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NOISE REDUCTION STUDIES FOR THE CESSNA MODEL 337 (O-2) AIRPLANE

By Andrew B. Connor, David A. Hilton
and Richard C. Dingeldein

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The results show that significant reductions in aural detection distance can be achieved by the combination of propeller geometry changes and the addition of engine exhaust mufflers. The best results were estimated for the aircraft equipped with a six-blade propeller operating at 3/4 engine speed in combination with a 3.49 ft^3 exhaust muffler installed on each engine. Detection distance for the modified aircraft is estimated to be reduced from about 4-1/4 miles to about 1-1/2 miles when the aircraft is operating at an altitude of 1,000 ft over grassy terrain. Reducing the altitude to 300 ft over a leafy jungle ground cover should reduce the aural detection distance to 0.9 miles.

Reduced aural detection distances were also indicated for a modification utilizing a direct-drive six-blade propeller of reduced radius along with smaller exhaust mufflers. The corresponding aural detection distances are reduced to about 1-3/4 miles and 1 mile, respectively (1,000 ft altitude over grass and 300 ft altitude over leafy jungle ground cover).

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SUMMARY

A study was undertaken by the NASA Langley Research Center to determine the noise reduction potential of the 0-2 airplane in order to reduce its aural detection distance. Static and flyover noise measurements were made to document the noise signature of the unmodified airplane.

The results show that significant reductions in aural detection distance can be achieved by the combination of propeller geometry changes and the addition of engine exhaust mufflers. The best results were estimated for the aircraft equipped with a six-blade propeller operating at 3/4 engine speed in combination with a 3.49 ft^3 exhaust muffler installed on each engine. Detection distance for the modified aircraft is estimated to be reduced from about 4-1/4 miles to about 1-1/2 miles when the aircraft is operating at an altitude of 1,000 ft over grassy terrain. Reducing the altitude to 300 ft over a leafy jungle ground cover should reduce the aural detection distance to 0.9 mile.

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INTRODUCTION

In response to a Department of Defense request, NASA has undertaken an analytical study of the noise reduction potential of the Cessna Model 337 (0-2) airplane in terms of the aural detection distance. This effort specifically involves: (1) measuring the noise characteristics of the basic airplane in low-speed cruising flight, (2) studying possible modifications and estimating the associated noise reductions, (3) evaluating the effects of these modifications on the aural detection distance of the aircraft, and (4) estimating the effects of such noise reduction modifications on the performance and stability of the aircraft. These preliminary studies represent an assessment of the potential overall reductions in noise level rather than a precise design concept that is the optimum from a design viewpoint. This paper documents the NASA efforts in accomplishing the above objectives.

SYMBOLS

A	propeller disk area
$A(x)$	area of blade cross section
B	number of propeller blades
C_D	drag coefficient, $\frac{\text{drag}}{1/2\rho V^2 S}$
C_L	lift coefficient, $\frac{\text{lift}}{1/2\rho V^2 S}$
C_P	power coefficient, $\frac{550\ \text{SHP}}{\rho\ n^3\ D^5}$
C_T	thrust coefficient, $\frac{\text{thrust}}{\rho\ n^2\ D^4}$
D	propeller diameter, ft
J	Bessel function of order mB
M_t	propeller rotational tip Mach number
N	revolutions per minute
Q	propeller shaft torque, lb-ft
R	propeller tip radius, ft
R_e	effective propeller radius, ft
S	wing area
T	thrust
V	velocity, true airspeed
X	slant range distance from airplane to observer, feet
dB	decibels, re 0.0002 dynes/cm^2
f	frequency, cps

fr	resonant frequency, cps
m	order of harmonic of propeller
n	revolutions per second
p	root-mean-square sound pressure of given harmonic, lb/ft^2
q_o	free-stream dynamic pressure
q_t	dynamic pressure at the tail
s	distance from propeller to observer, ft
x	percent propeller radius
ψ	azimuth angle measured from the thrust axis of propeller (0° is in front)
η	propeller efficiency, $\frac{C_T}{C_P} \cdot \frac{V}{nD}$
σ	propeller blade element solidity
ρ	mass density of air
ω	propeller angular velocity, rad/sec
cps	cycles per second
V/nD	propeller advance ratio parameter
M.A.C.	mean aerodynamic chord
MRP	military rated power
NRP	normal rated power
R/C	rate of climb
SHP	shaft horsepower
SPL	sound pressure level
TAS	true airspeed
THP	thrust horsepower
T.O.	takeoff

Subscripts

e	engine
p	propeller
t.p.	tail pipe
max	maximum

APPARATUS AND METHODS

Test Airplane

The test airplane for the studies of this paper is a 4,500 pound gross weight high-wing monoplane powered by two Continental 210 horsepower direct-drive engines. The propulsion system is uniquely configured with one engine nose mounted and driving a tractor propeller, and the other engine rear mounted and driving a pusher propeller. The propellers on each engine are constant-speed two-blade 76-inch diameter and are identical in respect to chord and pitch distribution. The photographs of figure 1 show the Cessna Model 337 test airplane which will hereafter be referred to as the O-2. A three-view line drawing with a list of the principal physical dimensions of the airplane is presented in figure 2. Aircraft and pilot were provided for the tests by the Cessna Aircraft Company, manufacturer of the O-2 airplane.

Test Conditions

Noise measurement tests were conducted on January 31, 1967, at the NASA Wallops Station, where use was made of the main paved runway surface and the associated flat terrain for locating instrumentation and for obtaining both static and flyby noise measurements.

Typical terrain features of the Wallops test area are shown in the photographs of figure 3(a), which is a view looking north from the runway center line, and figure 3(b), which is a view to the south. A schematic diagram of the microphone arrays for these tests is illustrated in figure 4.

Noise Measuring Equipment

The noise measuring instrumentation for these tests is illustrated by the block diagram of figure 5. The microphones were of a conventional piezoelectric ceramic type having a frequency response flat to within ±3 dB over the frequency range of 20 to 12,000 cps. The outputs of all the microphones at each station were recorded on multichannel tape recorders. The entire sound measurement system was calibrated in the field before and after the flight measurements by means of conventional discrete frequency calibrators supplied by the microphone manufacturers. The data records were played back from the tape (using the playback system shown in fig. 5) to obtain the sound pressure level time histories and both broad-band and narrow-band spectra.

Aircraft Operation

Noise measurements were taken of the aircraft under static run-up and flight conditions, recording individually the front engine, the rear engine, and both engines simultaneously. Operating conditions for the flight measurements were selected by the aircraft manufacturer's test pilot. After the flyover data were obtained, these same conditions were repeated for the static measurements. Table I lists the conditions for both flight and static tests for which data were obtained.

Static noise survey.- The static measurements were taken with the microphone array shown schematically by figure 4(a). The microphones were positioned at 30° intervals on a 50-ft radius from the hub of each propeller when the engines were operated individually and from a point midway between the two engines when both were operated together. Engine parameters, that is, rpm and manifold pressure, were recorded manually from the pilot's instrument display. Engine brake horsepower was determined from the pilot's handbook for the indicated parameters.

Flyover noise surveys.- The flyover noise measurements were taken with the recording equipment arrayed as shown schematically by figure 4(b). The airplane was flown at 300 and 1,000 ft altitudes on each engine individually and both engines simultaneously as listed in table I. Engine parameters, again, were recorded manually from the pilot's instrument display. Altitude and course over the recording equipment were tracked and recorded by a GSN/5 radar tracking unit for accurate position data. Radar position information was transmitted to the pilot as an assist so that course and altitude were maintained from approximately 1 mile prior to and 1 mile beyond the microphone position.

Atmospheric Conditions

Weather data were recorded in the vicinity of the test site. Surface winds were 2 to 4 knots variable, temperature ranged from -5° C to 1.7° C, and the relative humidity was approximately 70 percent during the time of these tests.

MEASURED NOISE CHARACTERISTICS OF THE BASIC AIRPLANE

The analytical study to define the noise-reduction potential for the O-2 airplane, and which will be summarized later in the paper, assumes a low cruising speed and twin engine operation at a combined brake horsepower of 120. The basic aircraft noise signatures used as a reference were obtained for conditions in which each engine was operated individually at approximately 120 horsepower, and with simultaneous engine operation at approximately 60 horsepower each.

Static Noise Signature

A sample narrow band analysis of the noise recorded in the plane of the front propeller at a distance of 50 ft is presented in figure 6. This record was taken at 2,400 engine rpm while the rear-mounted engine was shut down. These data were reduced with the aid of a 3 cps bandwidth filter and are depicted for the range of frequencies up to about 500 cps. Shown in the figure are the individual noise components corresponding to the significant engine firing frequencies and the propeller noise frequencies. The engine frequencies are indicated as some integral multiple times the cylinder firing frequency f, which for a four-cycle engine is equal to the revolutions per second divided by 2. The propeller noise components are identified by their mB values, where m is the harmonic number and B is the number of blades.

Records such as these disclose the most prominent sources of noise from the airplane over the frequency range and indicate where effort must be directed to reduce the external noise level.

Flyover Noise Signatures

Typical flyover noise data are presented in figure 7 where the sound pressure levels in the various octave bands are shown for the three measurements obtained during low-speed cruise flight at an altitude of 300 ft. These data compare the signatures for separate front and rear engine operation and for simultaneous engine operation. Somewhat lower noise levels are seen to be associated with only the rear engine operating. It is a fact that this mode also results in some improvement in performance (i.e., lower power required), probably as a result of cleaning up the airflow over the aft portion of the fuselage. The lower noise level shown, however, is believed primarily due to a small muffler installed on the rear engine as standard equipment.

The signature obtained with both engines operating was used in conjunction with the narrow band data to establish the baseline for the aural detection distance calculations. For each operating condition of figure 7, the octave band levels presented are the maximum values measured regardless of the time at which they occurred.

AIRCRAFT MODIFICATIONS ANALYZED FOR THIS STUDY

Using the measured noise spectrum obtained for the basic O-2 aircraft with normal engine operation, studies were made using available analytical techniques to estimate the aircraft noise reduction that might be expected from propeller changes and the use of engine exhaust mufflers. These studies were conducted with the view of obtaining significant noise reductions in the critical octave bands with minimum effect on aircraft performance. Hence, the propeller efficiency in various flight conditions, including its static-thrust capability, was an important factor, as was the ability of the muffler to quiet the engine without seriously penalizing the overall aircraft performance. The modifications selected as indicative of practical fixes that are estimated to provide substantial reductions in the aural detection distance of this aircraft are listed in table II, in which the modifications are briefly described. Details of the propeller and the muffler analyses are given in appendixes A and B, respectively. The effect on overall aircraft weight is presented in appendix C, and the estimated performance of the O-2 aircraft equipped with modification I (A or B) or modification II is presented and compared with the basic O-2 in appendix D.

Modification I-A and I-B

The simplest modification (modification I) involves changing the number of propeller blades from two to six, reducing the propeller diameter from 76 in. to 64 in. to reduce the tip Mach number without the need for a gearing change, and the addition of a single chamber resonator muffler to the exhaust system of each engine. Two mufflers have been considered; one having a volume of 2.22 cu ft (modification I-A), and another having a volume of 3.33 cu ft (modification I-B). Modification I was analyzed for twin-engine operation at 2,400 rpm, and the power required is 60 horsepower per engine.

The forward muffler was assumed to be externally mounted underneath the aircraft and aft of the nose wheel. From the information made available for this study, it appeared that the rear muffler could be installed inside the rear engine compartment (see appendix C).

Modification II

Modification II requires the use of a six-blade propeller, a return to the original propeller diameter of 76 inches, and the installation of a 3/4:1 propeller reduction gear box on each engine in order to reduce the blade tip Mach number. A 3.49 cu ft double expansion chamber muffler is also required for each engine. Both mufflers are 10 ft long and were assumed to be externally mounted alongside each other on the left side of the aircraft (see appendix C).

ESTIMATED NOISE CHARACTERISTICS OF THE MODIFIED AIRPLANE

Octave band noise spectra for the basic airplane and the suggested modifications were estimated from available measured results and prediction techniques as described in the appendixes for the cases just described. These spectra are presented in figure 8 and provide the basis for making the aural detection distance estimates.

The noise in the fifth and higher octave bands consists of a wide range of random frequencies to which the propeller vortex noise is an important contributor. This latter noise energy is shown in reference 1 to vary as the sixth power of the tip speed and the first power of the total propeller blade area.

The dependence of the sound pressure level, which is the quantity dealt with in this paper, is as the square root of the energy dependence. The measured sound pressure levels for the five highest octave bands are accordingly adjusted to account for the change in the vortex noise associated with the propellers used in modifications I and II.

DETERMINATION OF AURAL DETECTION DISTANCE FOR BASIC AND MODIFIED AIRCRAFT

This section is a summary of the techniques and procedures employed in this paper for determining aural detection distance, and it includes the assumptions upon which the estimates are based along with reference citations.

Basic Assumptions Relating to Detection

In addition to the noise source characteristics (see refs. 2 and 3), it is well-known that the aural detection of a noise involves such factors as the transmission characteristics of the path over which the noise travels (see refs. 4, 5, 6, 7, and 8), and the acoustic conditions at the observer location (see refs. 5 and 9), as well as the hearing ability of the observer (see ref. 10). Attempts have been made to account for all of the pertinent factors in the above categories for the calculations of detection distance which follow.

Attenuation factors.- The attenuation factors associated with the transmission of noise from the source to the observer are assumed to involve the well-known inverse distance law, and atmospheric absorption due to viscosity and heat conduction, and small-scale turbulence, along with terrain absorption. This latter effect is dependent upon the evaluation angle between the source and the observer (see ref. 4). For the purposes of this paper these factors are taken into account as determined by the following equation:

$$\text{P.L. }(f,x) = 20 \log_{10} \frac{x}{A} + \left[K_1 + K_2 + (K_3 - K_1)\, K_4\right] \frac{x}{1000}$$

where propagation loss (P.L.) is computed for each frequency and distance combination and where the first term on the right-hand side of the equation accounts for the spherical spreading of the waves. In this connection x is the distance for which the calculation is being made and A is the reference distance for which measured data are available. The remaining terms which represent propagation losses and which are given in coefficient form are defined as follows

K_1 represents the atmospheric absorption due to viscosity and heat conduction and is expressed in dB per 1,000 ft. The values of K_1 vary as a function of frequency and for the purposes of this paper are those of the following table. For frequencies up to 500 cps the data are taken from reference 4, and for the higher frequencies from reference 7.

Octave Band No.	Center Freq.	dB Loss per 1,000 ft
1	31.5	0.1
2	63	0.2
3	125	0.3
4	250	0.5
5	500	0.7
6	1000	1.4
7	2000	3
8	4000	7.7
9	8000	14.4

K_2 is the attenuation in the atmosphere due to small-scale turbulence. A value of 1.3 dB per 1,000 ft is assumed independent of frequency for the frequency range from 250 to 4000 cycles (see ref. 8).

K_3 also is expressed in dB per 1,000 ft and includes both atmospheric absorption and terrain absorption. The values used are those of reference 5 which are listed for widely varying conditions of vegetation and ground cover. The data of reference 5 have been reproduced in a more convenient form in reference 6. Calculations included herein make use of the data of reference 6, particularly curve (b) of figure 1 which represents the condition of heavy grass cover (18 inches high) and the upper bound of curve 3 of figure 2, which represents conditions of a leafy jungle with approximately 100 ft "see-through" visibility. K_4 is a weighting factor to account for the angle, measured from the ground plane, between the noise source and the observer. The values of K_4 assumed for the present calculations were taken from figure 3 of reference 6 and are seen to vary from zero for angles greater than 7° to 1.0 for an angle of 0°.

Ambient noise level conditions and human hearing.- The detectability of a noise is also a function of the ambient masking noise conditions at the listening station and the hearing abilities of the listener. Since they are somewhat related, they will be discussed together.

The ambient noise level conditions assumed for these studies were based on data from references 5 and 9 which were obtained in jungle environments. It was indicated in reference 4 that a noise made up of discrete tone components is detectable if it is within 9 dB of the background noise (random in nature) in any particular octave band. Thus, the corresponding measured spectra of references 5 and 9 have been reduced by 9 dB to account for the above difference in the masked and the masking spectra. The only exception to this procedure was employed in the evaluation of modification II. For this case the critical noise component for detection was the broad-band vortex noise. At frequency bands where vortex noise was critical the background noise levels referred to above were not reduced by 9 dB.

The resulting octave band spectra have been further adjusted to account for the critical band width of the human ear (ref. 10), according to the following equation, to give masking level values for each band.

$$\text{Masking level, dB} = \text{octave band level, dB} \quad - \quad 10 \log_{10} \frac{\Delta f_{octave}}{\Delta f_{critical}}$$

where the Δf_{octave} and $\Delta f_{critical}$ values corresponding to standard octave band center frequencies are given in the following table:

Octave band center freq., cps	31.5	63	125	250	500	1000	2000	4000	8000
Δf_{octave}, cps	22	44	88	177	354	707	1414	2828	5656
$\Delta f_{critical}$, cps	--	--	50	50	50	66	100	220	500
$10 \log_{10} \frac{\Delta f_{octave}}{\Delta f_{critical}}$	--	--	2.5	5.5	8.5	10.7	11.5	11.1	10.5

The values of the last row in the above table have been subtracted from the octave band values to adjust them to the masking level spectra which define the boundaries of the jungle noise criteria detection region of figure 9.

Likewise, a threshold of hearing curve for the unaided ear (taken from ref. 4) is made use of since it represents the levels of pure tone noise that is just detectable on the average by healthy young adults. The implication here is that noises having levels lower than those of the threshold of hearing curve at corresponding frequencies will not be detectable. Thus, the threshold of hearing curve is the determining factor of detection at the lower frequencies.

No attempt is made to account for possible binaural effects in the studies of the present paper.

Estimation Methods

Reference detection distances for each aircraft configuration for flight altitudes of 1,000 and 300 ft and for ground cover conditions representative of both 18-inch grass and 100-foot "see-through" leafy jungle, have been determined with the aid of figure 9 and the noise signature data of figure 8. In figure 9 the octave band noise levels at various distances have been estimated by taking into account the appropriate atmospheric and terrain losses. Also shown in the figure is a threshold of hearing curve and a band labeled "jungle noise detection criteria." The lower boundary of this area represents masking levels in a relatively quiet jungle location in the Canal Zone (ref. 5). The upper boundary on the other hand represents a relatively more noisy masking level condition based on measurements in Thailand (ref. 9). These data have been compared with and found to be generally compatible with results of recent, but unpublished, jungle noise surveys taken at Fort Clayton in the Canal Zone. In the determination of the maximum distance at which the aircraft can be detected aurally, it was assumed that such detection was possible at the distance at which the level of aircraft noise in any octave band equaled or exceeded either the masking level curve or the threshold of hearing curve.

Detection Distance Estimates

The aural detection distances estimated for the basic O-2 aircraft and the selected modifications using the previously discussed criteria are presented in table III.

Depending upon whether the ground cover consists of leafy jungle or 18-in. grass, respectively, the basic aircraft will be detected aurally at distances of about 2.9 and 4.2 miles when operating at an altitude of 1,000 ft. The distances are reduced to approximately 1.6 and 3.8 miles when the aircraft is flown at 300 ft. These detection distances are largely attributed to the propeller and engine exhaust noise in the second and third octave bands (center frequencies 63 and 125 cps, respectively).

Use of an ungeared six-blade propeller of reduced radius (32 inches compared to the standard radius of 38 inches) along with a single chamber resonator muffler installed on each engine is estimated to provide a significant reduction in the aural detection distance. Use of individual engine mufflers having volumes of 2.22 and 3.33 cubic feet is estimated to reduce the aural detection distances of modifications I-A and I-B for flight at an altitude of 300 ft over leafy jungle cover to approximately 1-1/4 mile and 1 mile, respectively.

