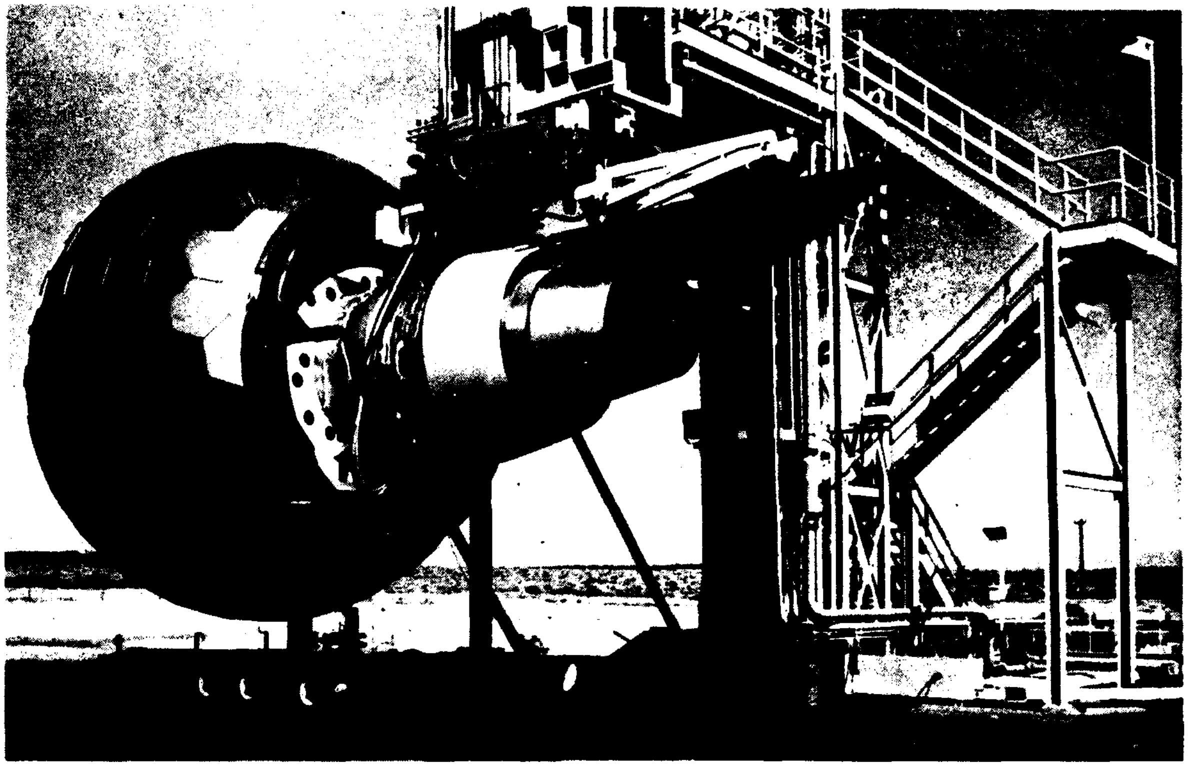
(a) JT9D on test stand; note meteorological test instruments on tower



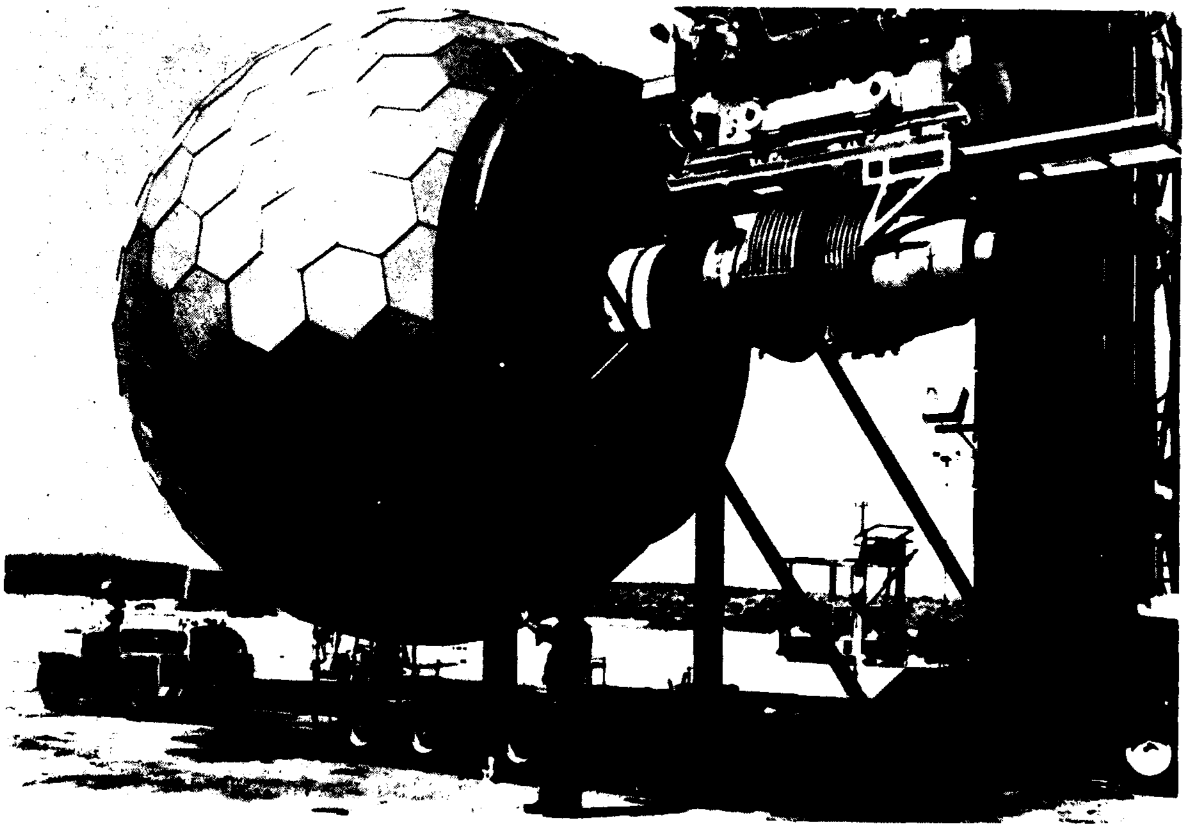
(b) inflow-control device around JT9D

Figure 12. JT9D on P&WA C11 stand without and with inflow-control device around inlet.

Figure 13. Front-quarter view of inflow-control device around inlet duct on JT9D on P&WA C11 test stand.



(a) around CF6



(b) around CF34

Figure 14. Inflow-control device at General Electric's EAFB test stand.

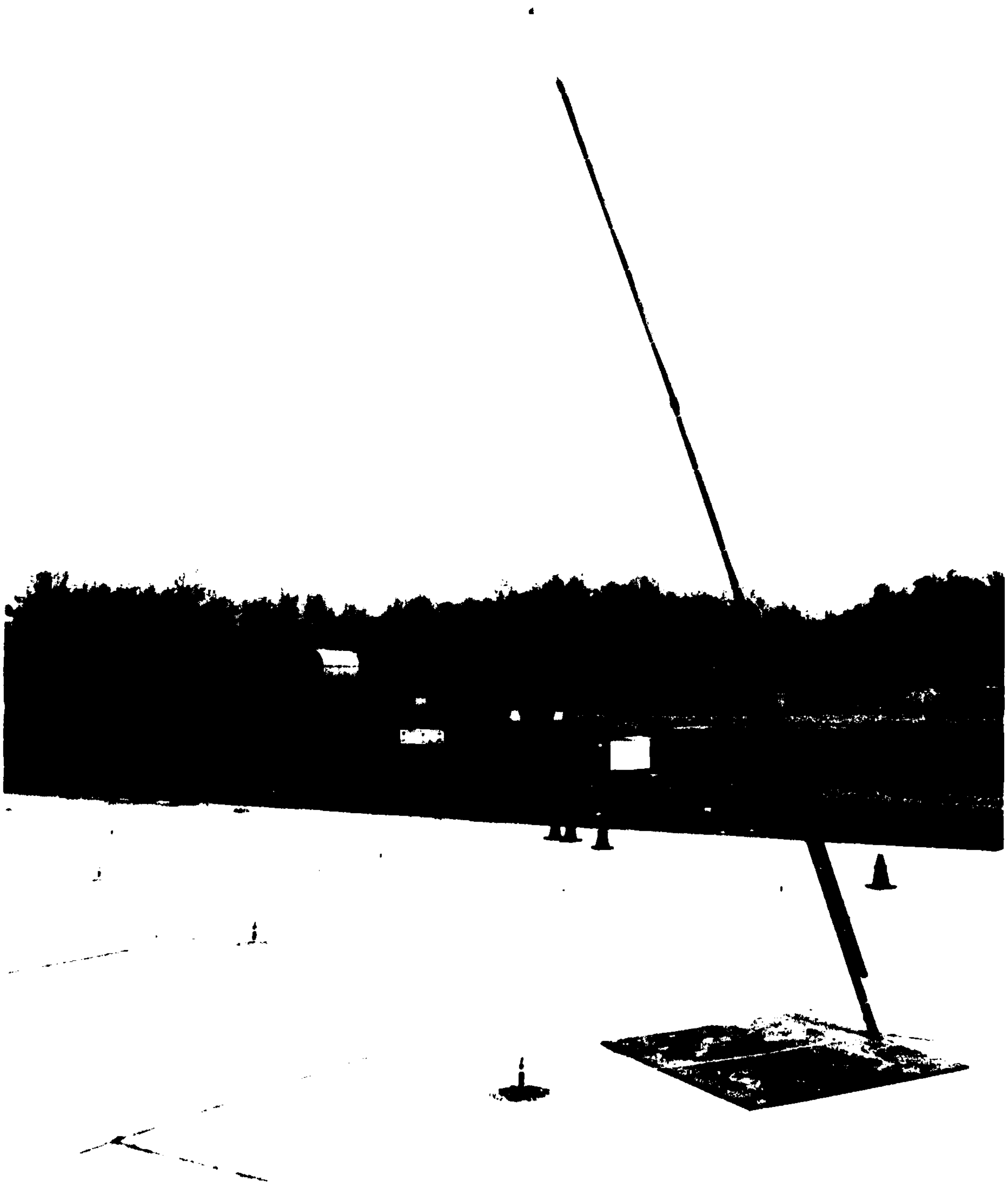


Figure 15. At Boeing's T2 test site at Tulalip, microphone on mast pointing up for 90° (grazing) sound incidence [note that the mast-mounted microphone is above an inverted near-ground microphone].

Figure 16. At General Electric's Peebles test site, microphones on masts pointing at engine for nominal 0° (perpendicular) sound incidence.

Figure 17. At NASA-Ames test site, microphones on masts pointing at engine for nominal 0° (perpendicular) sound incidence [note near-ground microphones below mast-mounted microphones].

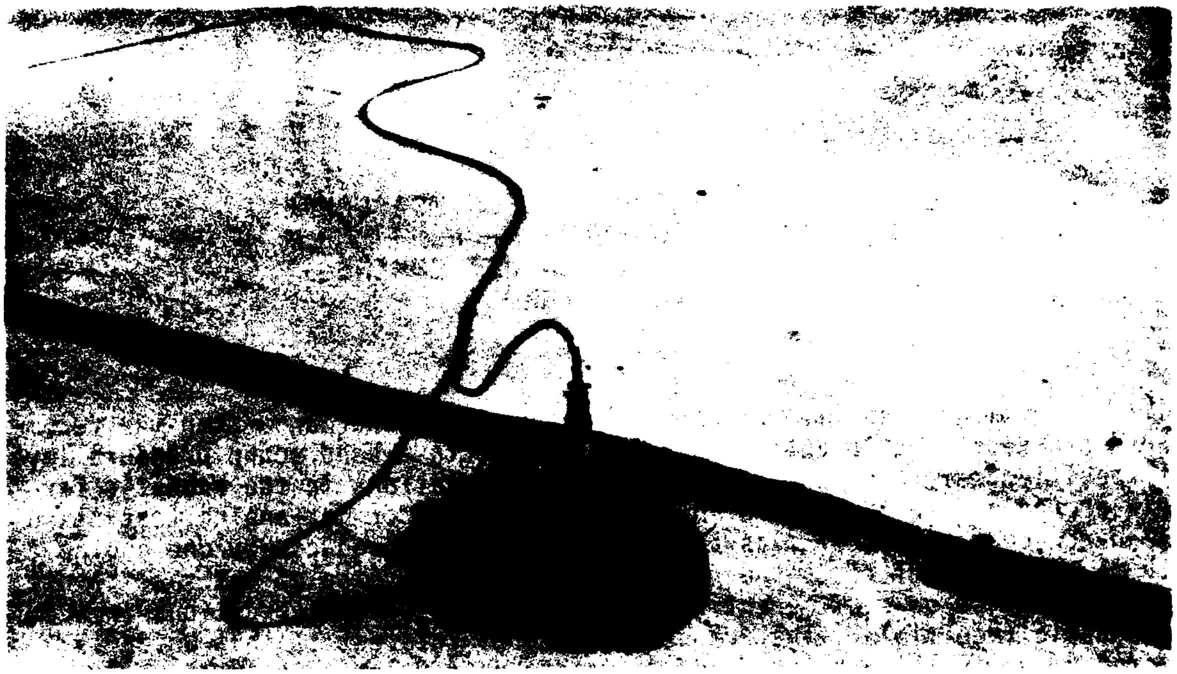


Figure 18. Vertical-axis inverted microphone above metal plate at Boeing's T2 test site at Tulalip.