Modification II provides about the most noise reduction that appears reasonable to accomplish with modifications to the propeller, propeller/engine gearing, and the use of exhaust mufflers. For this case requiring a six-blade, 6.33-ft diameter, 0.75:1 geared propeller and a 3.49 cu ft double expansion chamber exhaust muffler attached to each engine, the aural detection distance associated with the aircraft flying at an altitude of 1,000 ft over grassy terrain is reduced from about 4-1/4 miles to 1-1/2 miles. At an altitude of 300 ft over leafy jungle cover the minimum aural detection distance is estimated to be about 0.9 mile.

Effect of Ground Cover and Observer Position

Table III indicates clearly how the ground cover and observer position play an important part in the estimated aural detection distance. For flight over 18-in. grass, reducing the altitude of the aircraft tested (basic O-2) from 1,000 ft to 300 ft reduces the detection distance by only about 10 percent. Locating the observer in a moderately dense jungle, with an average "see-through" distance of 100 ft (leafy jungle case) is seen to reduce the detection distance from that for 18-in. grass cover by some 30 and 60 percent, respectively, for aircraft altitudes of 1,000 and 300 ft. For the leafy jungle ground cover, lowering the altitude of the aircraft from 1,000 ft to 300 ft is seen to reduce the estimated aural detection distance by 43 percent. As noted previously in the discussion of attenuation factors, the terrain has an increasingly larger influence as the elevation angle of the noise source as viewed by an observer on the ground becomes less than 7°. This approximately corresponds to ratios of the aircraft slant range to the aircraft altitude greater than 8.

EFFECTS OF AIRPLANE CONFIGURATION MODIFICATIONS

Selection of the configuration modifications considered the effects on the aircraft performance and stability in addition to the potential noise attenuation. For the modifications presented in this paper, estimated weight increases are approximately 16 pounds for modification I-A, 43 pounds for I-B and 117 pounds for modification II. These changes in empty weight were assumed to have no effect on useful load and their effect on other performance parameters in all cases turned out to be less than 1 percent. For a more detailed discussion, the reader is referred to appendix D.

The maximum change in the aircraft center-of-gravity location at maximum gross weight was 0.2 percent MAC for modification II.

CONCLUDING REMARKS

A study has been conducted to assess the external noise reduction potential and the aural detection distance of the O-2 airplane in cruise flight. The analysis is based in part upon ground and flight measurements of the noise of the unmodified aircraft and upon available methods of predicting the reductions associated with propeller changes and the use of exhaust mufflers.

The analysis indicates that the aural detection distance of the basic O-2 aircraft is due to the propeller and the engine-exhaust noise in the second and third octave bands (center frequencies 63 and 125 cps, respectively).

The results show that significant reductions in the aural detection distance can be achieved by changing the propeller geometry to lower the blade tip Mach number (reduction gearing or shortened radius) and decrease the blade loading and raise the blade passage frequency (additional blades). Exhaust muffling is also required in order to reduce the engine noise.

1. The largest practical reduction was predicted for a six-blade propeller, operating at a reduced tip speed through a 3/4:1 propeller-to-engine gear box used in conjunction with a 3.49 cu ft double expansion chamber muffler on each engine. Detection distance in this case, for the airplane operating 1,000 ft over grassy terrain, is reduced from roughly 4-1/4 miles to about 1-1/2 miles. At an altitude of 300 ft over leafy jungle cover the minimum aural detection distance is estimated to be about 0.9 mile.

2. Significant though smaller reductions were predicted for modifications consisting of an ungeared six-blade propeller of reduced diameter used in conjunction with single-chamber resonator mufflers. Two muffler sizes, 2.22 and 3.33 cu ft per engine, were also incorporated. The minimum aural detection distance estimated for the modified aircraft flying at 300 ft over leafy jungle cover is approximately 1-1/4 and 1 mile, respectively.

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Table I. - Summary of aircraft operating conditions for both the static and flyover noise measurements.

Item No.	Run No.	Altitude above ground, ft.	Lateral disp. from track ℄ ft.	Velocity, MPH	Engine no. 1			Engine no. 2		
					Engine speed, RPM	Manifold pressure, in. Hg	Engine brake horsepower	Engine speed, RPM	Manifold pressure, in. Hg	Engine brake horsepower
					STATIC					
1	1				2400	22	120	Engine shut down		
	2				2450	24	143			
2	1				2400	22	120	2400	22	120
	2				2400	24	138	2400	24	138
3	1				Engine shut down			2400	22	120
	2							2400	24	138
					FLIGHT					
1	1	300	0	90	2400	22	120	Engine shut down		
	2	300	0	120	2400	24	138			
	3	300	0	94	Engine shut down			2400	19.2	98
	4	300	0	132				2375	24	136
	5	300	0	104	2350	16	65	2350	16	65
	6	300	0	172	2400	24	138	2400	24	139
2	1	1000	0	88	2400	22	120	Engine shut down		
	2	1000	0	122	2400	24	138			
	3	1000	0	91	Engine shut down			2350	19	90
	4	1000	0	135				2400	24	138
	5	1000	0	98	2400	15	58	2400	15	58
	6	1000	0	175	2375	24	136	2375	24	136

Engine no. 1 - forward
Engine no. 2 - aft

Table II.- Summary of aircraft modifications analyzed for this study.

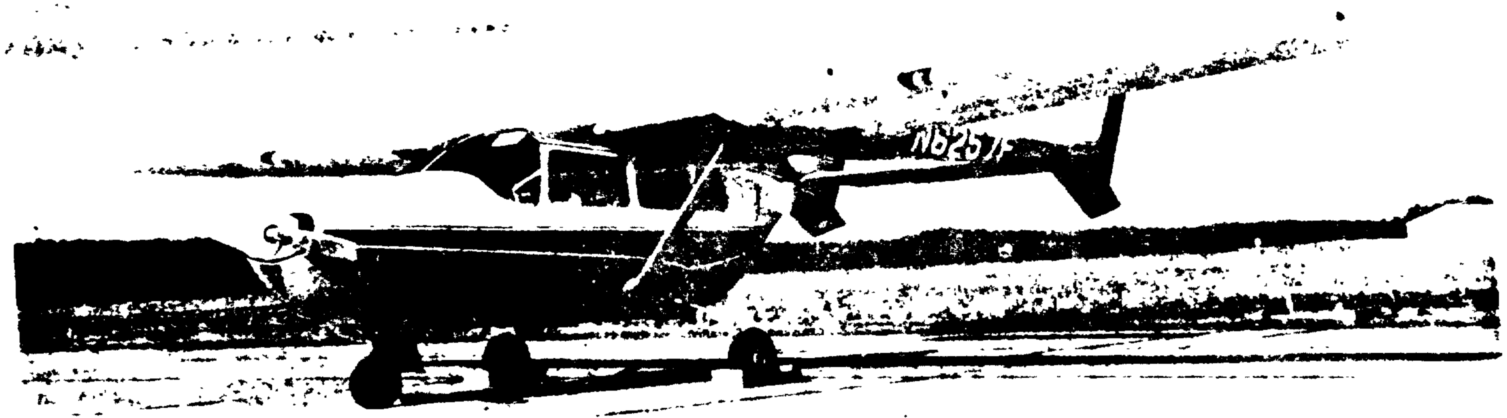
Configuration	Propeller to Engine gear ratio	Propeller radius, inches	Propeller blade no.	Engine rpm for 60 HP per engine	Muffler volume cu-ft.	Estimated overall SPL at 300 ft.
Basic Aircraft	1:1	38	2	2400		92 dB* 94 dB
Modification I-A	1:1	32	6	2400	2.22	82 dB
Modification I-B	1:1	32	6	2400	3.33	80 dB
Modification II	3/4:1	38	6	2400	3.49	78 dB

*** Measured**

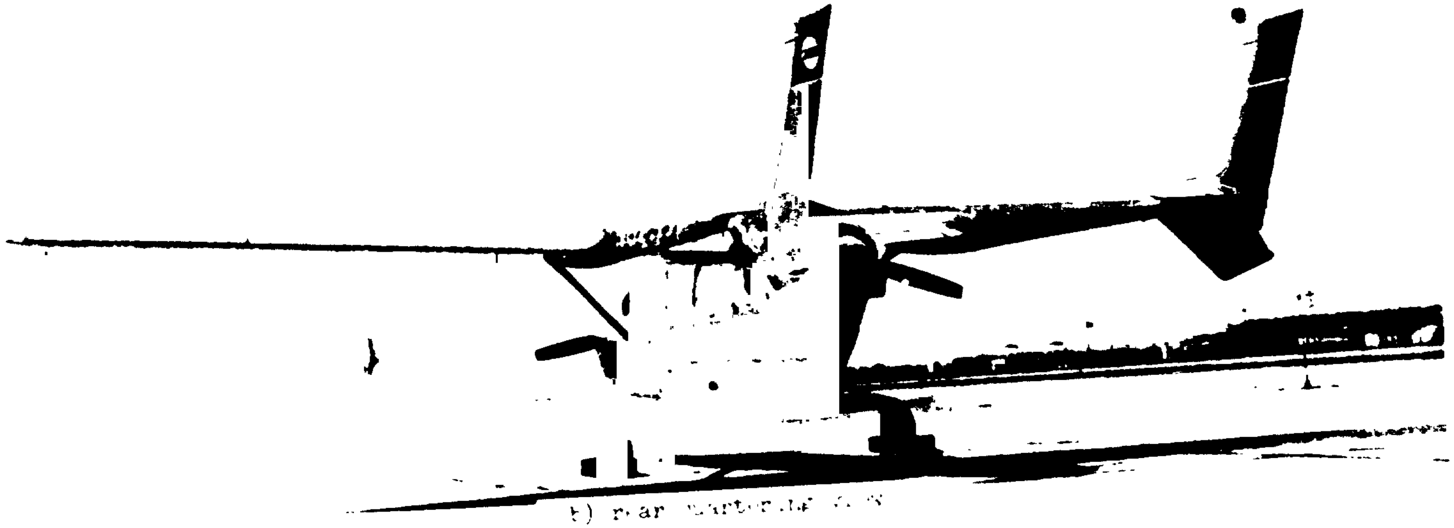
Table III.- Reference aural detection distances in feet for the basic O-2 aircraft and for three proposed modifications. Data are for two aircraft altitudes and for two ground cover conditions.

Aircraft Altitude ft.	Ground Cover	Reference Detection Distance, ft.							
		Aircraft Configuration							
		Basic Measurement		Basic Calculation		Mod. I-A		Mod. I-B	Mod. II
1000	Grassy	22,300	(b)	25,000	(b)	14,900	(b)	9,100 (c)	7,700 (d)
1000	Leafy	15,100	(b)	15,800	(b)	11,500	(b)	8,900 (c)	7,700 (d)
300	Grassy	20,000	(a)	20,300	(a)	9,200	(b)	6,550 (c)	5,100 (d)
300	Leafy	8,600	(b)	8,800	(b)	6,600	(b)	5,600 (c)	4.800 (d)

(a) data from 2nd. octave band
(b) data from 3rd. octave band
(c) data from 4th. octave band
(d) data from 5th. octave band

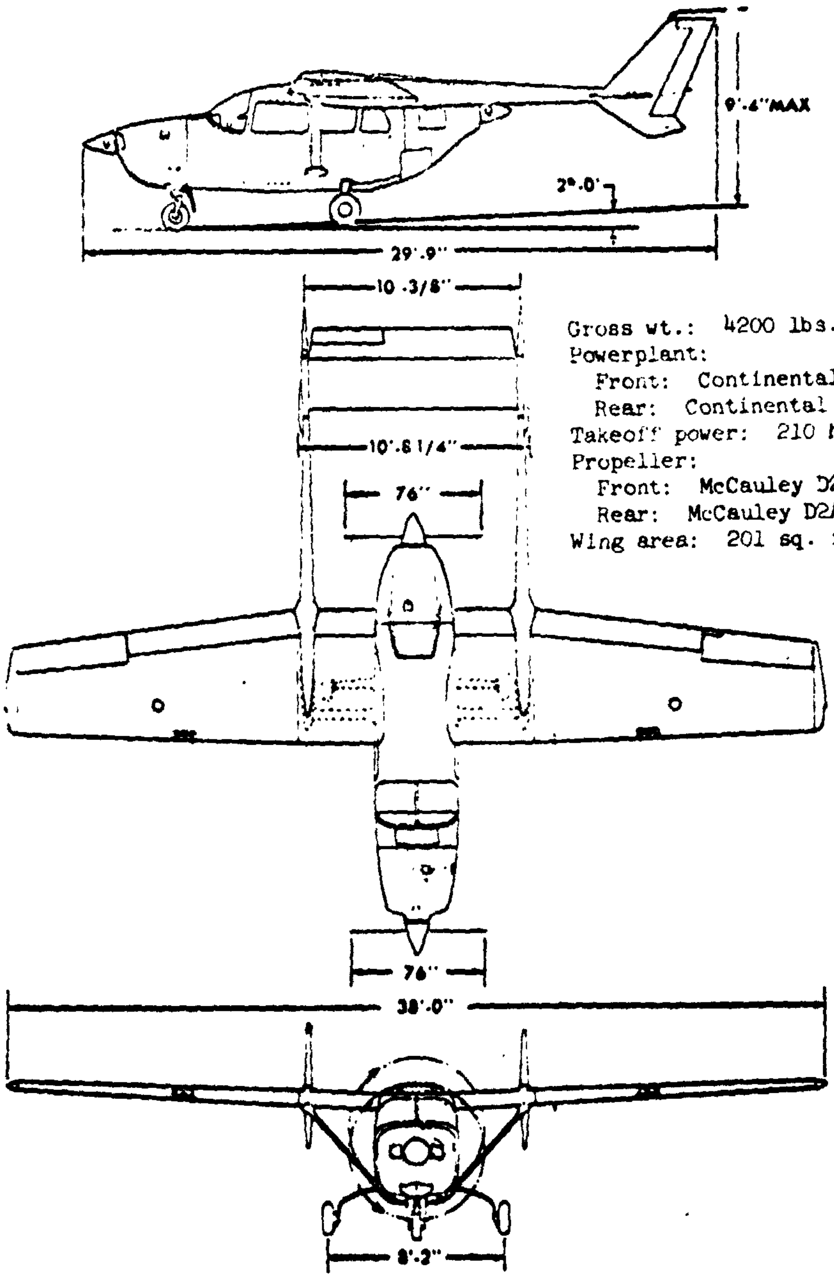


(a) Front quartering view.



(b) Rear quartering view.

Figure 1.- Photographs of the test airplane.



Gross wt.: 4200 lbs.; empty wt.: 2012 lbs.
Powerplant:
  Front: Continental IO-360-C
  Rear: Continental IO-360-D
Takeoff power: 210 hp at 2800 rpm; per engine
Propeller:
  Front: McCauley D2AF34C59/76C, 76" dia.
  Rear: McCauley D2AF34C61/L76C, 76" dia.
Wing area: 201 sq. ft.

Figure 2.- Three view sketch of the test airplane along with a listing of its principal physical features.

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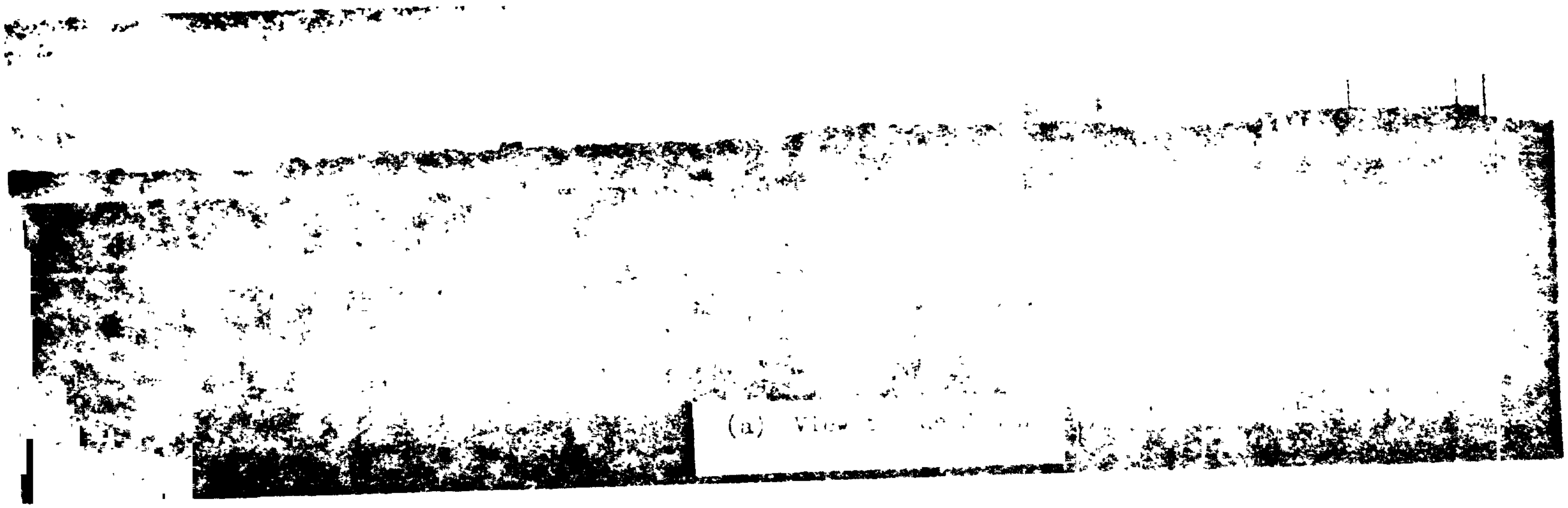
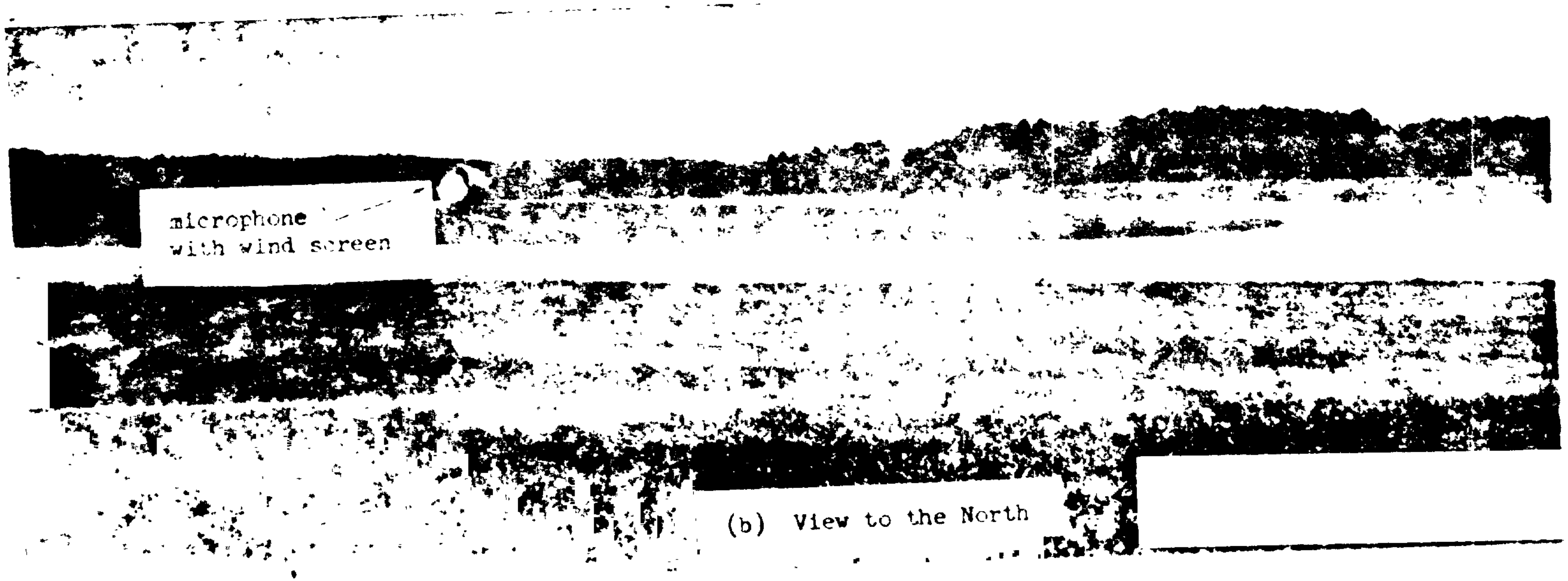
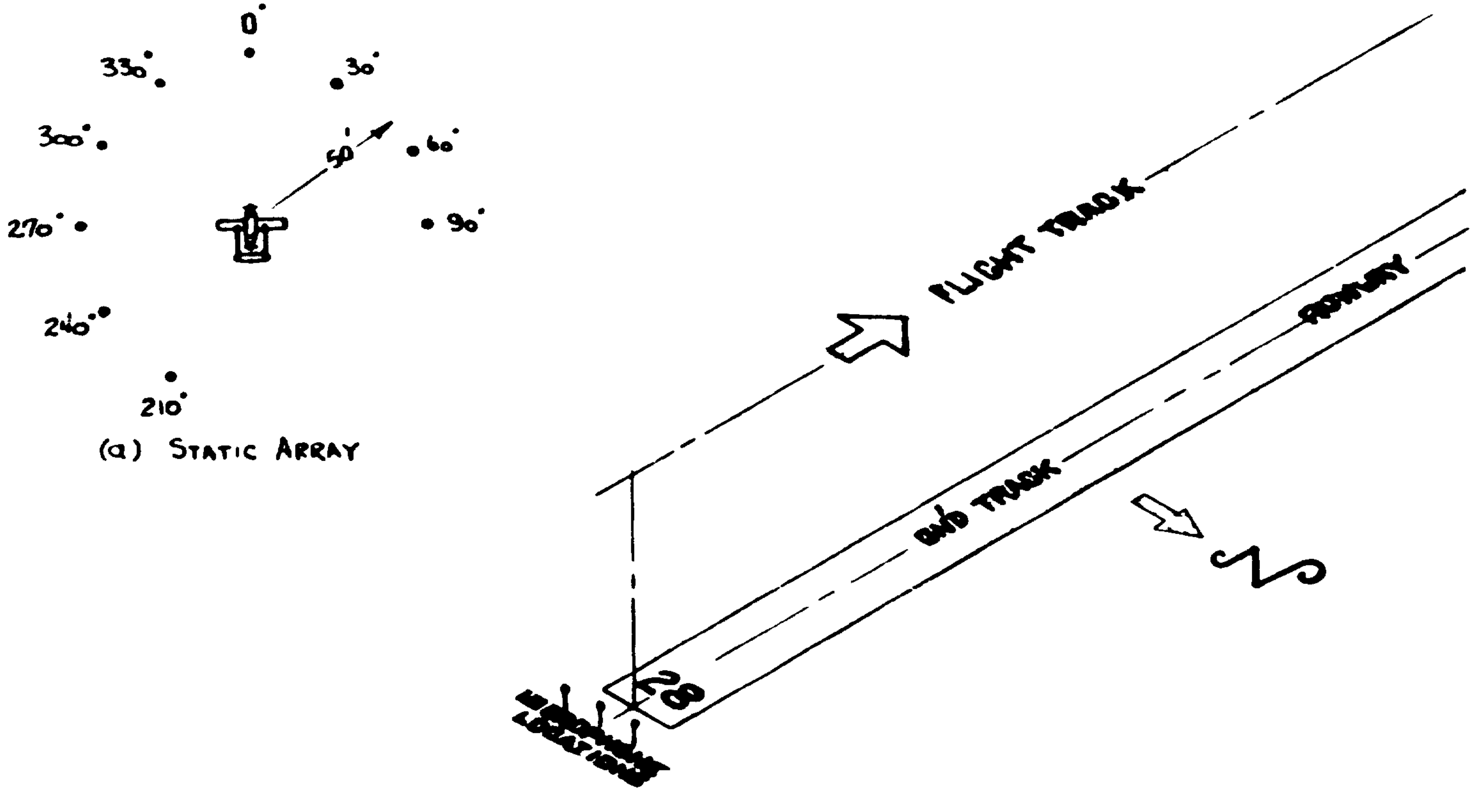


(a) View [illegible]



(b) View to the North

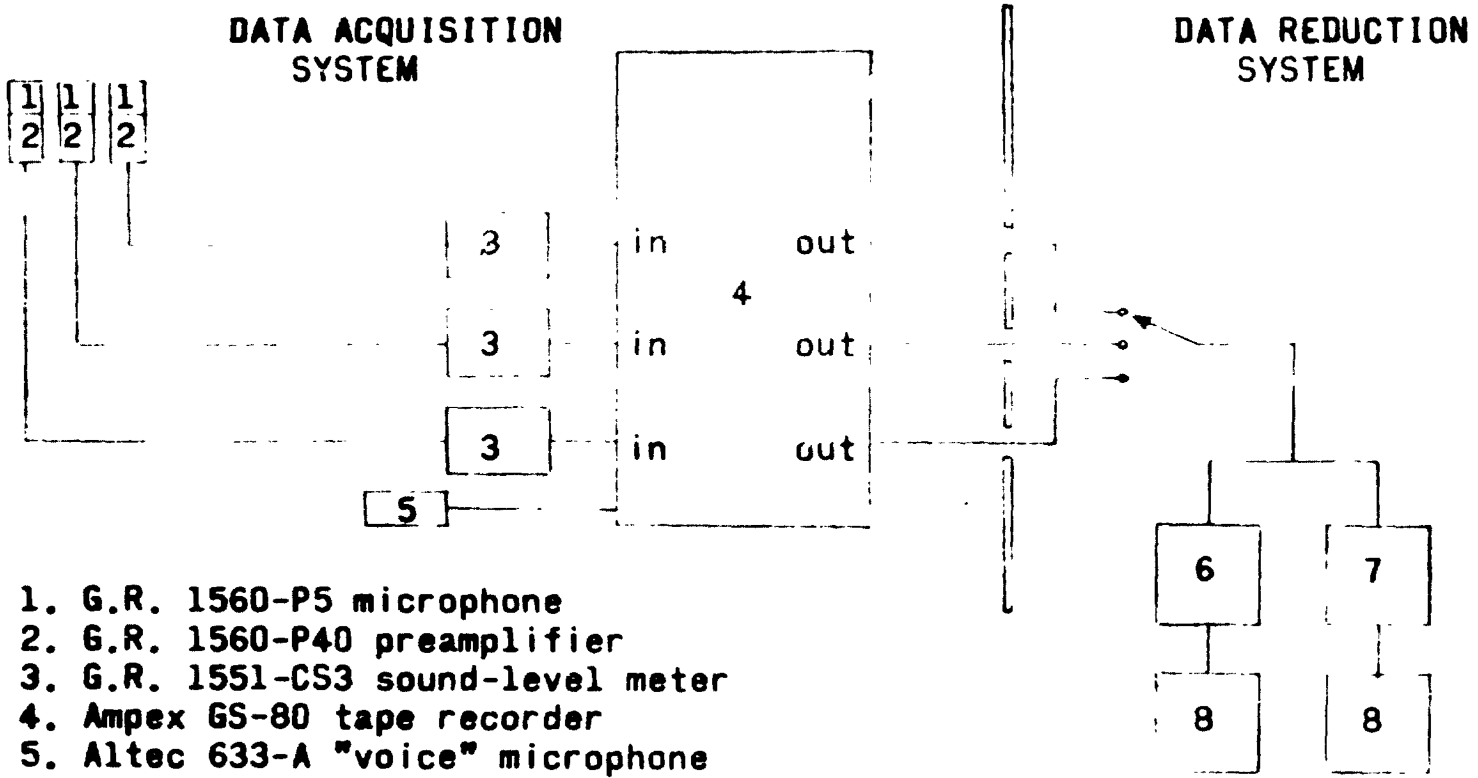
Figure 3.- Photographs of the NASA Wallops Island test area showing the runway and flat terrain.



(a) STATIC ARRAY

(b) FLYBY ARRAY

Figure 4.- Diagram of the microphone arrays illustrating the aircraft location for noise measurement during static and fly-by operations.



1. G.R. 1560-P5 microphone
2. G.R. 1560-P40 preamplifier
3. G.R. 1551-CS3 sound-level meter
4. Ampex GS-80 tape recorder
5. Altec 633-A "voice" microphone
6. G.R. 1558-AP octave-band analyzer
7. G.R. 1900-A wave analyzer
8. G.R. 1521-B graphic level recorder

Figure 5.- Block diagram showing system layout for noise data acquisition and reduction.

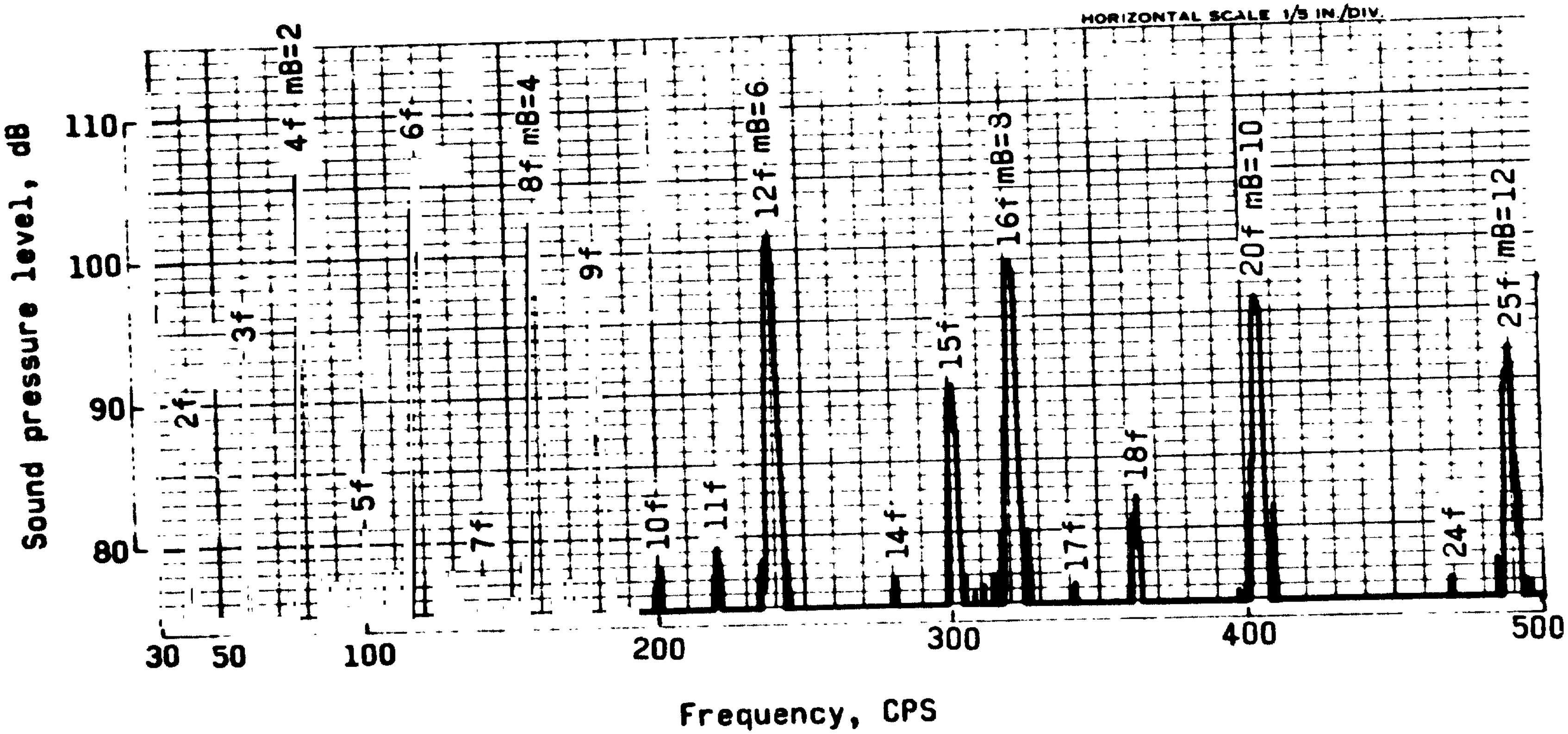


Figure .- Sample narrow band record of the propeller and engine noise from the test airplane. N_E - 2,400 rpm, MAP - 22 in. Hg., ψ 270°, r 50 ft. Front engine operating, rear engine off.

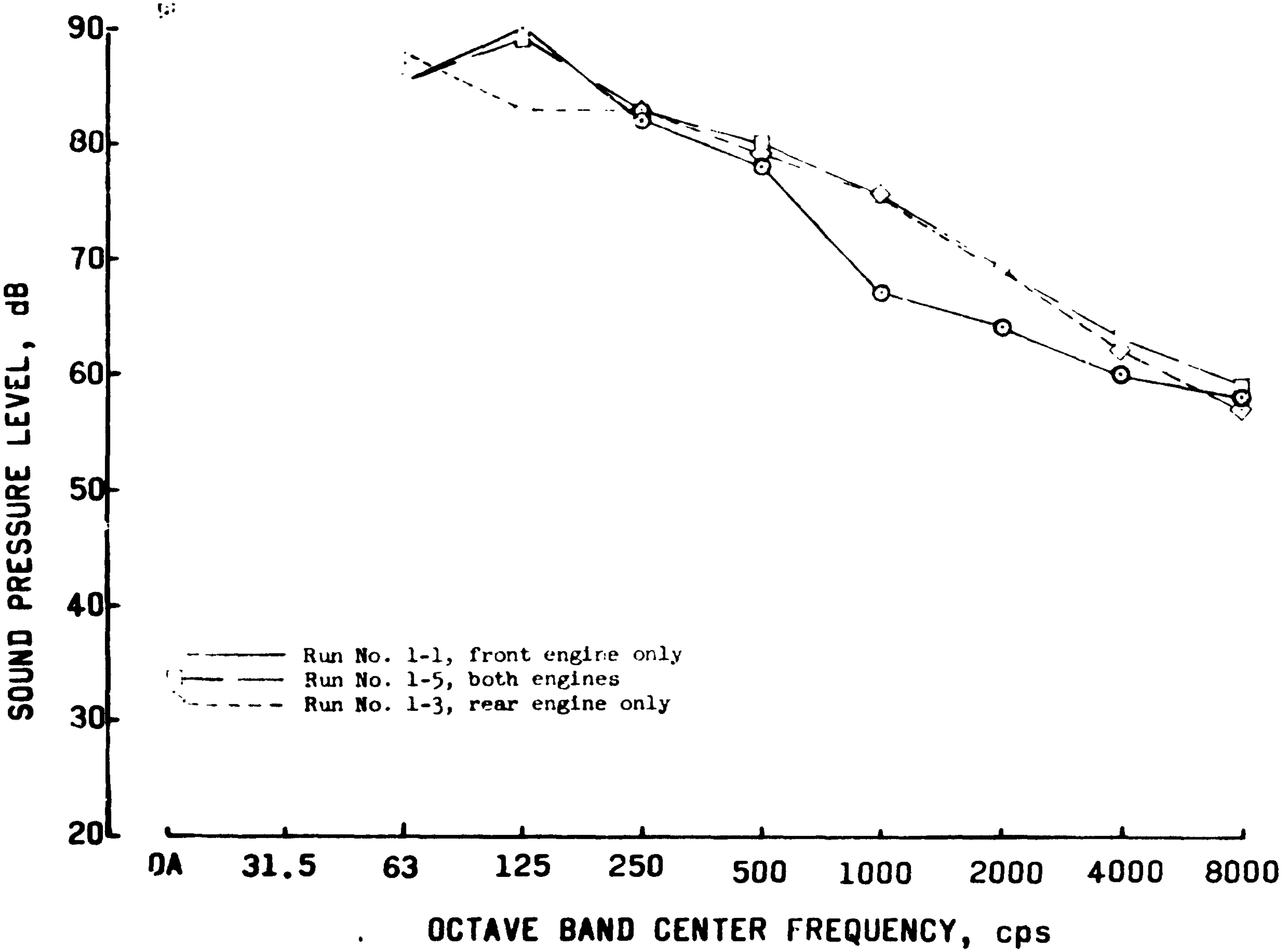


Figure 1.- Typical octave band levels from the flight measurements. Low-speed cruise flight at 300 feet altitude.

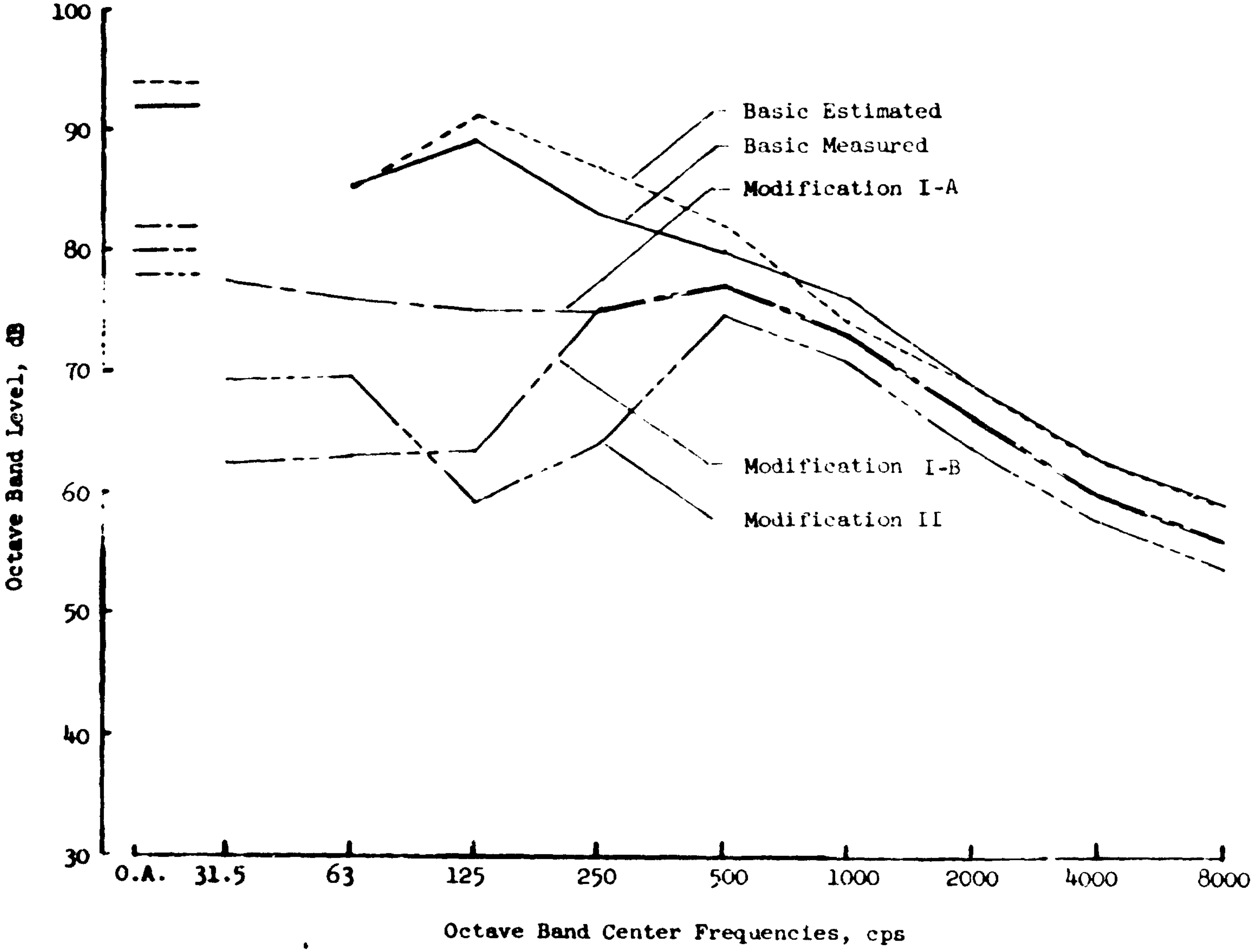


Figure 8.- Octave band spectra of the test airplane for each of the proposed modifications, and a comparison of the estimated spectrum with the measured spectrum. Altitude = 300 ft.