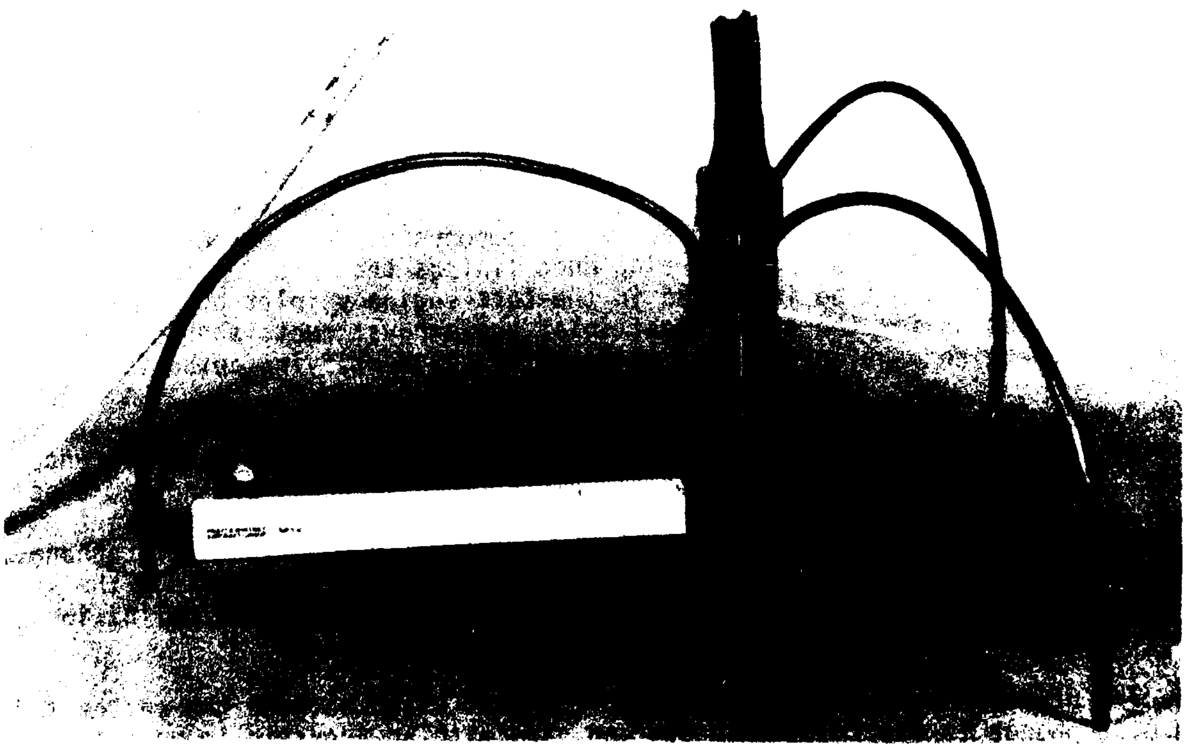


Figure 19. Arrangement used by P&WA for vertical-axis inverted microphone [scale is marked in inches].

APPENDIX

RECOMMENDED PROCEDURES FOR MEASUREMENT OF FARFIELD SOUND PRESSURE LEVELS AROUND AN OUTDOOR JET-ENGINE TEST STAND

0. SUMMARY

0.1 The specific objective of conducting tests in accordance with the recommended procedures is to determine average 1/3-octave-band sound pressure levels for specified reference conditions at several locations in the acoustic far field around a turbofan engine installed on an outdoor jet-engine test stand. To enhance comparisons of measurements of the sound produced by one engine with measurements of the sound produced by another engine of the same thrust class but tested on a different test stand, the reference conditions include an acoustic free field. The frequency range of interest is that which is covered by nominal 1/3-octave-band geometric mean frequencies ranging from 50 Hz to 10 000 Hz.

0.2 The specific purpose of conducting the tests is to determine whether the noise level produced by a test engine, for specified reference conditions, conforms with applicable noise-level standards.

0.3 The recommended procedures are applicable to any turbofan engine designed to produce a thrust force for airplane propulsion by the rate of change of the momentum of the air that passes through the engine. The recommended procedures are not intended to be applicable to jet engines operating with afterburning (or reheat) in the turbine-discharge or fan-discharge ducts.

0.4 The recommended configuration for the test engine includes a special inlet duct and special exhaust ducts so that the farfield sound pressure levels may represent measurements of the sound produced by a basic engine without the influence of unique airplane-dependent duct components, duct shapes, or duct lengths. Specifically, sound-absorbing duct linings that are not part of the basic engine should not be installed in the test engine's inlet or exhaust ducts. The design for the static-test inlet and exhaust ducts should be developed by the engine manufacturer and approved by the certifying authority.

0.5 Primary locations for measuring farfield sound pressure levels are at several fixed positions along a circular arc centered on the engine reference point. Because of the extent of the sources of low-frequency jet noise, especially at high engine power settings, for those microphones at measurement location angles greater than 90° it may be desirable to substitute microphone locations along a line parallel to the engine axis for locations along the circular arc. Microphone spacing should be close enough for good definition of directivity patterns in any 1/3-octave band of interest.

0.6 The preferred ground surface around the test stand between the engine and the microphones is one that is smooth and hard with an acoustic impedance which approximates that of a perfect sound reflector. If another type of ground surface is used, the difference between the acoustic impedance of the surface and the acoustic impedance of a smooth, hard surface should be taken into account.

0.7 If turbulent inhomogeneities in the airflow into the inlet or steady distortion in the inlet airflow have a significant effect on the sound generated by the engine, then an inflow-control device (or turbulence-control structure) should be placed around the test engine's inlet when farfield sound pressure levels are being measured.

0.8 Meteorological conditions at the time of the test should be limited to air temperatures greater than -10° C and relative humidities less than 95 percent with no condensation or precipitation of atmospheric moisture. The wind speed and wind direction should not have any significant effect on the stability of engine operation at any power setting or on the measurement of farfield sound pressure levels.

0.9 Sound pressure levels should be recorded for a duration of at least 30 seconds at several engine power settings ranging from approximately 20 percent to 100 percent of maximum available gross thrust. Engine rotational speed should be stable when sound pressure levels are being recorded. Engine performance parameters and meteorological data should be recorded.

0.10 The number of engine power settings per test run should be sufficient to define, with 90-percent confidence, the variation of the noise-evaluation quantity with referred net thrust. The number of engine power settings per test run should be between 10 to 15. The increment between adjacent values of the power-setting parameter should be relatively small around the values of referred net thrust established by the engine manufacturer for the engine-noise type certificate. Referred net thrust is actual net thrust divided by the ratio of ambient air pressure to the standard air pressure at mean sea level.

0.11 Farfield sound pressure levels should be measured during at least two test runs to provide sufficient data to establish, with confidence, the mean variation of the noise-evaluation quantity with referred net thrust. Prevailing meteorological conditions should be somewhat different during each test run.

0.12 A mean line for the variation of the average value of the noise-evaluation quantity with referred net thrust should be fitted to all data points by a regression technique or an approved engineering method. At least 90 percent of all data points should lie within ±1 dB of the mean line. The values of the noise-evaluation quantity at the values of referred net thrust applicable to the engine-noise type certificate should be determined from the mean line.

0.13 The recommended procedures include the following items:

(1) test objectives
(2) scope and applicability
(3) reference conditions
(4) frequency range of interest
(5) test site
(6) engine test stand
(7) engine reference point
(8) configuration of test engine
(9) test-time meteorological conditions
(10) measurement of meteorological conditions
(11) measurement of engine-performance conditions

(12) elements of the system for measurement of farfield sound pressure levels
(13) performance requirements for sound-measuring system
(14) microphone locations
(15) microphone installations
(16) test procedures
(17) determination of test-time sound pressure levels
(18) adjustments to reference conditions
(19) number of test runs
(20) determination of the noise-evaluation quantity
(21) information to be reported

1. TEST OBJECTIVES

For each engine power setting in each test run, the basic test objective is to obtain time-averaged one-third-octave-band sound pressure levels in the acoustic farfield around a turbofan engine installed on an outdoor engine test stand and equipped with a specific inlet duct and specific exhaust ducts. The microphones should be installed such that the measured sound pressure levels can be adjusted to equivalent free-field sound pressure levels. Engine-performance and meteorological conditions should also be measured so that the test-time sound pressure levels may be adjusted to reference engine and meteorological conditions. After the measured sound pressure levels have been adjusted to reference conditions, the final sets of sound pressure levels applicable to the reference engine power settings should be obtained from the ensemble average of the time-averaged sound pressure levels from the individual test runs.

2. SCOPE AND APPLICABILITY

The recommended test procedures are applicable to any air-breathing gas-turbine engine designed to operate with a turbofan thermodynamic engine cycle and to deliver a thrust force by means of the rate of change of the momentum of the air passing through the engine. The procedures are specifically applicable to turbofan engines designed for airplane propulsion. The basic engines may incorporate variable-geometry devices within the flow path, but not within the inlet or exhaust ducts. The procedures are not applicable to measurements of the sound produced when an engine is operated with afterburning (or reheat) in the turbine-discharge of fan-discharge ducts.