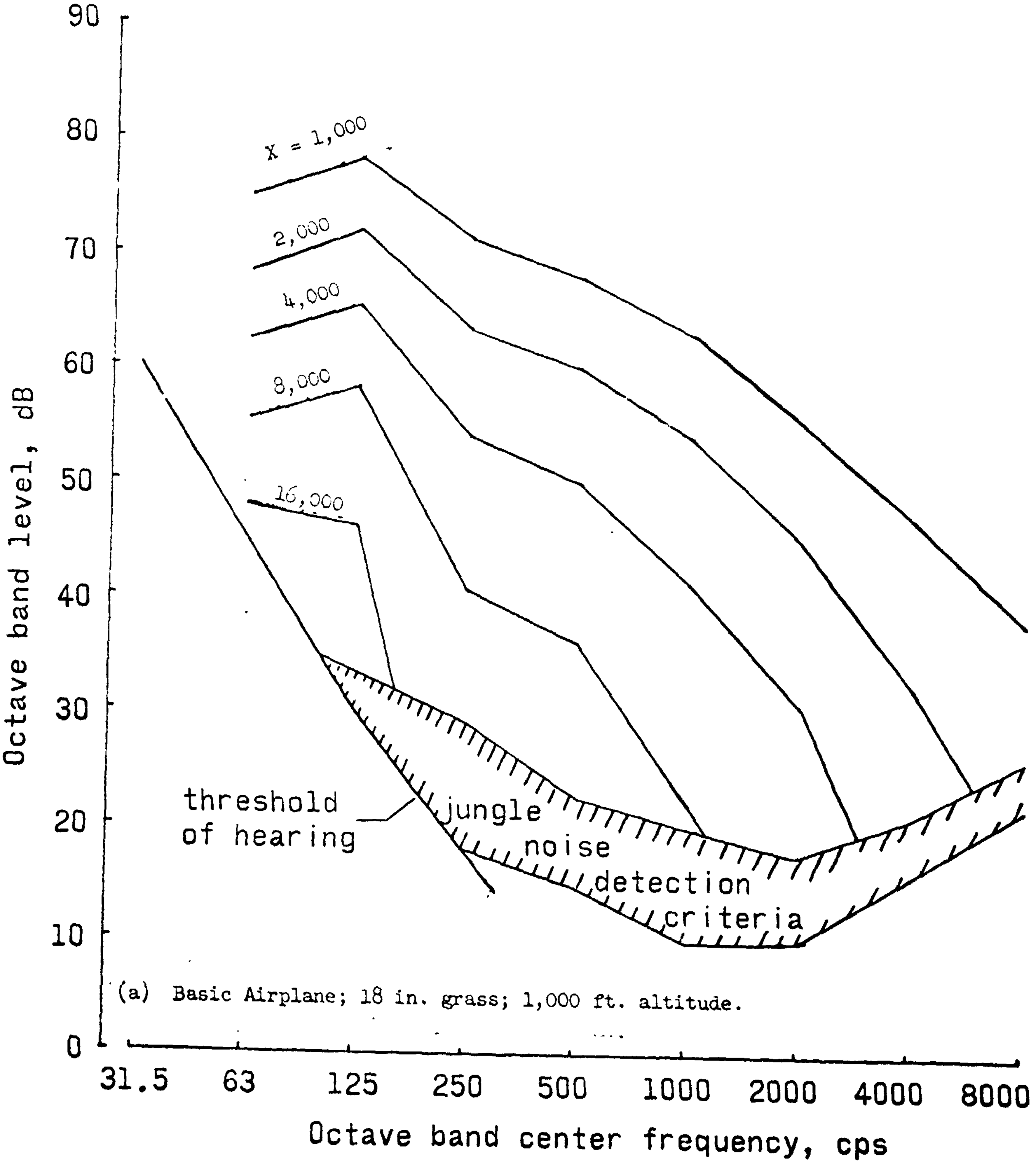


Figure 9.- Effect of slant range and terrain on the test airplane noise signature.

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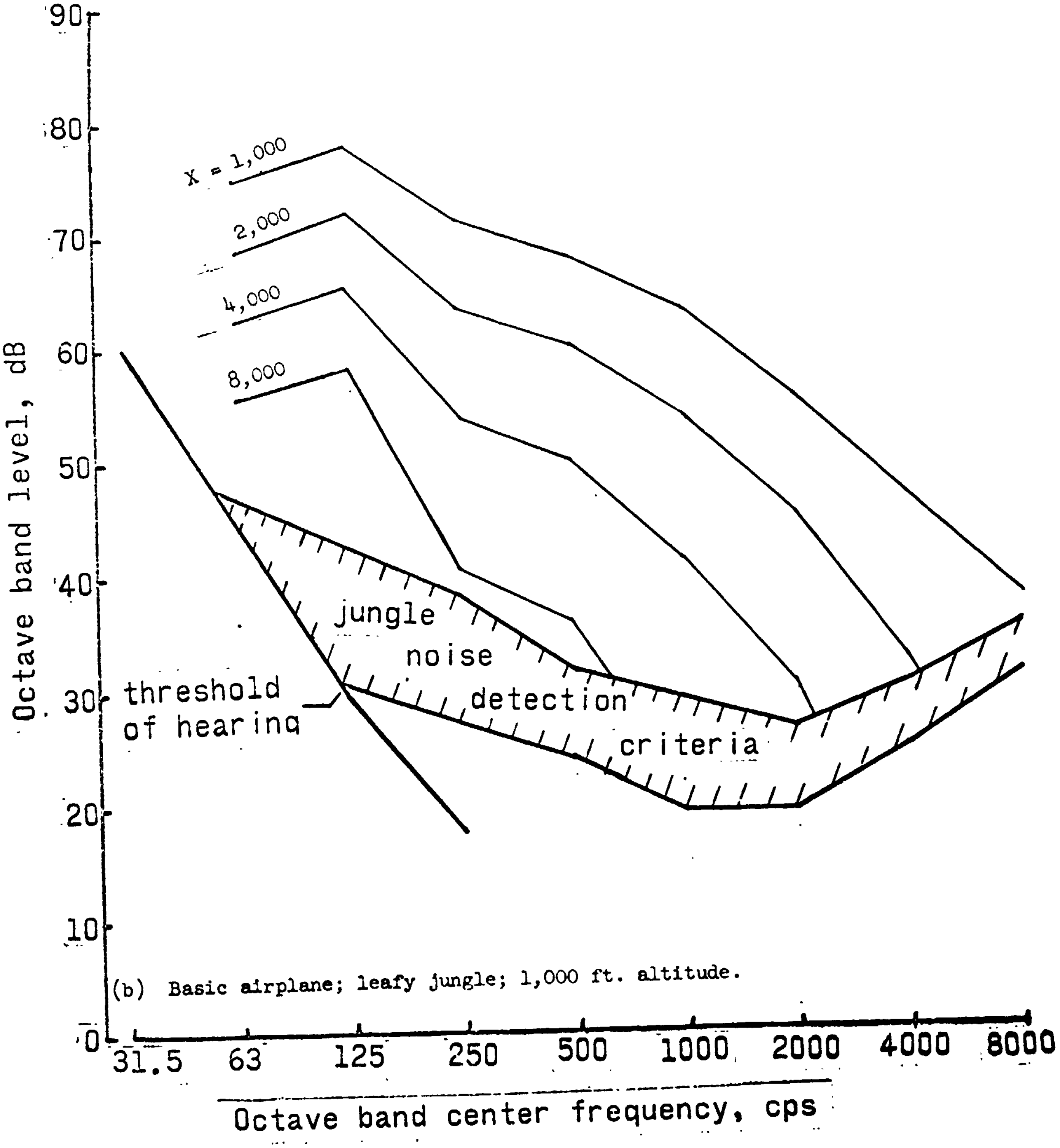
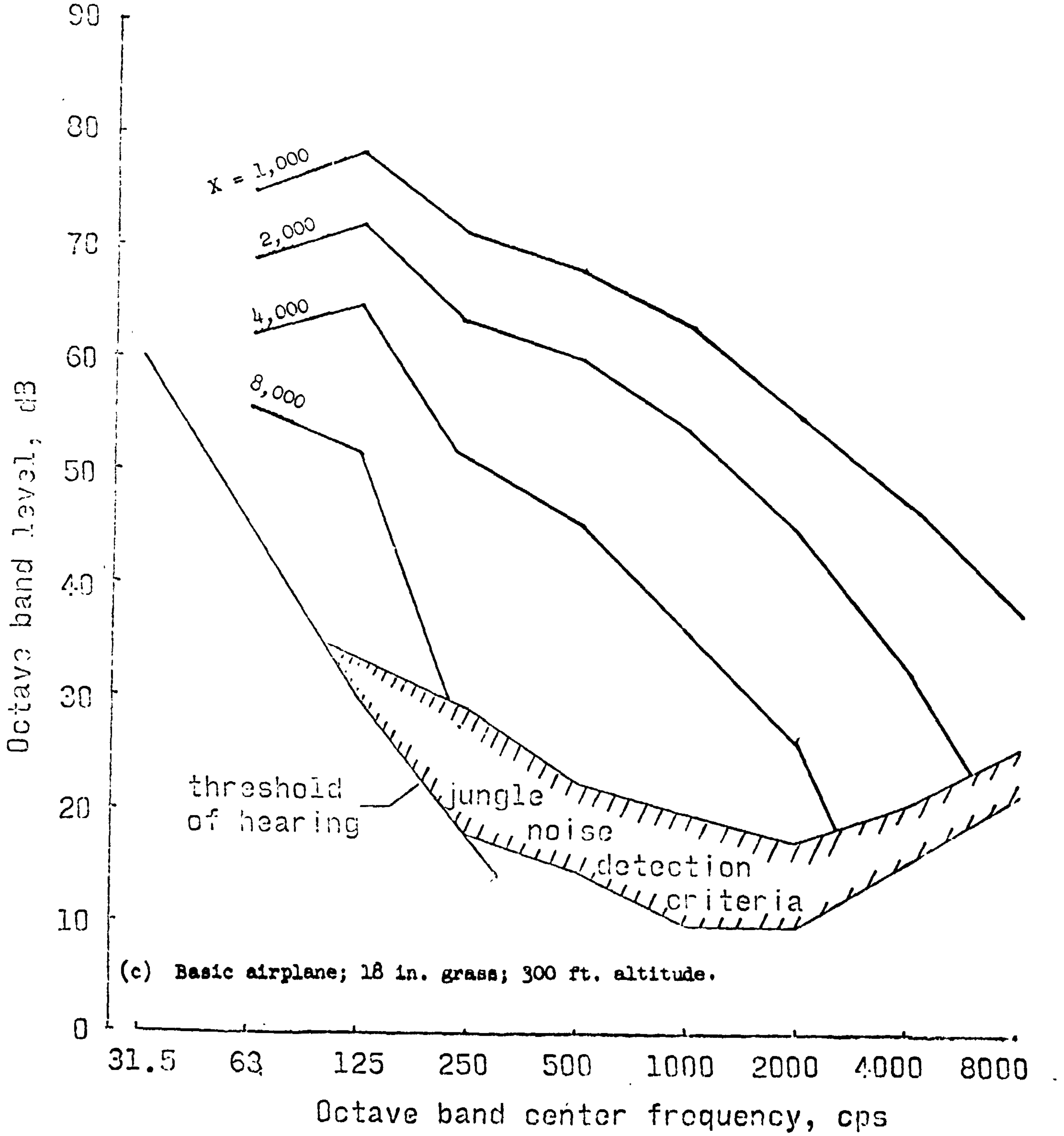
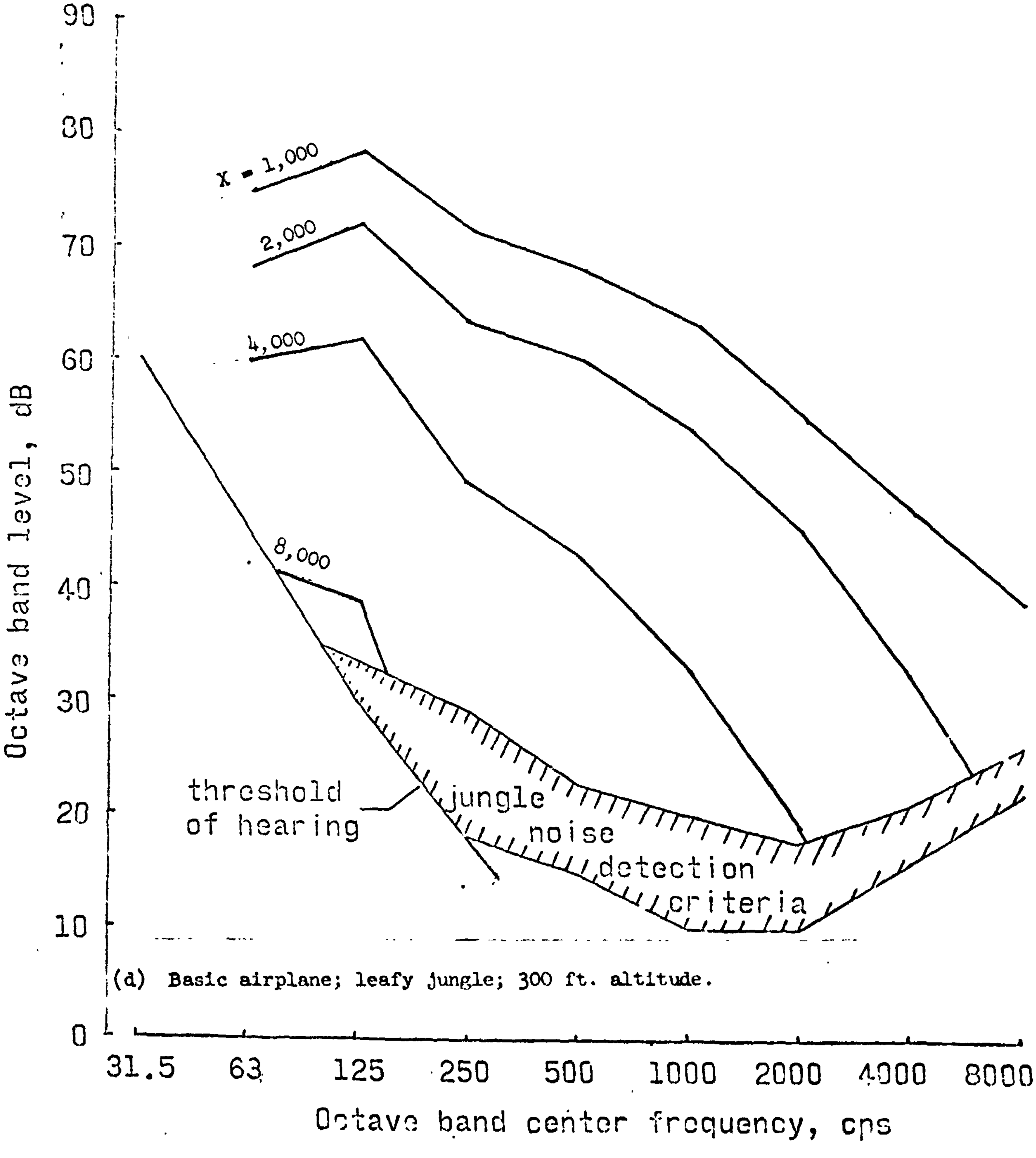


Figure 9.- Continued.



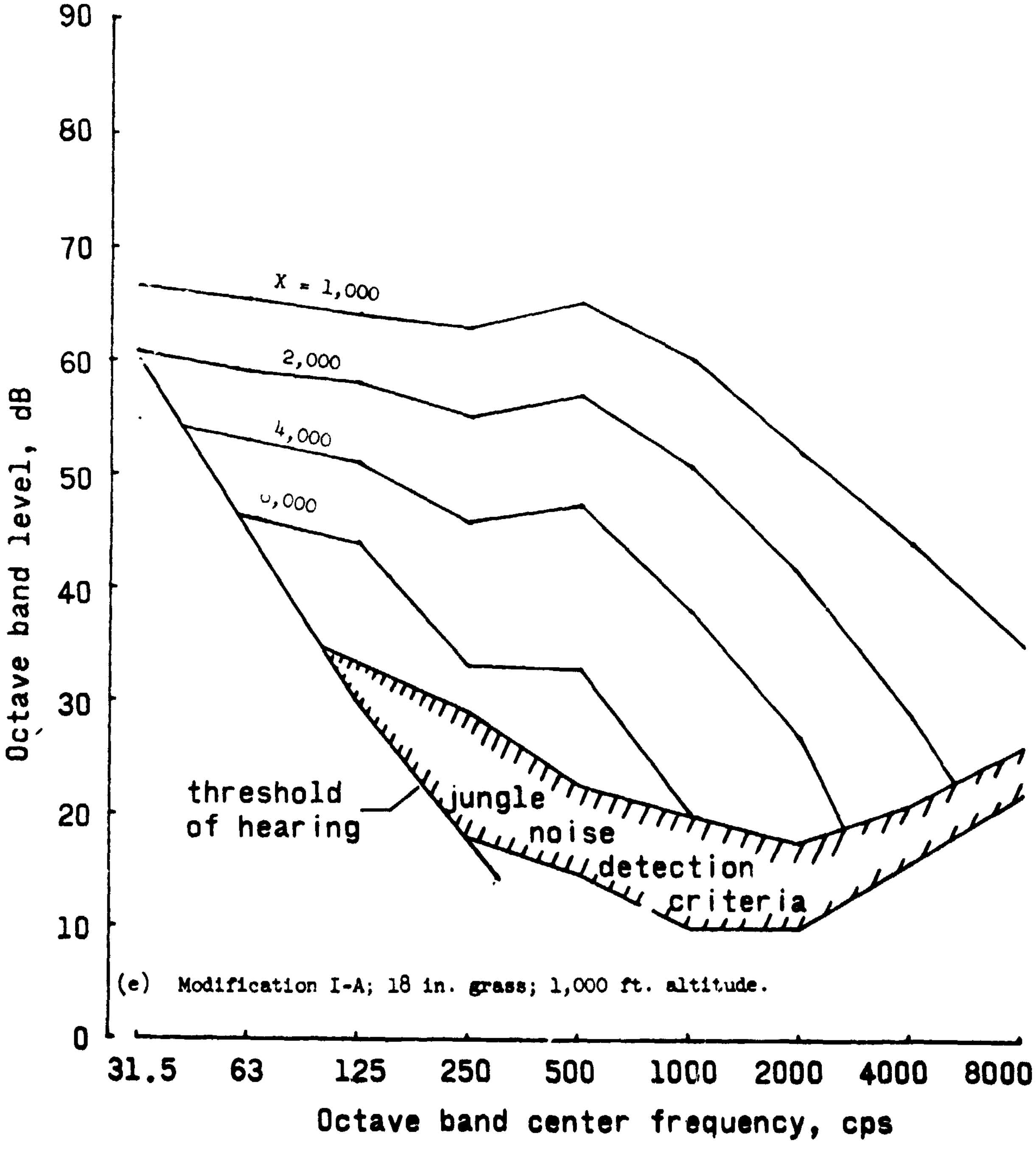
(c) Basic airplane; 18 in. grass; 300 ft. altitude.

Figure 9.- Continued.



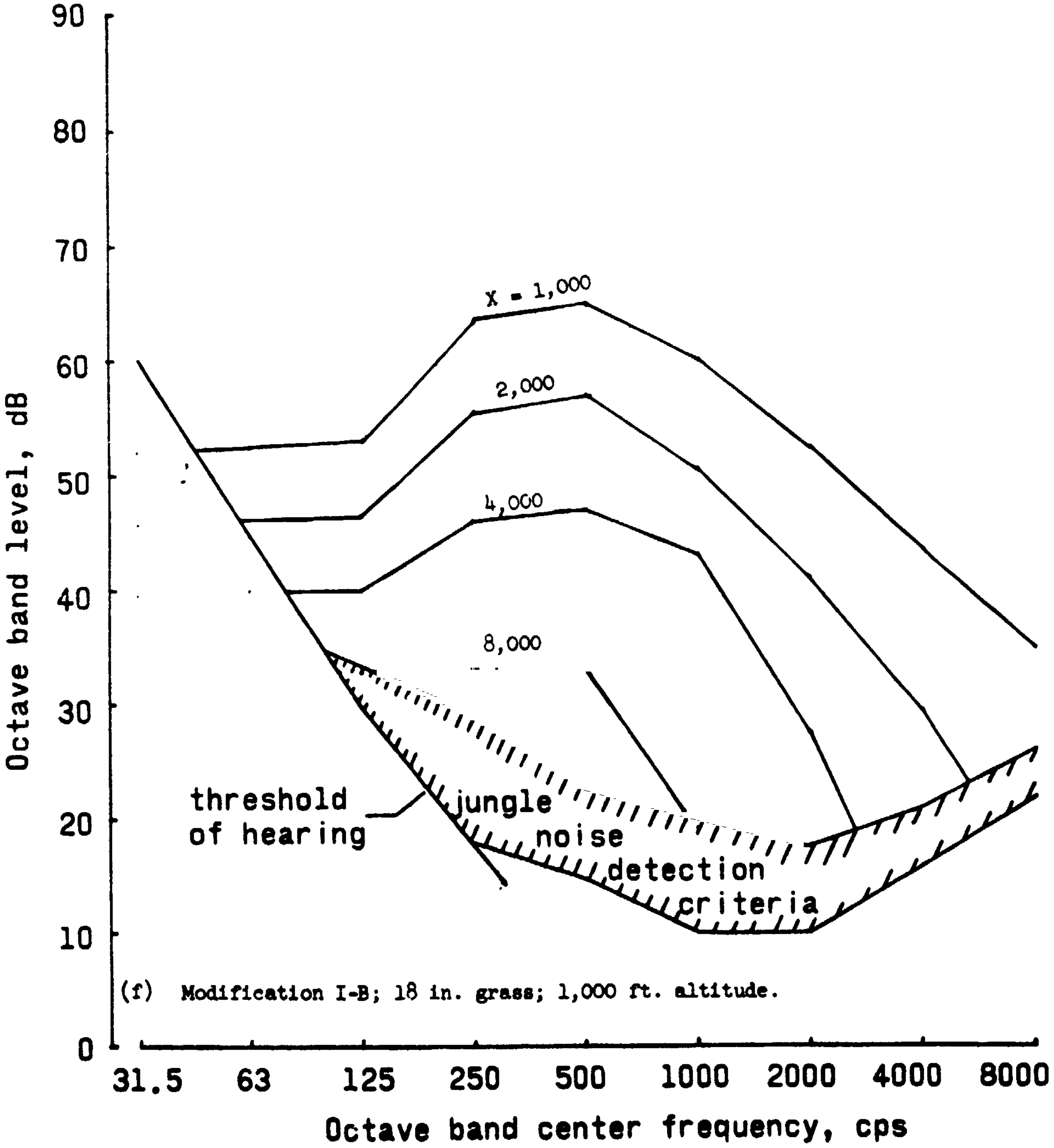
(d) Basic airplane; leafy jungle; 300 ft. altitude.

Figure 9.- Continued.



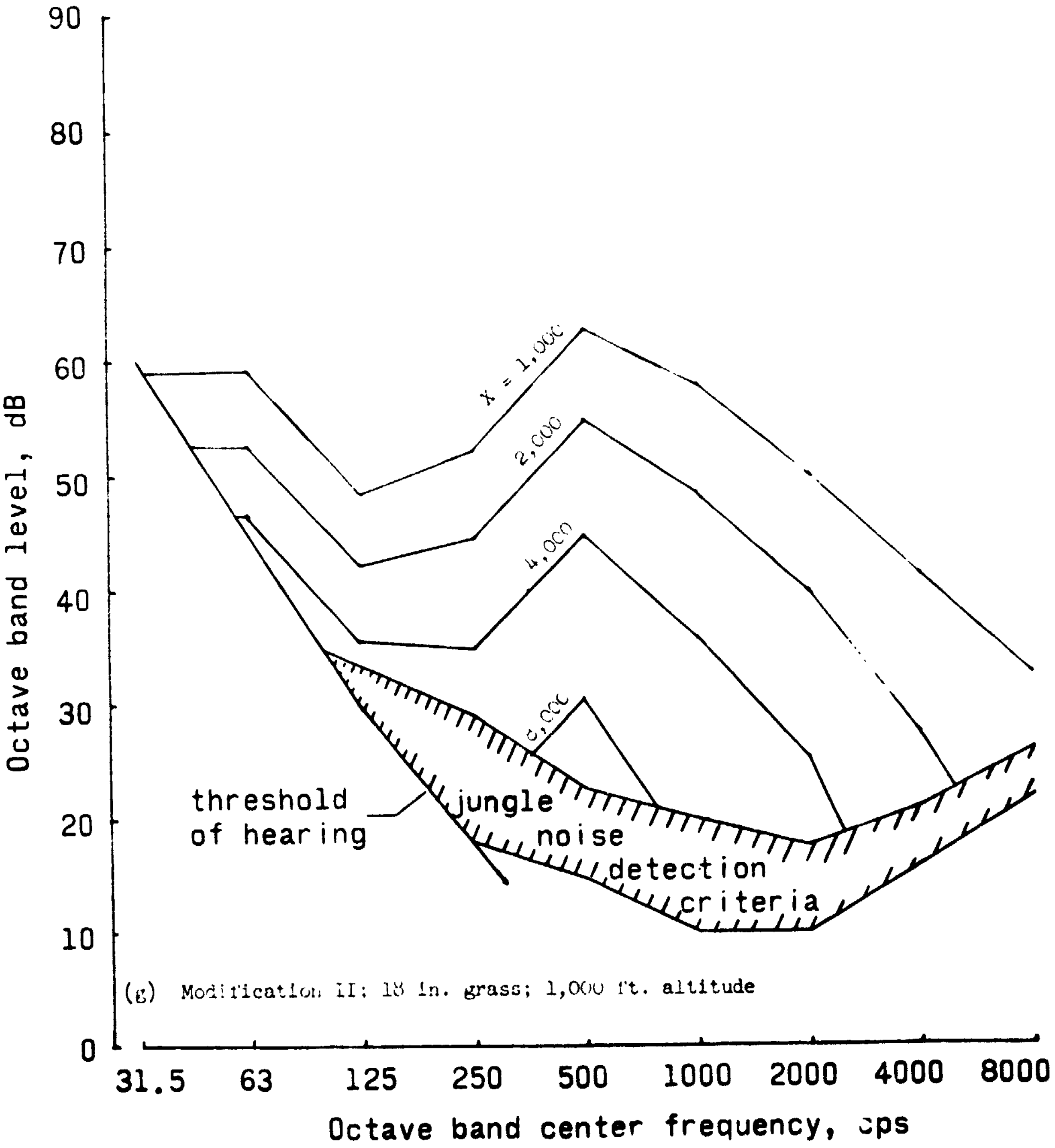
(e) Modification I-A; 18 in. grass; 1,000 ft. altitude.

Figure 9.- Continued.



(f) Modification I-B; 18 in. grass; 1,000 ft. altitude.

Figure 9.- Continued.



(g) Modification II: 18 in. grass; 1,000 ft. altitude

Figure 9.- Concluded.

APPENDIX A

PROPELLER NOISE AND PERFORMANCE CONSIDERATIONS

By John L. Crigler
Langley Research Center

For propeller-driven airplanes, the most important parameters to be considered in reducing the propeller noise are the propeller rotational tip speed and the number of blades. Experimental data (ref. A-1) show that for a given design condition of engine power and airplane speed, the propeller noise can be reduced by a reduction in propeller tip speed, or by an increase in blade number or both. Lesser reductions in noise may also be realized by decreasing the power-disc loading (larger, slower turning propellers, operating at the same tip speed).

This appendix contains a description of the procedure used to estimate the performance of several propellers that could be fitted to the design conditions of the O-2A airplane, along with estimates of the sound pressure levels generated by the propellers operating in a low-power level cruise-flight condition.

Propeller Selections

The unmodified O-2A is powered by two Continental engines rated at 210 hp at 2,800 rpm. Each engine directly drives a two-blade, 6.333-ft diameter variable-pitch propeller. The propeller is designed to absorb the rated power in cruise at 174 knots at sea level.

One alternate direct-drive propeller design entailed a reduction in diameter to 5.333 feet in order to reduce the rotational tip speed. Because of the reduced diameter, more blade area was required to absorb the power. The increased blade area was obtained by an increase in the number of propeller blades to six in order to give an additional reduction in the noise level. For the second modification an engine to propeller gear ratio of 0.75:1 was selected for a 6.333-ft diameter propeller. For noise considerations, six blades are recommended.

The performance of each of the propellers has been estimated and compared in table A-I. Also tabulated in table A-I are the number of blades, and the solidity per blade required (geometrically similar blades assumed). The performances listed in the table were estimated with the aid of references A-2, A-3, and A-4.

The propeller noise levels for all configurations were estimated for distance of 50 feet from the source by the method given in reference A-1 and by the method given in A-5, and are presented in table A-II. For convenience, equation (18) of reference A-5 (neglecting the thrust terms and in a slightly different form) is given as,

$$\rho = \frac{1}{\sqrt{2}}\left[\left\{\frac{\rho B^3 m^2 \omega^2}{2\pi s}\int_{0.2}^{1.0} J_{mB}\left(mBM_t x\right) A(x) R dx\right\}^2 + \left\{\frac{mBQ}{2\pi R_e^2 s} J_{mB}\left(0.8\ mBM_t\right)\right\}^2\right]^{\frac{1}{2}} \tag{A-1}$$

The first term in equation (A-1) gives the "thickness noise" or noise due to the blade cross section and is not considered in reference A-1. It may be seen that the second term in equation (A-1) is the same as equation (1) in reference A-1 when the thrust term is neglected. Examination of the equations for both methods shows that the calculated "thrust noise" becomes zero for the 90° azimuth. The measured noise levels taken on the 90° azimuth are also included in the table for comparison.

The noise levels for all propellers in table A-II are for the same engine power and speed (total brake horsepower for two engines operating at 2,400 rpm = 120). The cruise level flight velocity of the 0-2A airplane at sea level is approximately 87 knots for 120 hp.

The calculations indicate that about 10 dB reduction in noise can be realized by reducing the blade diameter to 5.333 feet and increasing the blade number to six, with no change in engine gearing. Larger reductions in noise can be realized by lowering the ratio of propeller speed to engine speed with no reduction in propeller diameter. For 6.333-ft diameter propellers geared to 3/4 the engine speed the calculations indicate a reduction of about 17 dB at the blade passage frequency when the power absorbed is 60 horsepower per propeller. The performance calculations in table A-I indicate the above reductions in noise may be realized without any loss in propeller performance.

REFERENCES

A-1. Hubbard, Harvey H.: Propeller Noise Charts for Transport Airplanes. NACA TN 2968, 1953.

A-2. Crigler, John L.; and Jaquis, Robert E.: Propeller-Efficiency Charts for Light Airplanes. NACA TN 1338, 1947.

A-3. Crigler, John L.: Comparison of Calculated and Experimental Characteristics for Four, Six, and Eight-Blade Single Rotating Propellers. NACA ACR No. 4B04, 1944.

A-4. Biermann, David; and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single and Dual Rotating Tractor Propellers. Report No. 747, NACA, 1942.

A-5. Dodd, K. N.; and Roper, G. M.: A Deuce Programme for Propeller Noise Calculations. Royal Aircraft Establishment Technical Note No. M.S.45, Jan. 1958.

Table A-1.- Summary of performance calculations for basic and modified propeller configurations.

Configuration	D	N_p	B	πnD	M_t	$\sigma_{0.7R}$	η@174 kts.	η@94 kts.	Static Thrust
Basic	6.333	2800	2	928	.832	.0340	.88	.79	800
Modification I	5.333	2800	6	782	.701	.0215	.88	.78	800
Modification II	6.333	2100	6	696	.624	.0180	.88	.79	825

Table A-II.- **Summary** of sound pressure levels for basic and modified propeller configurations.

Propeller Configurations													
Basic Propeller **$B = 2$, $D = 6.333$** **$N_p = 2400$; $M_t = .712$**					Modification I $B = 6$; $D = 5.333$ $N_p = 2400$; $M_t = .600$				Modification II $B = 6$; $D = 6.333$ $N_p = 1800$; $M_t = .535$				
Two Propellers, 60 **HP** each Direct Drive					Two Propellers, 60 HP each Direct Drive				Two Propellers, 60 HP each GR = .75:1				
f	**mB**	$dB_{calc.}$ **Ref. A-1**	$dB_{calc.}$ **Ref. A-5**	$dB_{meas.}$	**f**	**mB**	$dB_{calc.}$ Ref. A-1	dB_{calc} Ref. A-5	**f**	**mB**	$dB_{calc.}$ Ref. A-1	$dB_{calc.}$ Ref. A-5	
80	2	96.2	96.6	101	240	6	84.7	86.7	180	6	78.2	79.6	
160	4	93.6	94.5	103	480	12	62.5	70.4	360	12	51.2	56.0	
240	6	89.5	91.1	101	720	18	38.9	55.8	540	18	—	35.5	
320	8	85.0	87.7	99									
400	10	80.0	84.4	96									

APPENDIX B

O-2 ENGINE NOISE REDUCTION

By Tony L. Parrott
Langley Research Center

Throughout the study of noise reduction for the O-2 aircraft, the engine noise spectrum that was measured with only the front engine operating has been taken as the noise signature of the unmodified engine. This is necessary because the basic configuration of this aircraft, as supplied by the manufactuer, included a small muffler fitted to the aft engine. Hence, the measured spectrum for the forward engine is assumed to be similar to what would be measured for the aft engine if the present muffler were removed, thereby enabling the results of the study to be applicable to the aft as well as the forward engine.

Muffler Design

Three muffler configurations were analyzed for the O-2 aircraft. The relative performance of these configurations is indicated in figure B-1 where the estimated overall sound pressure level resulting from the application of each muffler configuration is plotted against the muffler volume. It will be noted that two of the configurations (single chamber resonators) differ only in their tailpipe resonance frequency. It can be seen from the performance estimate that all three configurations provide approximately the same attenuation to within five decibels over the range of volumes considered.

Engine noise.- The unmuffled exhaust sound pressure level corresponding to an engine speed of 2,400 rpm is shown by the dashed curve in figure B-2. This spectrum was obtained from a 3 cps bandwidth analysis of tape recordings made during static aircraft runs at a distance of 50 feet. The spectrum shows that the overall noise level from the engine is approximately 111 decibels with the major contribution coming from a 120 cps component which corresponds to the engine fundamental frequency at 2,400 rpm. The dashed line, in figure B-2, connecting the discrete component levels of the spectrum shown by the symbols will be called the spectrum envelope in order to emphasize the fact that a discrete frequency spectrum is being discussed. It was found to be more convenient to deal with the envelope for the purpose of estimating the effect of various muffler designs on the noise spectrum.

Single chamber resonators.- The lower curve of figure B-2 shows the estimated spectrum resulting from a 2.22 cubic foot single-chamber resonator with a tailpipe resonance of 1,000 cps (tailpipe length = 1 ft). Similarly, figure B-3 shows the spectrum modification due to a 3.33 cubic foot single chamber resonator with a tailpipe resonating at 377 cps (tailpipe length equals 2.65 feet). Note that the overall performance of these muffler configurations differ by only 3 dB; however, the details of the spectrum modification are quite different. Their difference is due entirely to the different tailpipe frequencies. It should be clear from this comparison that some degree of trial and error is necessary to optimize a given set of filter elements for desired overall noise reduction and spectrum detail.

Double expansion chamber.- In figure B-4 is shown the spectrum modification due to a double expansion chamber-type muffler with a tailpipe length of 1 foot and hence, a resonance frequency of 1,000 cps. This configuration is seen to be very effective from about 75 to 360 cps. For this type muffler, as well as the resonator type, a considerable amount of iteration is required to locate the lower cutoff frequency of the attenuation band such as to appreciably reduce the sound pressure levels at the lower frequencies. In fact, it is not infrequent that amplification occurs at frequencies of 50 cps or less as indicated in figure B-2 at 40 cps, where an amplification of 6 dB is present even though the overall noise reduction is 14 dB. The reader should therefore be aware that the results stated in this report are of a preliminary nature which attempt to explore the amount of noise reduction that is feasible. If actual hardware is desired, then the proposed configuration should be optimized by means of more detailed analysis.

Methods and Procedures

Nature of exhaust noise.- Reciprocating engine exhaust noise is characterized by a discrete frequency spectrum. The frequency spectrum depends upon engine speed, number of cylinders, firing order and exhaust manifold geometry as well as the exhaust-mass-flow-time-history details of the individual cylinders. For an engine whose exhaust manifold geometry is such that the acoustic disturbances from the various cylinders travel the same distance to a common point of expulsion into the atmosphere, then the dominant contribution to the exhaust noise will occur at the so-called engine fundamental frequency which is given by

$$f_d = \frac{SN}{120}$$

S = engine speed, rpm

N = number of cylinders

In actuality, however, the exhaust manifold geometry may be such that an engine harmonic or subharmonic may contribute the major portion of the total exhaust noise. It is for this reason that measurement and analysis of the exhaust noise for operational conditions must be conducted in order to accurately locate the frequencies at which the major noise components are being radiated. From this knowledge a muffler design and/or modification of the exhaust system can be undertaken to provide some exhaust noise reduction.

Muffling of exhaust noise.- Mufflers for engine-exhaust systems are perhaps more accurately described as low-pass acoustic filters designed to have a minimum impedance for steady volume flows and to have a high impedance for oscillating volume flows characteristic of acoustic waves. The high impedance for the sound waves is provided by reactive-type acoustic devices and/or by an absorbing medium. The reactive devices consist of expansion chambers or side branch resonators which impede the exhaust noise by reflecting it back into the source. Absorbing media simply convert acoustic energy into heat, hence bringing about attenuation of noise by means of a dissipation process. Reactive devices work well for frequencies up to about 500 to 600 cps, whereas dissipation devices work better for the higher frequencies above 600 cps. Since aircraft engine noise spectra indicate that the greater part of the noise lies in the 20 - 500 cps frequency range, only reactive mufflers will be considered in this report.

Successful aircraft muffler design requires that three criteria be satisfied:

1. Acoustical criterion: Specifies the overall attenuation or noise reduction to be achieved and the detailed modifications of the spectrum by the addition of the muffler.