3. REFERENCE CONDITIONS

3.1 Reference meteorological conditions are:

(1) air pressure of 101.325 kPa
(2) air temperature of 25° C
(3) relative humidity of 70 percent
(4) wind speed of zero.

3.2 The reference acoustical condition for sound propagation is that of an acoustic free field in spherical space.

4. FREQUENCY RANGE OF INTEREST

The frequency range of interest is that covered by one-third-octave-band filters having geometric mean frequencies ranging from 50 Hz to 10 000 Hz. The lowest frequency of interest is thus approximately 45 Hz, the highest is approximately 11 000 Hz.

5. TEST SITE

5.1 The test site where the outdoor engine test stand is located should be in a location that, on an annual average basis, has long periods with low ambient noise levels, low wind speeds, moderate temperatures, and little precipitation.

5.2 The test site is preferably located in an area with relatively flat and open terrain. There should be no structures or natural obstacles that reflect or scatter sound waves toward the farfield microphones so as to significantly interfere with measurements of engine noise.

6. ENGINE TEST STAND

6.1 The preferred arrangement for supporting the test engine is by a structure that has minimal influence on engine noise generation or propagation. The structure should not be the source of distorted airflow into the engine's inlet so as to significantly influence sound generation. Exhaust gases should not impinge on any test-stand structure.

6.2 There should be only a minimum of test-stand structure that could reflect sound toward the microphones or interfere with the propagation of sound waves from the engine to the microphones. Large reflecting surfaces should be avoided or covered with a sound-absorbing material if they reflect significant sound energy toward the microphones.

6.3 The surface below the engine should preferably be a concrete pad.

6.4 The height of the engine centerline above the ground plane should be at least 1.5 times the diameter of the fan rotor blades.

6.5 The test stand should be equipped with calibrated instruments capable of measuring and recording various internal engine parameters such as shaft speeds, pressures, and temperatures. It is recommended that the test stand be equipped with a calibrated system for direct measurement of the thrust force produced by the engine. Simultaneous measurement of engine-performance parameters and farfield sound pressure levels is preferred.

6.6 If turbulent inhomogeneities in the airflow into the inlet or steady distortion in the inlet airflow have a significant effect on the sound generated by the engine, then an inflow-control device (or turbulence-control structure) may be placed around the test engine's inlet duct when farfield sound pressure signals are being measured. The device should be essentially transparent to sound waves in the frequency range of interest and should not alter the directivity of the sound generated by the engine. The device should produce only a minimal drag force on the engine and is preferably supported independent of the engine-support structure.

6.7 The surface of the ground plane between the engine and to at least two meters beyond the most-distant microphone in any direction should be light-colored to minimize solar heating and thermal gradients, uniform in texture, smooth with minimal gaps, and hard with an acoustic impedance which approximates that of a perfect acoustic reflector at the lowest frequency of interest. Such a surface may be provided by troweled concrete or smooth, well-sealed, white-painted asphalt. The ground surface may have a slight slope for drainage. When sound pressure levels are measured, the surface of the ground plane should be free of snow, ice, or standing water.

6.8 The surface of the ground plane under and around the instruments used to measure meteorological conditions should have the same acoustical characteristics as the surface of the ground plane between the test engine and the microphones.

6.9 The engine control room and other test stand related structures should not be located between the test engine and the farfield microphones. The structures may be located below the level of the ground plane or above the ground plane. If the structures are above the ground plane, the exterior surfaces may be slanted so that sound from the test engine is reflected away from the microphones. The exterior surfaces of the above-ground structures may be covered with sound-absorbing material if reflections from the surface cause significant interference with the measurements of farfield sound pressure signals.

6.10 Simulated sections of airplane structure (such as a wing or fuselage) should not be installed when farfield sound pressure signals are being measured.

7. ENGINE REFERENCE POINT

The preferred location for the engine reference point is on the engine centerline at the center of the exit plane of the turbine-exhaust nozzle, if the engine has separate nozzles for the fan and turbine exhausts, or at the center of the exit plane of the final nozzle if the engine has a mixed-flow exhaust system. Other locations are acceptable, but it is recommended that all sound pressure levels be reported in terms of a coordinate system centered on the preferred engine reference point.

8. CONFIGURATION OF TEST ENGINE

8.1 The internal configuration of the test engine should be that for which an engine-noise type certificate is sought. All noise-control features included as components of the basic engine should be installed.

8.2 The preferred configuration for the inlet and exhaust ducts to be installed on the test engine does not have airplane-specific items such as variable-geometry devices, sound-absorbing duct linings, or thrust reversers.

8.3 The preferred shape for the test engine's inlet duct is that of an axisymmetric bellmouth symmetric about the engine centerline. A cylindrical section may be included ahead of the engine manufacturer's inlet flange.

8.4 The length of the exhaust ducts and shape of the exhaust nozzles can influence the generation of external jet-mixing noise. It is preferred that the exhaust nozzles have a fixed, round (or essentially round), axisymmetric, convergent shape. For engines designed to be operated with separate-flow exhaust systems, a relatively short fan-exhaust duct is preferred over a mid-length or long fan-exhaust duct. Engines designed to be operated with mixed-flow exhaust systems should be tested with an appropriate mixed-flow nozzle. The exhaust flow should be directed to the rear with the thrust vector essentially parallel to the engine centerline.

8.5 The engine manufacturer, or applicant for an engine-noise type certificate, should develop recommendations for the design of a test inlet and test exhaust ducts. The recommendations should be submitted to the certifying authority for approval.

8.6 The structure of an engine nacelle may be simulated and installed downstream of the exit of the nozzle on short fan-exhaust ducts if necessary to prevent the exhaust gases from impinging on engine accessories or components.

9. TEST-TIME METEOROLOGICAL CONDITIONS

Measurements of farfield sound pressure levels should not be considered valid for engine-noise type certification purposes except when meteorological conditions at the test site conform to the following:

(1) no measureable precipitation in any form including dew, frost, snow, or ice
(2) air temperature greater than -10° C
(3) relative humidity less than 95 percent
(4) over the duration of the sound pressure recordings, the time-average wind speed low enough to not have any significant effect on the stability of engine operation or on the measurement of farfield sound pressure signals. Consistent with those objectives, it is recommended that the wind speed be not greater than 5 m/s, with short-duration wind gusts not greater than 10 m/s, and that the wind direction be as a headwind within ±45° of the inlet axis
(5) if the wind direction is primarily that of a crosswind or primarily as a tailwind, the maximum permissable average wind speed may be less than when the wind direction is as a headwind because of the effect of crosswinds or tailwinds on the ability of the engine to maintain a stable running condition; crosswinds may also affect the measurements of farfield sound pressure signals.

10. MEASUREMENT OF METEOROLOGICAL CONDITIONS

10.1 Instruments to measure the temperature and relative humidity of the ambient air and the speed and direction of the wind should be at a distance from the engine reference point that is of the order of two meters greater than the distance to the farfield microphones and over the same ground-plane surface. The instruments should be mounted on a mast in the inlet quadrant between 0° and 90° from the inlet axis. The height of the instruments over the ground plane should be chosen to provide meteorological data representative of conditions along the sound propagation paths from the sources of engine noise to the various farfield microphones. If near-ground microphones are used, additional instruments should be installed to measure gradients and fluctuations of air temperature near the ground surface.

10.2 Atmospheric pressure may be measured at any convenient location near the test site.

10.3 Meteorological conditions should be recorded at a relatively high sample rate, preferably continuously, whenever acoustical and associated engine-performance data are being recorded.