2. Back pressure criterion: Specifies the minimum pressure drop through the muffler at given operating conditions of temperature and mass flow.

3. Aerodynamic criterion: Specifies the maximum allowable volume and weight as well as restrictions on shape.

Although there is necessarily a trade-off between these three criteria for a given practical application, only the acoustical performance of mufflers will be discussed at present in order to give the reader an appreciation for the upper limits of noise reduction that are possible. The criteria of minimum back pressure and minimum aerodynamic penalty will then be seen to place definite limits on the attainable noise reduction for a given aircraft and operating conditions. Also, it is clearly impractical to reduce engine noise levels more than 9 dB below the levels of other noise sources on the aircraft since the higher level effectively masks the other for differences of this order or greater.

The sound attenuating characteristics of a muffler system are determined by examining the sound pressure spectrum of the exhaust noise that is to be reduced. Then, by essentially a trial and error procedure, various combinations of expansion chamber - resonator combinations are analyzed by means of a general computer program which produces a graph of the attenuation through the muffler as a function of frequency. Usually it is most efficient to begin with the simplest system and progress to more complicated systems until one is found adequate for the job. A flow chart describing this procedure is shown in figure B-5.

It was not necessary to go through the above entire procedure for each configuration investigated in this report. For example, it was obvious as more experience was gained that a particular type of muffler would be most efficient for a given situation, in which case the design computations were carried out without further ado. Also, it should be pointed out that, whereas many assumptions underlie the computational procedure, the resulting attenuation curves were biased in accordance with experimental results in reference B-1. Hence, it is believed that the resulting estimates of engine noise attenuation are, to some extent, conservative.

REFERENCE

Davis, Don D., Jr.; Stokes, George M.; Moore, Dewey; and Stevens, George L., Jr.: Theoretical and Experimental Investigation of Mufflers With Comments on Engine-Exhaust Muffler Design. NACA Report 1192, 1954.

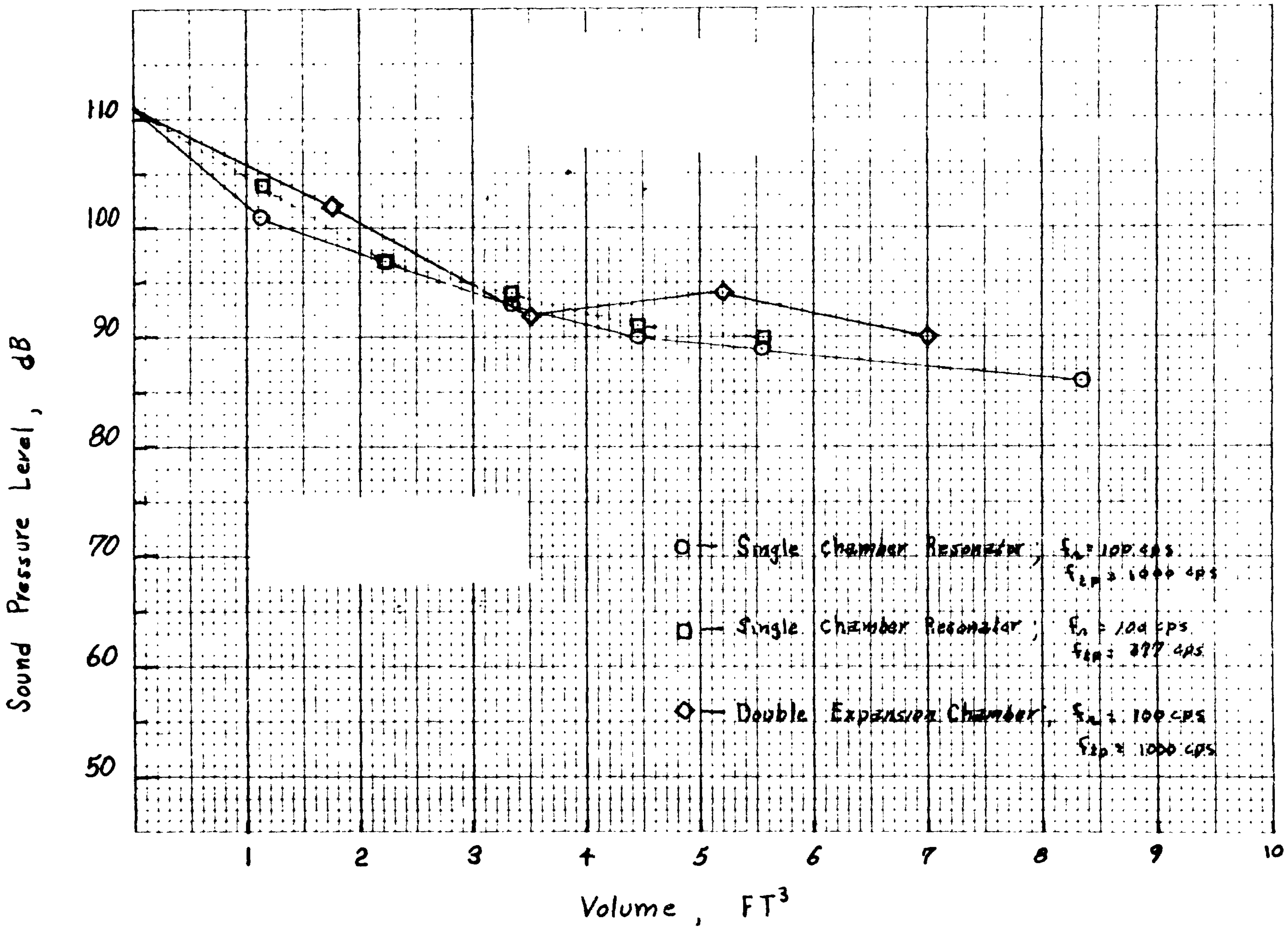


Figure B-1.- Estimated overall muffler performance as function of volume.

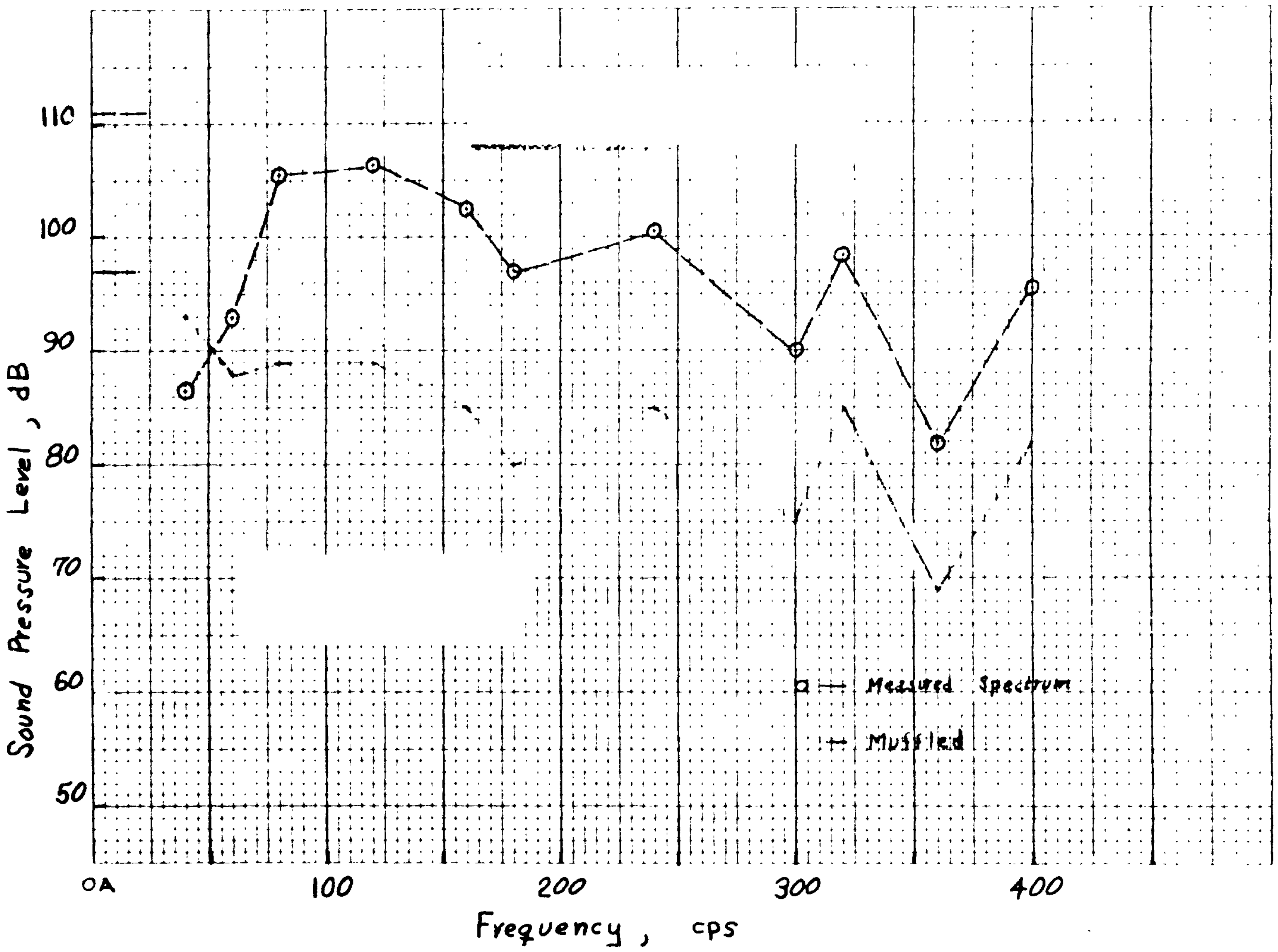


Figure B-2.- Estimated spectrum change due to 2.22 ft.^{3} single chamber resonator with 1 ft. tailpipe.

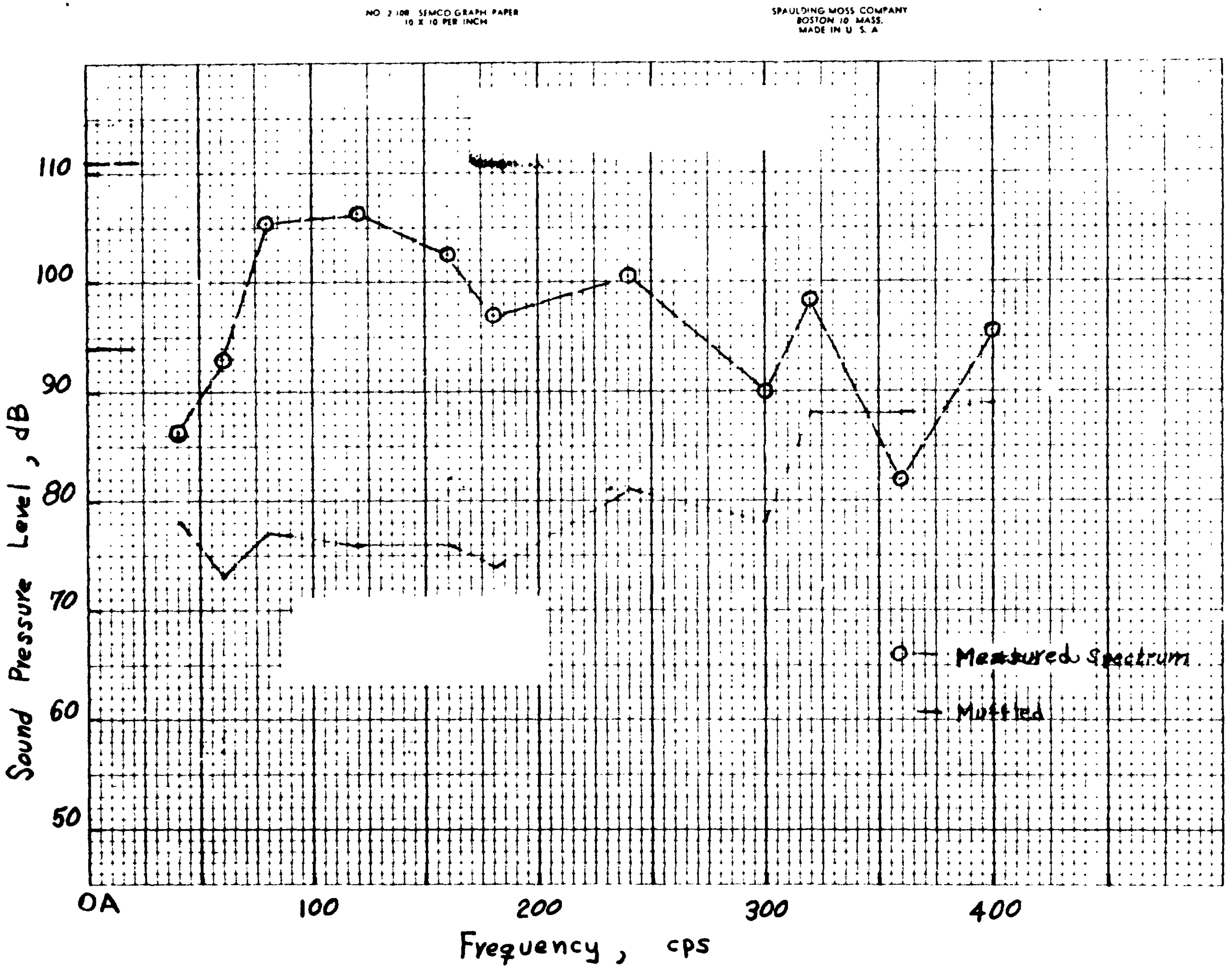


Figure B-3.- Estimated spectrum change due to 3.33 ft.^{3} single chamber resonator with 2.65 ft. tailpipe.

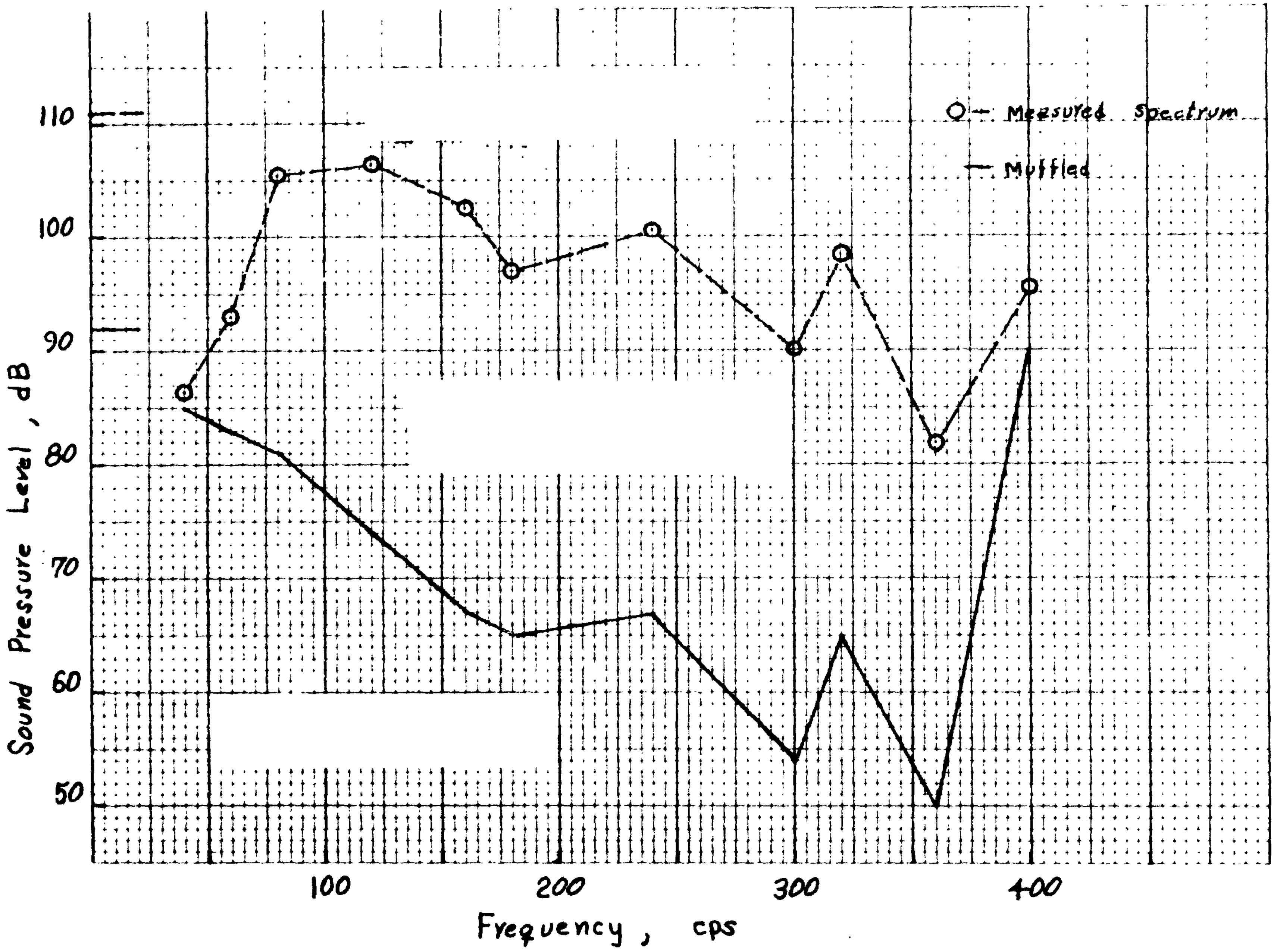


Figure B-4.- Estimated spectrum change due to 3.49 ft.^{3} double expansion chamber with 1 ft. tailpipe.

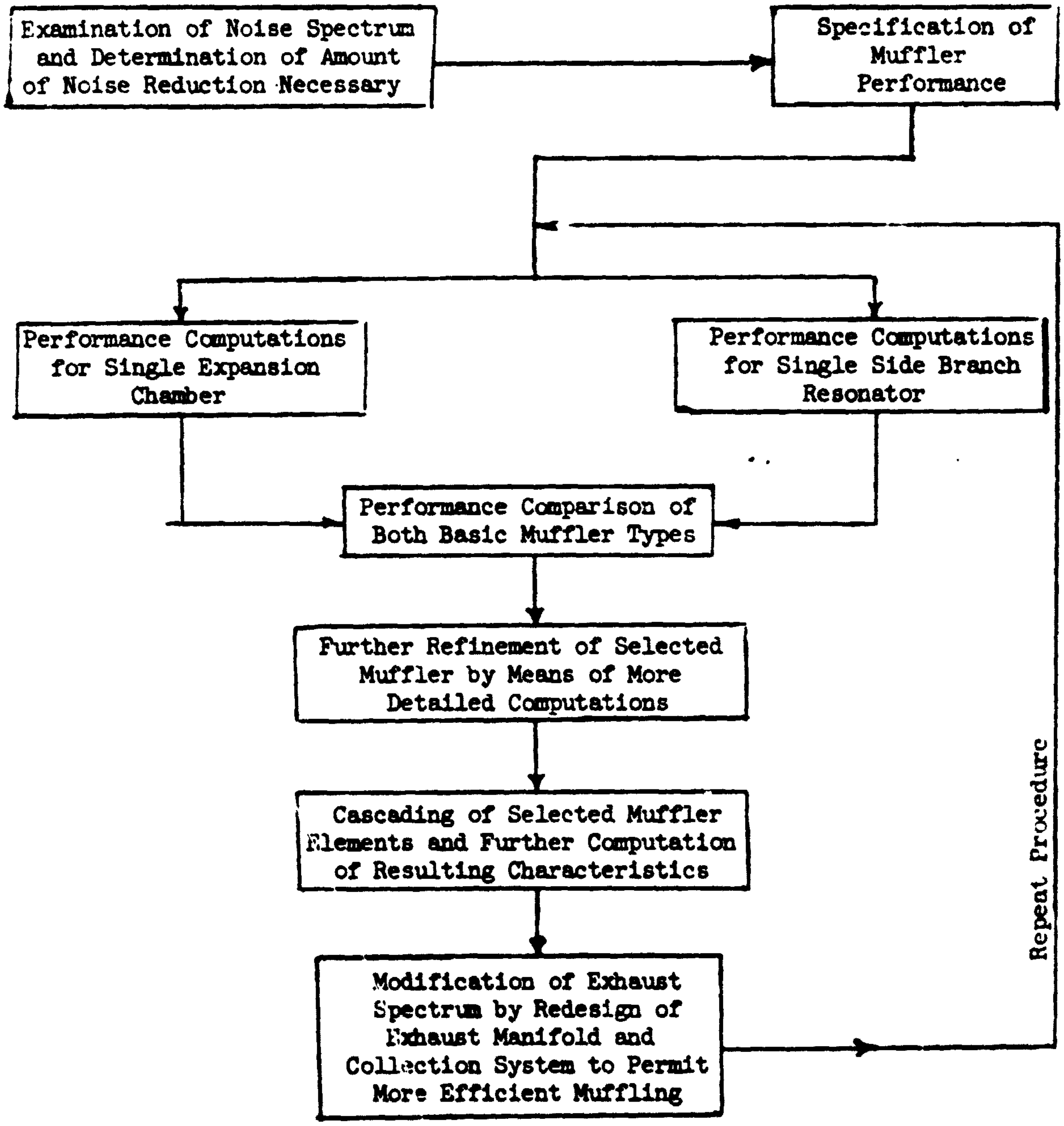


Figure B-5.- Flow diagram illustrating muffler computation procedure employed for this study.

APPENDIX C

WEIGHT ESTIMATES

M. L. Sisson

Propeller and Reduction Gear Weight Estimation

Propeller blade weights are based on scaling factors applied to the existing aluminum alloy blade. This method assumes that the thickness-to-chord ratio at each percentage of propeller tip radius station is maintained. The weight of each aluminum alloy blade becomes:

$$\text{weight}_1 = \frac{\text{chord}_1}{\text{chord}_0} \times \frac{\text{diameter}_1}{\text{diameter}_0} \times \text{weight}_0 ,$$

where subscript "0" refers to the original blade and subscript "1" refers to the new blade.

Propeller hub weights were scaled from the existing controllable pitch hub. The scaling factor used was the total blade centrifugal force (centrifugal force per blade times the number of blades) raised to the eight-tenths power.

Weights of production reduction gears of three reciprocating engines were obtained by subtracting the weights of direct drive engines from the weights of the same engines with reduction gearing. These three weights were then plotted versus normal rating output torque on log-log graph paper (figure C-1). It was found that a straight line very accurately fitted these cases. Weights for reduction gears were read from this curve.

Exhaust System Weight Estimation

Two different sized single cavity resonator mufflers and one double expansion chamber were investigated. For the front engine the single cavity resonator mufflers were assumed to be basically cylindrical and mounted under the cabin behind the nose wheel and forward of the main landing gear. The two sizes of mufflers would be approximately 12 and 13 inches in diameter by 2.8 and 3.8 feet long. The present exhaust pipes would be extended along-side the nose wheel, being brought together behind the nose wheel at the muffler entrance. The single cavity resonator mufflers for the rear engine would be mounted below the engine within the cowling. The double expansion chamber mufflers were assumed to be combined into one common shell of modified eliptical cross section approximately 6.6 by 19.8 inches in cross section and 10 feet long mounted along the left side of the fuselage.

The weights of the mufflers are based on the use of .037 inch (20 ga.) stainless steel for pipes and the 2.22 cubic foot cylindrical and the double expansion chamber mufflers, and .050 inch (18 ga.) stainless steel for the other muffler shells.

Weights of the various proposed modifications are summarized in table C-1.

Figure C-2 shows the muffler installations which form the basis of the weight estimates presented herein. It is noted that the ground clearance of the Modification I circular cross section mufflers is one or two inches less than that of the front propeller. The muffler ground clearance can readily be increased by approximately three inches by using eliptical or oval cross section mufflers at a weight penalty of two or three pounds.

TABLE C-1

O-2 Weight Summary

Modification I-A

Front engine propeller weight increase	-17.4	lbs.
Front engine muffler installation	29.65	
Rear engine propeller weight increase	-18.05	
Rear engine muffler weight increase	22.1	
Total weight increase	16.30	lbs.

Modification I-B

Front engine propeller weight increase	-17.4	lbs.
Front engine muffler installation	48.1	
Rear engine propeller weight increase	-18.05	
Rear engine muffler weight increase	30.0	
Total weight increase	42.65	lbs.

Modification II

Front engine propeller and gear weight increase	13.3	lbs.
Rear engine propeller and gear weight increase	13.0	
Exhaust system weight increase	90.2	
Total weight increase	116.5	lbs.

TABLE C-1

Propeller Weight Summary

Basic Propeller - 2 blade, D=6.33 ft.

Weight of 2 blades	21.2 lbs.
Front propeller hub weight	34.8
Weight of front propeller	56.0 lbs.
Weight of 2 blades	21.2 lbs.
Rear propeller hub weight	36.8
Weight of rear propeller	58.0 lbs.

Modification I - 6 blade, D=5.33 ft., b=.533 x basic

Weight of 6 blades	15.25 lbs.
Weight of front propeller hub	23.35
Total weight of front propeller	38.60 lbs.
Less basic propeller weight	56.00
Weight increase, front propeller	-17.4 lbs.
Weight of 6 blades	15.25 lbs.
Weight of rear propeller hub	24.70
Total weight of rear propeller	39.95 lbs.
Less basic propeller weight	58.00
Weight increase, rear propeller	-18.05 lbs.

Modification II - 6 blade, D=6.33 ft., b=.53 x basic

Weight of 6 blades	17.9 lbs.
Weight of front propeller hub	30.4
Total weight, front propeller	48.3 lbs.
Less weight of basic propeller	56.0
Weight increase, front propeller	-7.7 lbs.
Reduction gear weight increase	21.00 lbs.
Weight increase for front engine	13.3 lbs.
Weight of 6 blades	17.9 lbs.
Weight of rear propeller hub	32.1
Total weight, rear propeller	50.0 lbs.
Less weight of basic propeller	58.0
Weight increase, rear propeller	-8.0 lbs.
Reduction gear weight increase	21.0
Weight increase for rear engine	13.0 lbs.

TABLE C-1

O-2 Muffler Weight Summary

Modification I-A

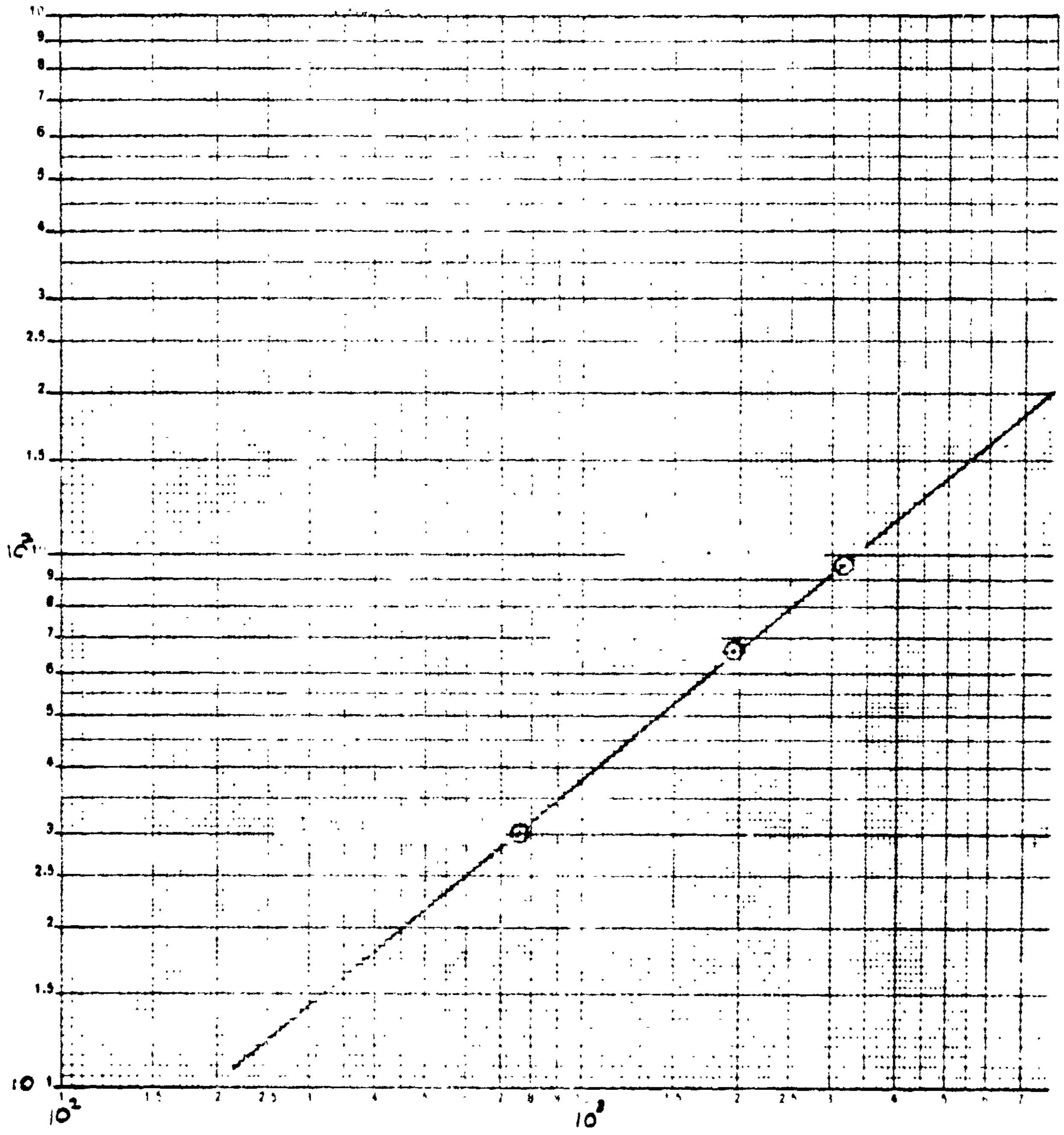
Front engine muffler installation	29.65	lbs.
Rear engine muffler installation	33.7	
Total muffler system weight	63.35	lbs.
Less existing muffler installation	11.6	
Weight increase due to mufflers	51.75	lbs.

Modification I-B

Front engine muffler installation	48.1	lbs.
Rear engine muffler installation	41.6	
Total muffler system	89.7	lbs.
Less existing muffler installation	11.6	
Weight increase due to mufflers	78.1	lbs.

Modification II
(3:1 ellipse with center divider)

Shell weight with divider	61.8	lbs.
Internal piping, tailpipes, and fittings	40.0	
Total muffler system weight	101.8	lbs.
Less existing muffler installation	11.6	
Weight increase due to mufflers	90.2	lbs.



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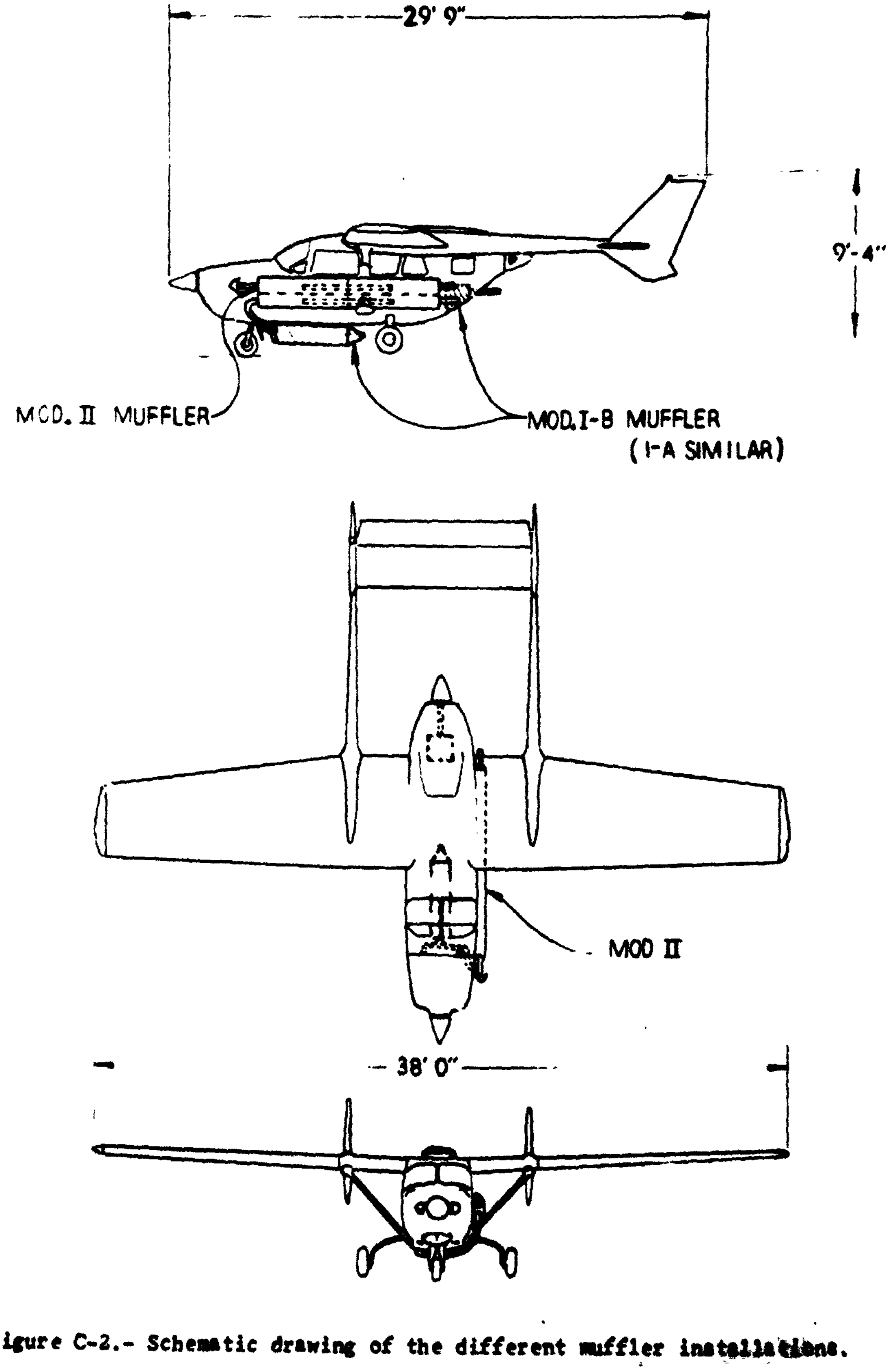

Figure C-2.- Schematic drawing of the different muffler installations.

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APPENDIX D

PERFORMANCE, STABILITY AND CONTROL

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The O-2A airplane is the military version of the Cessna Model 337 light plane which is powered by two Continental IO-360 engines rated at 210 horsepower each and equipped with McCauley 2-blade, 76-inch diameter, constant-speed, full-feathering propellers. This airplane is characterized by the unusual design feature of tandem power plants; the front engine and propeller operating as a tractor and the rear engine and propeller operating as a pusher.

The basic performance of the unmodified O-2A airplane was obtained from full-scale flight-test results reported in reference D-1. There are no wind-tunnel data available for this configuration.

Basis for estimating the performance of the modified configurations.- Factors which affect performance may be broken down into three categories: (1) weight, (2) thrust, and (3) drag. The manner in which each of these factors is affected by the modifications proposed for noise reduction is as follows:

Incremental weight reductions would result from each of the modified propellers, and weight penalties would be incurred due to installation of mufflers and reduction gearing, as reported in appendix C. The overall effect of changes in weight for each modification is presented in table D-I which shows that the maximum weight penalty (mod. II) based on take-off gross weight was only 2.76 percent.

Thrust can be affected by installation power losses and propeller efficiency. The power losses for the modified configurations were assumed to be the same as for the basic O-2A. With the simple resonating chamber-type mufflers proposed in this study, back-pressure losses would be inconsequential - that is, no more than would occur with comparable increased tailpipe length. Propeller efficiencies for the modified configurations were assessed to be equal to the basic propeller efficiencies (except for modification I at speeds corresponding to that for maximum rate of climb, which was only 1 percent less than for the basic case, as shown in appendix A). Static thrust was assessed to be equal to or better than that of the basic O-2A airplane for all modifications (see, also, appendix A). From this assessment, only modifications I-A and I-B would suffer performance losses as a result of decreased thrust, and then only in the speed range corresponding to that for maximum rate of climb.

Profile drag would increase as a result of the external muffler installations. The proposed mufflers for modifications I-A and I-B would fit completely within the rear engine cowl, and therefore, no drag penalty would be incurred; however, the front engine mufflers for these two modifications would be mounted under the belly of the airplane between the nose gear and main gear wells. In the case of modification II, however, both the front engine and rear engine mufflers would be located in a package along the left side of the fuselage as described in appendix C. The incremental drag coefficient due to each muffler installation was estimated on the basis of a moderately streamlined body and included an interference drag factor. Results were obtained as follows:

	Mod. I-A	Mod. I-B	Mod. II
Muffler, volume, ft^3	2.22	3.33	3.49 (each)
Muffler diameter, in.	12.1	12.7	6.6 x 19.8 ellipse
Muffler frontal area, S_π, ft^2	0.79	0.88	0.70
Length/diameter ratio	2.8	3.6	9.0
C_{D_π} (ref. D-2)	0.0337	0.0395	0.0870
Interference drag factor, k_1	2.0	2.0	1.75
Imperfect streamline factor, k_2	1.5	1.5	1.50
ΔC_{D_o}	0.00040	0.00052	0.00080

where

$$\Delta C_{D_o} = C_{D_\pi} \cdot \frac{S_\pi}{S} \cdot k_1 \cdot k_2$$

and

$$S = \text{wing area} = 201 \text{ ft}^2$$

These incremental drag values amount to only 1.7 to 3.4 percent of the basic O-2A zero-lift drag coefficient and would be inconsequential at the higher lift coefficients. Therefore, muffler drag would have a small effect on the top speed of the modified configurations but would have essentially no effect on the take-off and rate-of-climb performance.

Results of performance analysis.- A comparison of the estimated performance of the modified versions of the O-2A airplane with that of the basic airplane are presented in table D-II. The performance listed under "Basic" are full-scale flight test results, whereas that listed under each modification is estimated on the basis of the factors given in the preceding section and the data presented in figures D-1 through D-4. The basic lift-drag polars of figure D-1 were modified by adding the incremental zero-lift drag coefficients of the appropriate mufflers to determine the drag of the modified configurations. Take-off performance is presented in figure D-2 for the basic O-2A and modified versions, and was affected only by changes in weight and average thrust during the take-off. Rate-of-climb performance for the modified configurations was also only affected by weight and thrust (in the case of mod. I-A and I-B) and the results are compared with that for the basic O-2A in figure D-3. The manner in which the incremental drag due to the mufflers affects the power required for level flight and the consequent effect on top speed is illustrated in figure D-4. Note that the ordinate, horsepower per engine, must be doubled in order to obtain the total horsepower required.

The tabulated results of table D-II indicate relatively minor performance losses for the modified configurations throughout the flight envelope. The poorest take-off performance results with modification I-B and showed only about 5.6 percent longer distance to take-off and clear a 50-foot obstacle. Modification I-B also had the poorest rate-of-climb performance, but again, this was only about 3.4 percent less than for the basic O-2A airplane. Stall speed and speed for maximum rate of climb were essentially unaffected by the various modifications. Maximum speed suffered by 1 or 2 knots depending mainly on the drag penalty of muffler installation.