10.4 Instruments used to measure meteorological conditions should be accurate within the following tolerance limits:

(1) ±0.3° C for air temperature
(2) ±5 percentage points for relative humidity
(3) ±1 m/s for wind speed for speeds greater than 1 m/s
(4) ±5° for wind direction
(5) ±5 kPa for air pressure

11. MEASUREMENT OF ENGINE-PERFORMANCE CONDITIONS

11.1 Measurements of internal engine conditions should be sufficient to accurately characterize engine performance, to determine the degree of engine stability at a given engine power setting, and to provide the information needed to adjust the measured sound pressure levels to reference conditions. As a minimum, the following engine-performance parameters should be measured and recorded:

(1) rotational speed of each compressor and turbine shaft
(2) total pressure in each exhaust nozzle
(3) total temperature in each exhaust nozzle

11.2 If the engine test stand is equipped to measure and record the thrust produced by the engine, then the gross thrust should also be measured and recorded. If the engine test stand is not equipped to measure the thrust produced, then an approved alternative procedure is required to determine the thrust that was produced when farfield sound pressure signals were being recorded.

11.3 The sampling rate for measurement of engine-performance conditions should be consistent with the stability of engine operation. Although continuous recordings are preferred, engine-performance parameters may be sampled at a rate rapid enough to ensure that engine speed and other conditions are within tolerance limits for stable operations.

11.4 The accuracy of the instruments used to measure engine-performance parameters should be consistent with customary practice for engine-performance testing.

11.5 Measurements of engine-performance parameters should recognize the possibility that instruments installed in the engine's gas-flow passages may introduce unwanted flow disturbances and may act as sources of extraneous noise. Installation of nonessential instruments or other objects in the engine's gas-flow passages should be avoided. However, if the instruments or other objects are considered by the engine manufacturer to be components of the basic engine and are to be installed in every engine of that type, then they should be in place when the farfield sound pressure signals are measured.

12. ELEMENTS OF THE SYSTEM FOR MEASUREMENT OF FARFIELD SOUND PRESSURE LEVELS

12.1 The following items should be available to record calibration signals in the field:

(1) an acoustical calibrator
(2) a generator of wideband random-amplitude electrical signals having a pink-noise frequency spectrum or a generator that produces constant-amplitude sinusiodal signals over the frequency range of interest

12.2 The total system for measuring and recording farfield sound pressure signals and determining one-third-octave-band sound pressure levels should include at least the following components or their equivalent:

(1) measurement microphones
(2) signal-conditioning and transmission components (including preamplifiers, electrical power supplies, and cables)
(3) multi-channel recording devices
(4) multi-channel reproducing devices
(5) one-third-octave-band filter systems

12.3 Windscreens should be available to place around the microphones if necessary.

12.4 High-pass electrical filters having a turnover frequency of the order of 15 Hz may be incorporated in the measurement system before the multi-channel recording devices to prevent the recording of spurious wind-generated low-frequency signals or low-frequency ambient noise.

12.5 It is recommended that an electric time-code generator be available to permit the recording of time-code signals on one channel of the multi-channel recording device whenever sound pressure or calibration signals are recorded.

13. PERFORMANCE REQUIREMENTS FOR SOUND-MEASURING SYSTEM

13.1 The acoustical calibrator should produce a sinusoidal signal at a frequency of 250, 500, or 1000 Hz. The actual frequency should be within ±5 percent of the nominal frequency. The sound pressure level of the calibration signal should be at least 15 dB greater than the greatest expected value of the wideband ambient noise level. The actual sound pressure level of the signal produced by the calibrator at the sensing element of the microphone should be determined by a laboratory calibration. Procedures should be available from the manufacturer of the acoustical calibrator to account for the change in output sound pressure level resulting from the air pressure and air temperature at the time of the test being different from the pressure and temperature of the air applicable to the laboratory calibration of the calibrator.

13.2 The spectrum of the pink-noise signal from the random noise generator should be within ±1 dB of the theoretical spectral slope of -1 dB per octave of frequency over the frequency range from 40 Hz to 11 000 Hz. The wideband (20 Hz to 20 000 Hz), open-circuit, root-mean-square pink-noise output voltage should be at least 500 mV and should be adjustable.

13.3 Measurement microphones may be those designed to have the flattest frequency response over the widest range of frequencies for sounds incident on the sensing element with either random incidence or 0° incidence (perpendicular incidence). Microphone diameter should be consistent with the need for high sensitivity and low electrical noise in order to yield high ratios of signal-to-noise at the input to the multi-channel recorder. When tested under acoustic free-field conditions, microphone response should be essentially omnidirectional for frequencies in the range of interest.

13.4 In an acoustic free field, the response of the microphone and its associated preamplifier to sinusoidal sound signals that impinge on the microphone's sensing element in the calibration direction should be within the following tolerance limits relative to the response at 1000 Hz:

from 45 Hz to 4500 Hz: ±1 dB
from 4500 Hz to 11 200 Hz: +1.5, -2 dB

13.5 When exposed to sinusoidal signals in an acoustic free field, the response of the microphone and its associated preamplifier, relative to the response in the calibration direction, should be within the following tolerance limits for sound waves that impinge on the sensing element within ±30° of the calibration direction:

from 45 Hz to 2250 Hz: ±1 dB
from 2250 Hz to 4500 Hz: ±1.5 dB
from 4500 Hz to 9000 Hz: ±2 dB
from 9000 Hz to 11 200 Hz: ±3 dB

13.6 If random-incidence microphones are used, calibration procedures should be specified by the microphone manufacturer.

13.7 In an acoustic free field, the amplitude response of the microphone and associated preamplifier to sinusoidal sound signals, of any frequency and signal amplitude in the ranges of interest, should be within ±0.3 dB of a linear relationship between mean-square output voltage level and mean-square input sound pressure level.

13.8 The effect on microphone sensitivity of any windscreen, to be used around a farfield measurement microphone, should not exceed ±1 dB, relative to the sensitivity determined without a windscreen around the microphone, for any 1/3-octave-band center frequency between 50 Hz and 10 000 Hz. The effect of a windscreen on microphone response should be determined as a function of frequency, sound-incidence angle, and wind-incidence angle for various steady wind speeds.

13.9 The overall frequency response of the data-acquisition and data-reduction system (exclusive of the microphones and any windscreens) to electrical signals should be within ±1 dB of the response at 1000 Hz over the frequency range from 40 Hz to 11 000 Hz. The overall electrical response should be within the ±1 dB tolerance limits for all recording-system gain-control settings that are used when acoustical data are being recorded.

13.10 The number of data-recording channels on the recording device should permit the simultaneous recording of as many acoustical data channels as possible.

13.11 The electrical transmission-loss response of the one-third-octave-band filters should conform with the latest revision of American National Standard Specification for Octave and Fractional-Octave-Band Filters, ANSI S1.11-1966 or the comparable publication of the International Electrotechnical Commission, IEC Publication 225 (1966) for at least Class 3 filters. Each filter should also meet the applicable requirements for effective bandwidth and passband uniformity.

13.12 For each one-third octave band, the output of the data-reduction system should be one-third-octave-band sound pressure levels, in decibels, represented mathematically by

$$L_p(f) = 10 \lg\left\{\left[(1/T)\int_0^T p_f^2(t)\mathrm{d}t\right]\Big/ p_0^2\right\} \tag{A1}$$

where $p_f(t)$ is the instantaneous time-varying sound pressure signal, in pascals, at the output of a filter having geometric mean frequency f, T is the averaging time in seconds, p_0 is the reference sound pressure of 20 micropascals, and lg is the symbol for common or base-10 logarithms.

13.13 The data-processing system that performs the squaring, integrating, time averaging, logarithm taking, and scaling functions may use analog techniques, digital techniques, or a combination of analog and digital techniques to approximate the process indicated by Eq. (A1).