Results of stability and control analysis.- The manner in which the various modifications affect the airplane center-of-gravity location is presented in table D-I. Inasmuch as each modification consisted of adding or subtracting about the same weight in the vicinity of each engine (approximately equidistant from the basic center of gravity of the airplane), there were no appreciable effects of the various modifications on center-of-gravity location. None of the modifications were considered of sufficient magnitude to affect the aerodynamic neutral points. Consequently, the stability characteristics of the modified configurations should be essentially the same as the basic O-2A airplane.

Longitudinal control sensitivity at low flight speeds and with high power settings (such as during take-off) would probably increase as a result of the smaller diameter propellers of modifications I-A and I-B. This is because the slipstream dynamic pressure at the tail is a function of propeller disc loading, which is somewhat larger for the decreased diameter propellers.

REFERENCES

D-1. Latas, Joseph: Performance Data for the 1965 and 1966 Cessna Model 337 Airplane. Cessna Aircraft Company Report No. F-337-5, 1965.

D-2. Hoerner, S. F.: Aerodynamic Drag, pp. 69 and 70, published by the author, Midland Park, N J., 1951.

TABLE D-I.- WEIGHT AND BALANCE SUMMARY

Case	Basic Weight Empty, lb	Useful Load, lb	Gross Weight, lb	Gross-Weight Center of Gravity, % MAC
Basic	3015	1185	4200	25.1
Mod. I-A	3032	1185	4216	25.1
Mod. I-B	3068	1185	4243	25.0
Mod. II	3132	1185	4317	24.3

Note 1.- Useful Load:

Pilot	200 lb at fuselage station 103
Passenger	200 lb at fuselage station 109
Fuel and Oil	785 lb at fuselage station 150

Note 2.- Basis for Change in Basic Weight Empty:

Case	Item	Incremental Weight Change, lb	Fuselage Station, in
Mod. I-A	Front propeller	-17.4	23
	Rear propeller	-18.0	231
	Front muffler	29.7	96
	Rear muffler	22.1	205
	Total	16.4	
Mod. I-B	Front propeller	-17.4	23
	Rear propeller	-18.0	231
	Front muffler	48.1	96
	Rear muffler	30.0	192
	Total	42.7	
Mod. II	Front propeller	- 7.7	23
	Rear propeller	- 8.0	231
	Front muffler	50.9	128
	Rear muffler	39.3	128
	Front gear	21.0	28
	Rear gear	21.0	226
	Total	116.5	

TABLE D-II.- SUMMARY OF PERFORMANCE

Configuration and Item		Basic	Mod. I-A	Mod. I-B	Mod. II
Propeller diameter, ft		6.33	5.33	5.33	6.33
Number of blades		2	6	6	6
Incremental weight due to propellers		---	-35	-35	-16
Reduction gearing		---	---	---	0.75:1
Incremental weight due to gearing		---	---	---	42
Mufflers, ft^3		---	2,22	3.33	3.49
Incremental weight due to mufflers		---	51	78	91
Incremental C_D due to mufflers		---	.00040	.00052	.00080
Take-off gross weight, lbs		4,200	4,216	4,243	4,317
Ground distance, ft		805	840	850	860
Air distance to clear 50-ft, ft		630	665	665	640
Total to clear 50-ft, ft		1,435	1,505	1,515	1,500
Stall speed power off, kn		59.3	59.4	59.6	60.1
Maximum rate of climb, fpm	SL	1,305	1,270	1,260	1,270
	5,000 ft	1,010	975	970	985
	10,000 ft	715	680	675	695
	15,000 ft	420	390	385	410
	20,000 ft	130	100	100	125
Service Ceiling, ft		20,500	20,000	20,000	20,300
Velocity for maximum rate of climb, kn TAS	SL	93	93	94	94
	5,000 ft	98	98	98	99
	10,000 ft	103	103	103	104
	15,000 ft	108	108	109	109
	20,000 ft	114	114	115	116
V_{max}, knots TAS	SL	174	172	172	172
	5,000 ft	172	170	170	170
	10,000 ft	168	166	166	166
	15,000 ft	156	155	155	155
	20,000 ft	136	135	135	135

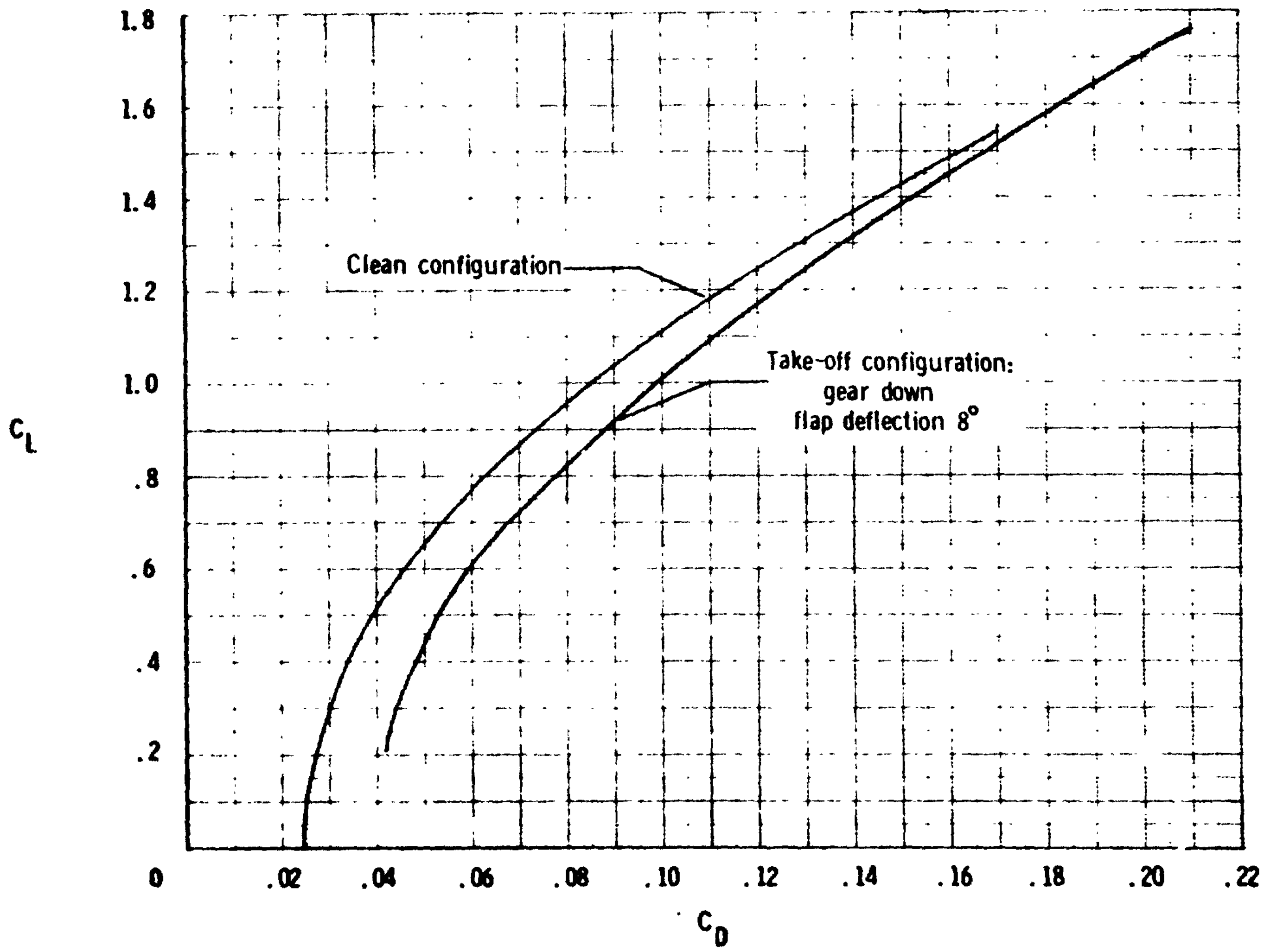

Figure D-1.-Lift drag polars for basic O-2A airplane as determined from full-scale flight tests.(ref. D-1)

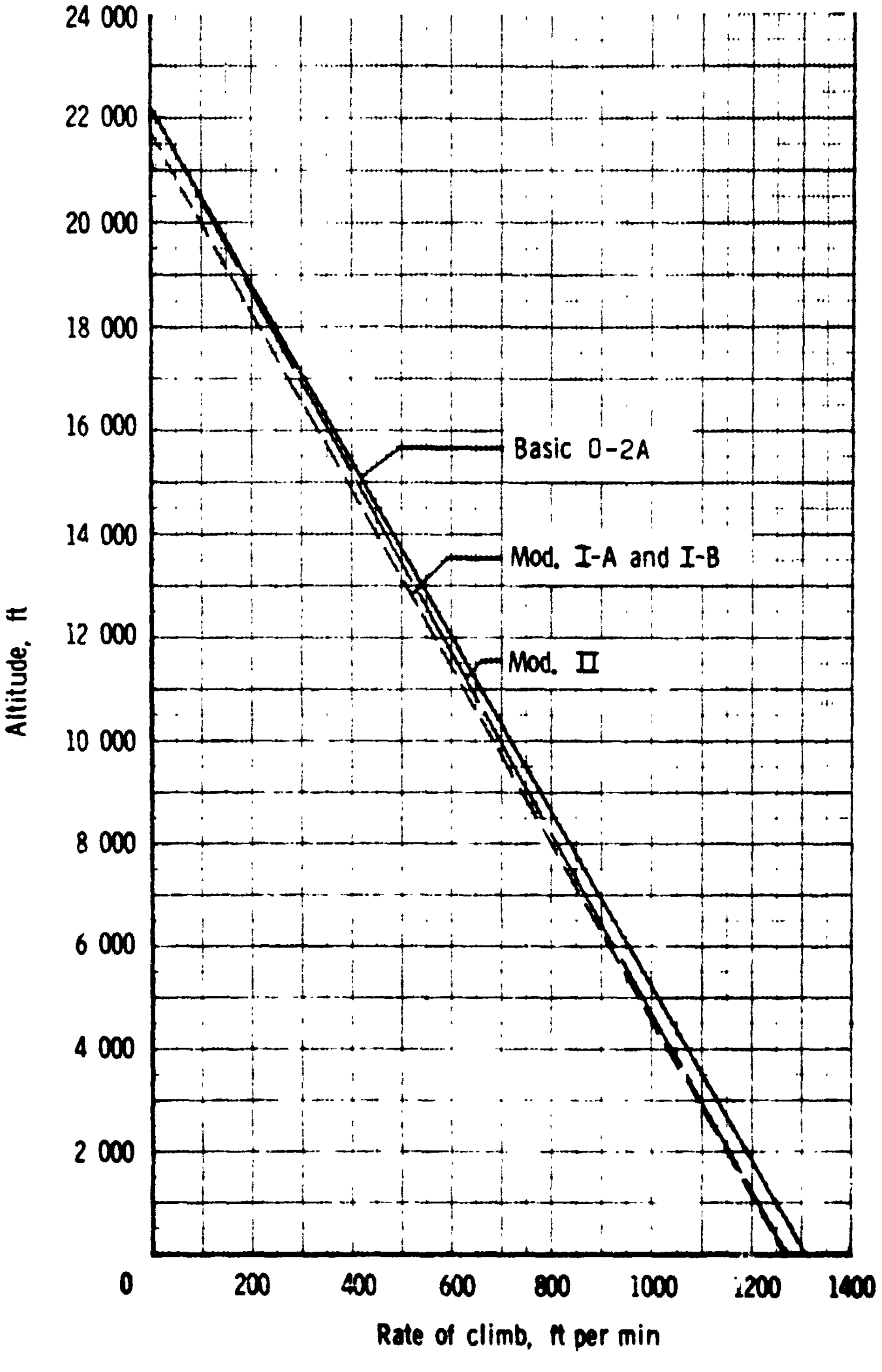

Figure D-2. - Variation of maximum two-engine rate of climb with altitude for basic O-2A and Modifications I-B and II.

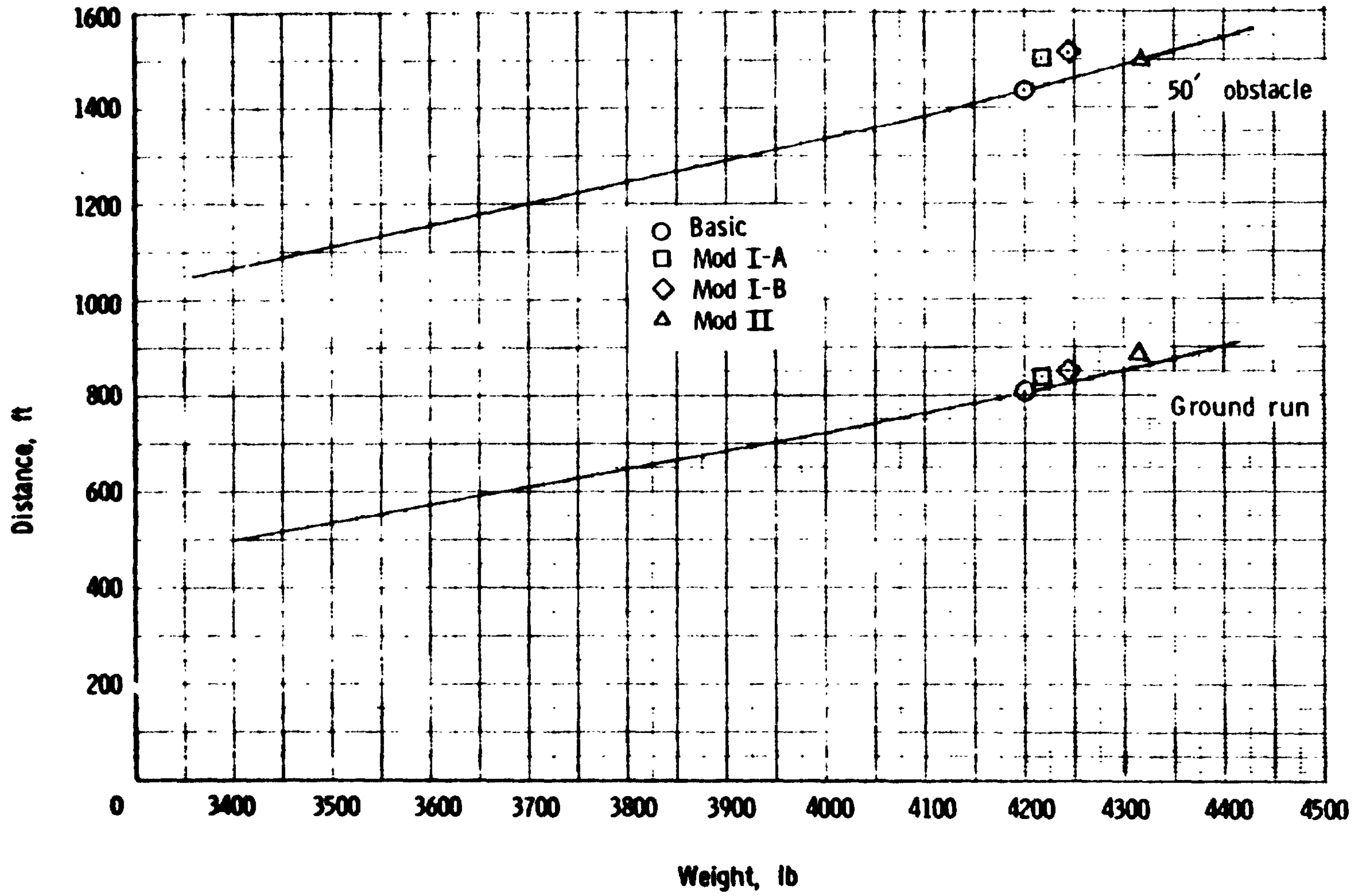

Figure D-3.-Comparison of take-off performance of basic O-2A airplane and modified configurations.

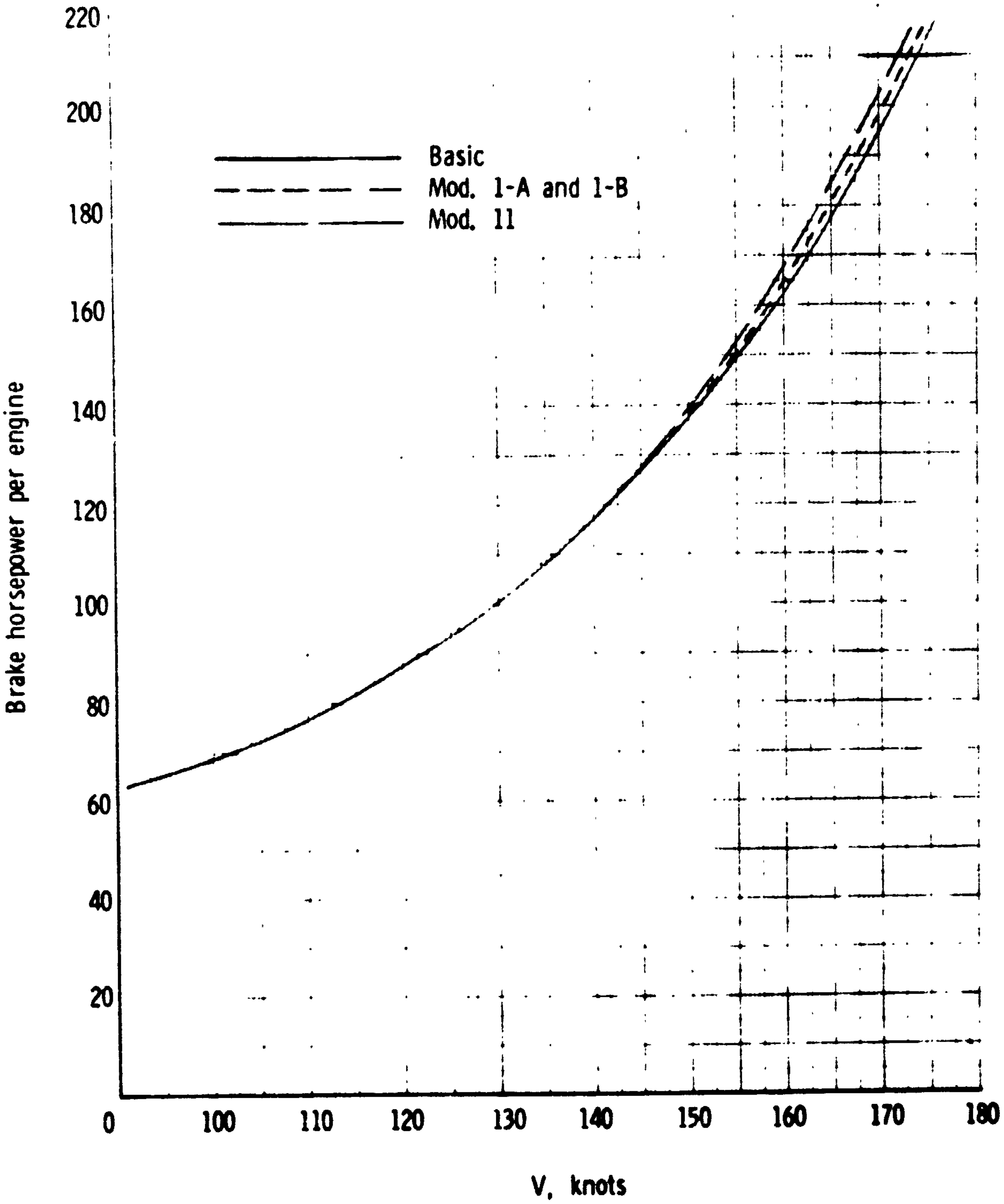

Figure D-4.-Power required for level flight for basic O-2A airplane and modified configurations. (Based on flight test results of ref. D-1)

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