13.14 The resolution of the one-third-octave-band sound pressure levels at the output of the data-processing system should be consistent with the purpose of the test.

14. MICROPHONE LOCATIONS

14.1 Microphones should be located at several locations in the farfield over the surface of the special ground plane. Primary locations are along a circular arc centered on the engine reference point. Microphone locations should be identified by radial distance and polar angle with 0° in the forward direction and 180° in the aft direction.

14.2 The radius of the circular arc should be at least 15 times the diameter of the fan rotor blades or 25 times the effective nozzle exit diameter, whichever is greater. The effective nozzle exit diameter, D_e, should be determined from the total nozzle exit area using the relationship

$$D_e = \sqrt{4(A_p + A_f)/\pi} \tag{A2}$$

where A_p is the nominal exit area of the primary or turbine-discharge nozzle and A_f is the nominal exit area of the fan-discharge nozzle.

14.3 If microphones on the primary circular arc at polar angles greater than 90° are considered to not be in the acoustic farfield for sources of low-frequency jet-mixing noise, especially at high engine power settings, then supplemental microphone locations may be chosen along a line extending aft and parallel to the engine centerline. The length of the sideline array should be determined from preliminary tests and should be sufficient to ensure adequate measurement of low-frequency jet-mixing noise.

14.4 Figure A1 is a schematic illustration of the use of forward and aft circular arcs and a sideline. Microphone locations on the circular arcs should be chosen so as to avoid impingement by exhaust flow.

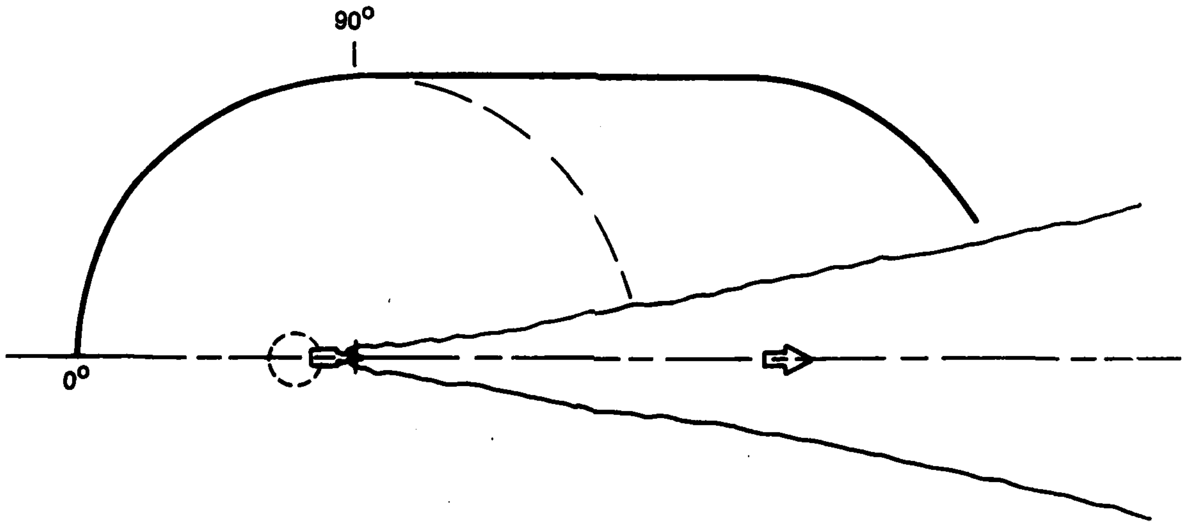


Figure A1.-Schematic illustration of combination of forward and aft circular arcs with sideline for far-field microphone locations around engine on static engine test stand

14.5 Microphones may be located along paths other than those recommended here providing all locations are in the acoustic farfield at the lowest frequency of interest for the noise source that is largest in extent. Alternative microphone locations should continue to be designated by polar radius from the engine reference point and polar angle relative to the engine centerline and the forward direction.

14.6 The total number of microphones and their placement at positions along the farfield arrays should be sufficient to define, with good resolution, the farfield directivity of the sound produced by the test engine. Microphone spacing along the circular arcs should not exceed 10°. Suitable microphone spacing along a sideline array should be determined from preliminary tests. Microphones should be spaced at less than 10° intervals in regions where the sound radiation patterns have maximum directivity.

15. MICROPHONE INSTALLATIONS

15.1 There are two types of microphone installation recommended for farfield sound pressure level measurements. Valid data can be obtained from each type of microphone installation.

15.2 In one type of microphone installation, the microphone is located near the ground plane. The distance above the ground plane should be small enough that the direct and reflected sound signals from the engine are essentially in phase without spectral-interference effects. The resulting measurements of sound pressure level are, theoretically, 6 dB greater than the equivalent free-field sound pressure levels at all frequencies in the range of interest. To minimize the effort required to determine appropriate corrections for microphone directional response, the preferred orientation for installation of a near-ground microphone is that which provides grazing (or near-grazing) incidence for all sources of engine noise.

15.3 To ensure that the ground surface simulates an acoustically hard surface as closely as possible, the region around the locations of the near-ground microphones may be treated locally with a special coating. The use of a board or plate under a near-ground microphone is not recommended.

15.4 Since microphones may be mounted near the ground plane in a variety of ways, the organization responsible for conducting the tests should be able to provide experimental evidence that a proposed installation for a near-ground microphone does yield sound-pressure-level spectral data which are free of interference effects. One technique that has been used successfully is described as an inverted-microphone installation where the microphone axis is vertical and the microphone's sensing element is approximately one microphone diameter above the surface of the ground plane. The use of the inverted-microphone method is described in Society of Automotive Engineers Aerospace Information Report AIR 1672A (March 1981), "Practical Methods to Obtain Free-Field Sound Pressure Levels from Acoustical Measurements Over Ground Surfaces, Appendix B - Procedures Developed by The Boeing Company to Determine Equivalent Free-Field Sound Pressure Levels Around an Engine Test Stand, January 1979".

15.5 The other type of microphone installation involves mounting the microphone on a mast at a height above the ground plane at least equal to the height of the engine centerline. The axis of the microphone is preferably vertical with the microphone pointing up and with the plane through its sensing element also passing through the engine centerline. That orientation should provide grazing (90°) incidence at all locations of mast-mounted microphones for any source of sound produced by the test engine. Other microphone orientations may be used, but different microphone directivity corrections may then be required at each location for the various sources of engine noise. The organization responsible for conducting the tests should develop appropriate microphone-response corrections to use with mast-mounted microphones.

15.6 Windscreens may be installed around near-ground or mast-mounted microphones. However, if the tests are conducted only when the average wind speed is less than the maximum recommended wind speed, then wind-generated noise and wind effects on the microphones should have little influence on the measurements of engine noise levels. Under those conditions, it may not be necessary to install windscreens, thereby avoiding the requirement to determine and apply corrections for the effects of the windscreens on microphone response. Windscreens also collect dirt and dust and require periodic cleaning. The material from which some windscreens are made also tends to deteriorate in an outdoor environment and small particles of windscreen material can penetrate the protective grid over the microphone's diaphragm and thereby interfere with the operation of the microphone.

16. TEST PROCEDURES

16.1 A test run consists of a set of acoustical, engine-performance, and meteorological data recorded for a given configuration of the test engine. A test run usually includes several test conditions, one for each target value of an engine power-setting parameter. Atmospheric conditions should remain constant (or nearly so) throughout the duration of the data recordings at each test condition.

16.2 The following items should be accomplished before starting the engine:

(1) Measure the temperature, relative humidity, and pressure of the atmosphere, and the speed and direction of the wind averaged over the duration of the periods when acoustical data are being recorded. Tests should be delayed or postponed if the meteorological conditions are not projected to be within acceptable limits.
(2) Through each data channel, record a single-frequency reference amplitude-calibration signal from an acoustical calibrator, or equivalent, for a duration of at least 30 seconds.
(3) Through each data channel, record a pink-noise electrical signal for a duration of at least 30 seconds. [Alternatively, record constant-amplitude sinusoidal signals at frequencies corresponding to the geometric mean frequencies of each one-third-octave-band in the frequency range of interest.]
(4) Through each data channel, record a sample of the ambient sound for a duration of at least 30 seconds. The recordings of ambient sound should be made a few minutes before starting the engine.

16.3 If magnetic tape recorders are used to record sound-pressure signals, each data tape should contain recordings of amplitude-calibration signals. Recordings of the pink-noise signals should be on at least one data tape for each test run.

16.4 After the engine has been started and is operating properly, the recordings of test data can begin. For each test condition, the engine should be allowed to stabilize at the target value of the engine-power-setting parameter before data recording is initiated. Suitable criteria for determining an acceptable measure of engine stability should be developed by the engine manufacturer.

16.5 A schedule of target values of the engine-power-setting parameter should be available as part of the test plan. The schedule should include thrust settings ranging from approximately 20 percent to 100 percent of maximum available gross thrust. The number of scheduled engine power settings per test run should be sufficient to define, with a high degree of confidence, the variation of the noise-evaluation quantity with referred net thrust. The total number of engine power settings per test run should be of the order of 10 to 15. The increment between adjacent values of the power-setting parameter should be relatively small around the values of referred net thrust established by the engine manufacturer for the engine-noise type certificate.

16.6 At each engine power setting, sound pressure signals from each microphone should be recorded for a duration of at least 30 seconds after the engine's internal conditions have stabilized. Recordings of acoustical data also should include recordings of a time-code signal, a signal proportional to the rotational speed of the low-pressure compressor, a reference sinusoidal signal for regulation of the speed of the recording device, and as necessary, appropriate announcements and annotations. Air temperature, relative humidity, and air pressure should be measured at least once, preferably continuously, while sound pressure signals are being recorded. Wind speed and wind direction should be recorded continuously. Engine-performance parameters should be recorded while sound pressure signals are being recorded.

16.7 After the engine has been shut down, the post-test efforts should include the following items:

(1) Through each data channel, record the ambient sound for a duration of at least 30 seconds.
(2) Through each data channel, record single-frequency reference amplitude-calibration signals and pink-noise electrical signals (or sinusoidal signals) for a duration of at least 30 seconds.

16.8 If the inlet and exhaust ducts on the test engine conform with the recommendations for shape and other features, then the farfield radiation patterns of the sound produced by the sources of engine noise should be rotationally symmetric about the engine centerline and measurements in one plane through the centerline should be sufficient to characterize the farfield radiation patterns in each 1/3-octave band in the frequency range of interest. However, if the test engine's inlet and exhaust ducts do not conform approximately to the recommendations, then the farfield radiation patterns may not be rotationally symmetric. In that case, additional tests may be required to evaluate the sound field in other planes through the engine centerline. The additional tests may be accomplished by rotating the test engine's inlet and exhaust ducts on their mounting flanges, if feasible, or by alternative approved methods.

16.9 The general test procedures also include laboratory calibrations of the frequency response of the acoustical test instruments used for data acquisition and data analysis. The laboratory calibrations should be performed within three months before the scheduled start of engine noise tests. The response of the instruments determined from the acoustical and electrical tests should be within the specified tolerance limits or should meet the performance requirements of applicable specifications for instrument performance. Although they do not have to be performed within the three-month period prior to the beginning of a series of tests, laboratory calibrations should also be conducted to determine the representative effect of the ground plane on the response of near-ground microphones and the representative effect of windscreens, if used, on the response of mast-mounted and near-ground microphones.

17. DETERMINATION OF TEST-TIME SOUND PRESSURE LEVELS

17.1 Recordings of engine-noise and ambient-noise signals should be processed through the data-reduction system to yield indicated 1/3-octave-band sound pressure levels. The averaging time for each data sample should be at least 30 seconds. Sound pressure levels should be determined in decibels relative to the standard reference sound pressure of 20 micropascals. The precision of the indicated sound pressure levels should not be less than the resolution of the data-processing system.

17.2 Corrected test-time sound pressure levels should be obtained by adding appropriate corrections to the indicated sound pressure levels. The following four types of corrections should be considered to account for:

(1) for those types of windscreens actually used, the representative effect of the windscreen on microphone response as a function of frequency, sound-incidence angle, wind-incidence angle, and average wind speed
(2) nonuniformities in microphone response as a function of frequency and sound-incidence angle
(3) nonuniformities in the average electrical frequency response of the complete data-acquisition and data-reduction system, as determined from the recordings of the pink-noise (or sinusoidal) signals
(4) the contributions of ambient or background noise if the difference between the indicated sound pressure level of engine noise and the indicated average sound pressure level of the samples of corresponding ambient noise is 5 dB, or more. The correction for background noise contamination will be negligible if the difference is greater than 15 dB. Differences of less than 5 dB indicate that high levels of ambient or background noise may have been present at the time of the recording and that the sound pressure levels of the engine noise signal cannot be reliably determined.

17.3 If the contributions of high levels of ambient noise cannot be reliably removed, then the indicated sound pressure levels for the affected 1/3-octave bands should not be included in the determination of the noise-evaluation quantity. However, the fact that some 1/3-octave-band sound pressure levels at certain microphone locations and engine power settings have been rejected because of contamination by a high level of ambient noise does not necessarily mean that the remainder of the data is invalid and that the test should be repeated. A test should re-run (e.g., to obtain data when ambient noise levels are lower) only when the inclusion of maximum reasonable values for the rejected sound pressure levels causes a significant change in the value of the noise-evaluation quantity. An approved empirical procedure should be used to estimate maximum reasonable values for those sound pressure levels contaminated by ambient noise.

18. ADJUSTMENTS TO REFERENCE CONDITIONS

18.1 For each test condition in each run, the test-time, corrected sound pressure levels should be adjusted to reference conditions. Adjustments to reference conditions include: (1) adjustments to acoustic free-field conditions for spherical space, and (2) adjustments to account for differences in atmospheric absorption under test-time and reference conditions.

18.2 For sound pressure level spectra measured by mast-mounted microphones, adjustments to free-field conditions include (1) removal of low-frequency spectral irregularities caused by interference between sound waves radiating directly from the engine and sound waves reflected from the ground plane, and (2) a subtraction of 3 dB to account for radiation into spherical space instead of hemispherical space above a reflecting ground plane. Guidance on procedures for removing interference effects from the measured spectra may be obtained from the Society of Automotive Engineers Aerospace Information Report AIR 1327 (January 1976), "Acoustic Effects Produced by a Reflecting Plane" and from the Society of Automotive Engineers Aerospace Information Report AIR 1672A (March 1981), "Practical Methods to Obtain Free-Field Sound Pressure Levels from Acoustical Measurements Over Ground Surfaces". Appendixes A and C of SAE AIR 1672A are applicable to sound pressure levels measured by mast-mounted microphones. Appendix A is titled "Procedure Developed by SNECMA to Remove Ground Reflection Effects from Sound Pressure Levels Measured by Microphones Located Above a Hard Surface, March 1979". Appendix C is titled "Procedures Developed by Pratt & Whitney Aircraft (P&WA) to Determine Equivalent Free-Field Sound Pressure Levels at a Static Jet-Engine Test Stand, August 1980". If the surface of the ground plane is not smooth and hard, differences between the acoustic impedance of the ground surface at the time of the tests and the acoustic impedance of a smooth and hard ground surface should be accounted for in the process of removing ground-reflection interference effects.

18.3 The empirical method used to remove ground-reflection interference effects from data measured by mast-mounted microphones should be able to distinguish between spectral irregularities caused by interference effects and spectral irregularities caused by discrete-frequency components of the engine noise signal, such as multiple-pure-tone or buzzsaw noise, or by narrowband random noise. The procedures described in Appendixes A and C of SAE AIR 1672A are applicable only to broadband sounds such as produced by jet-mixing noise.

18.4 Sound pressure level spectra measured by near-ground microphones should be essentially free of spectral irregularities caused by interference effects. In such cases, subtraction of 6 dB from the test-time sound pressure levels should yield equivalent free-field data, see Appendix B of SAE AIR 1672A. The measured values of high-frequency sound pressure levels, however, may be influenced by refraction effects associated with sound waves propagating at shallow angles through atmospheric turbulence or thermal gradients near the ground plane. Special approved procedures may be required to determine equivalent free-field sound pressure levels for those 1/3-octave-band sound pressure levels influenced by such refraction effects.

18.5 If farfield sound pressure levels are measured by a combination of mast-mounted and near-ground microphones at the same radial distance and angle, then the equivalent free-field 1/3-octave-band sound pressure levels may be determined from a composite of the two sets of measurements. For example, low-frequency free-field data could be obtained from measurements made by the ground-plane microphone; high-frequency free-field data could be obtained from measurements made by the mast-mounted microphone. Measurements from the two microphones could be used to derive mid-frequency free-field data.

18.6 Adjustments to account for differences in atmospheric absorption effects should be applied after the corrected sound pressure levels have been adjusted to equivalent free-field conditions. Procedures to account for atmospheric absorption are available in the Society of Automotive Engineers Aerospace Recommended Practice ARP 866A (March 1975), "Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity", or the "American National Standard Method for the Calculation of the Absorption of Sound by the Atmosphers", ANSI S1.26-1978. The latter standard is available from the American Institute of Physics.

19. NUMBER OF TEST RUNS

19.1 Farfield sound pressure levels should be measured during at least two test runs to provide sufficient data to establish, with confidence, the mean variation of the noise-evaluation quantity with referred net thrust.

19.2 Prevailing meteorological conditions should be somewhat different during each test run. Test-time meteorological conditions should always be within the recommended ranges.

20. DETERMINATION OF THE NOISE-EVALUATION QUANTITY

20.1 For each test condition, the specified noise-evaluation quantity should be calculated from the time-averaged 1/3-octave-band sound pressure levels that were adjusted to acoustic free-field and reference atmospheric conditions.

20.2 Regression techniques or an approved engineering method should be used to establish a mean line through the calculated data for the variation of the noise-evaluation quantity with referred net thrust.

20.3 At least 90 percent of the data points from all the test conditions from all test runs should lie within ±1 dB of the mean line. [For example, if there were two test runs with 15 test conditions per run, then 27 data points should lie within ±1 dB of the mean line.]

20.4 The values of the noise-evaluation quantity applicable to the engine-noise type certificate should be determined from the mean line established for the variation of the average value of the noise-evaluation quantity with referred net thrust. Extrapolation, if necessary, of the mean line should be approved by the certifying authority.

21. INFORMATION TO BE REPORTED

Information to be reported includes:

(1) manufacturer, type, model, and serial number of the test engine
(2) dimensions of relevant components of the test engine, e.g., the diameter of the fan rotor blades
(3) a description and a dimensioned drawing showing the noise-control design features incorporated by the manufacturer within the test engine
(4) a description, and a dimensioned drawing and photographs, of the air-inlet and exhaust ducts installed on the test engine including the exit areas of the fan and turbine-discharge nozzles
(5) a description, with accompanying drawings and photographs, of the relevant characteristics of the engine test stand including the height of the test engine's centerline above the ground plane and the location of the engine reference point
(6) a description, with dimensioned drawings and photographs, of the device, if any, installed around the test engine's air-inlet duct to control turbulence and distortion in the airflow into the inlet
(7) a description, with accompanying drawings and photographs, of the relevant characteristics of the test site around the engine test

stand, particularly the ground plane between the test stand and the locations for the farfield microphones at the time of the tests; microphone locations should be given in terms of the radial distance from the engine reference point and an angle, with vertex at the engine reference point, between the engine centerline and the radial vector to the microphone.

(8) for the test results being reported, a definition of the frequency range of interest in terms of the range of 1/3-octave-band nominal center frequencies

(9) a description of the equipment and instruments (including manufacturer, type, model, and serial number) used to measure and record the acoustical, engine-performance, and meteorological data

(10) a description, including photographs, of typical installations for the microphones, showing height above the ground plane, orientation, and the microphone's windscreen, if used

(11) a description, including photographs, of the installation of the instruments used to measure meteorological conditions during the tests

(12) a description of the general test procedure including (1) field and laboratory calibrations, (2) a definition of the method for determining when engine operating conditions have become stable enough to permit data to be recorded at any test condition, (3) the schedule of engine power settings with target values of engine-power-setting parameters for a run, and (4) if thrust was not directly measured by instruments on the test stand, a description of the procedures used to determine the net thrust produced by the test engine at each test condition

(13) a description of the special test procedures that were used to measure the farfield sound pressure levels if the sound field produced by the test engine was considered not to be rotationally symmetric about the engine centerline because of the configuration of the inlet or exhaust ducts

(14) for each test condition, a listing of average test-day meteorological parameters (air temperature, relative humidity, air pressure, wind speed, and wind direction)

(15) a description of the equipment and instruments (including manufacturer, type, model, and serial number) used to process the recorded acoustical data and produce time-averaged 1/3-octave-band sound pressure levels; the duration of the averaging time should be stated

(16) a description of the general procedures used during the processing of acoustical data including a discussion of the development of instrument corrections that were applied to the measured values of time-averaged sound pressure levels of background noise and engine noise; the discussion of instrument corrections should present typical values for windscreen frequency-response corrections and microphone frequency-response corrections for applicable sound-incidence angle(s)

(17) a description of the procedure used to determine 1/3-octave-band sound pressure levels of average background noise and to remove the effects, if any, of background noise in the 1/3-octave-band sound pressure levels measured when the test engine was operating

(18) a description of the procedures used to evaluate the consequences of the loss of data if some of the measured 1/3-octave-band sound pressure levels of engine noise, at some microphone locations and engine power settings, were rejected because the corresponding levels of

background noise were too high, or for any other reason which should be stated

(19) a discussion of the procedure used to remove ground-reflection effects from the measured and corrected 1/3-octave-band sound pressure levels at each microphone location and to adjust the measured data to equivalent acoustic free-field conditions; if an empirical procedure was used to remove ground-reflection effects from a spectrum of the sound measured by a microphone, the discussion should describe the basis for the procedure and present experimental evidence to demonstrate the applicability of the procedure to the tests being reported

(20) a description of the procedure used to adjust the 1/3-octave-band sound pressure levels for differences between the atmospheric absorption under test-time and reference meteorological conditions

(21) the number of test runs and the test dates

(22) the average value of the noise-evaluation quantity at the values of referred net thrust established by the engine manufacturer as applicable to the engine for which an engine-noise type certificate is sought and to a precision compatible with the resolution of the data-processing system for 1/3-octave-band sound pressure levels

(23) the values of referred mass-flow rate of the discharge through the exhaust ducts, referred fan rotational speed, and the fully-expanded jet velocities associated with each value of referred net thrust applicable to the engine-noise type certificate

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