SEG-TR-65-4

ENVIRONMENTAL CONDITIONS TO BE CONSIDERED IN THE STRUCTURAL DESIGN OF AIRCRAFT REQUIRED TO OPERATE AT LOW LEVELS

WILLIAM H. AUSTIN, JR.

TECHNICAL REPORT SEG-TR-65-4

JANUARY 1965

SYSTEMS ENGINEERING GROUP
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OHIO

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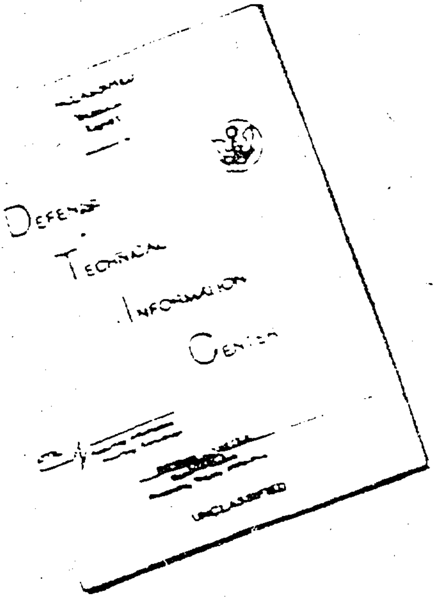

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FOREWORD

This report was prepared by personnel of the Requirements Branch, Structures Division, Directorate of Airframe Subsystems Engineering under System 139A, the Advanced Manned Strategic Aircraft. A preliminary version of this report was presented to the Advisory Group for Aeronautical Research and Development (AGARD) Interpanel Specialist's meeting on Low-Altitude High-Speed Flight in Paris on 23 October 1964. Work conducted from June 1964 to December 1964 is reported.

This report was submitted by the author 22 January 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

One of the greatest problems facing structural engineers at the present time is a proper definition of the turbulence-environment at low level. The power spectral density approach is considered to be the most reasonable to use in defining this environment. Presently published data, while in power spectral form, do not appear to be adequate. Because a critical need for low-level design criteria exists, low-level power spectral exceedance curves have been derived from a B-66 low-level gust study, an F-106 low-level high-intensity gust program, and B-52 fleet service experience. These data indicate that low-level lateral turbulence is from 15 to 30 percent more severe than vertical turbulence. Much additional effort is required in the area of low-level turbulence before structural engineers can have complete confidence in their low-level turbulence design criteria.

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SYMBOLS

A	gust response factor, σ_y/σ_u
b	scale parameter in probability density distribution of root-mean-square gust velocities
$F(U_T)$	probability of equalling or exceeding true gust velocity, U_T
$f(\sigma_u)$	probability density distribution of root-mean-square gust velocities
L	spectral scale parameter (scale of turbulence), feet
$M(y)$	average number of cycles of specified response per second of flight exceeding y
N_o	average number of cycles of specified response per second
P	proportion of total time in turbulence
$T(\Omega)$	amplitude of response to unit sinusoidal gust of frequency Ω
U_T	true gust velocity, feet per second
V	true airspeed, feet per second
y	any response parameter
σ_u	root-mean-square gust velocity
σ_y	root-mean-square of response
$\Phi(\Omega)$	power spectral density function
Ω	reduced frequency, $\frac{\omega}{V}$ radians per foot
ω	frequency, radians per second

SUBSCRIPTS

1	normal (non-storm) turbulence
2	severe (storm) turbulence
u	gust
y	response

SECTION I

INTRODUCTION

When an aircraft must be designed to operate for extended periods close to the terrain over which it is flying, a number of problems must be solved by the structural engineer. Most of these problems have known solutions when the environment can be defined. However, when the environment has not been properly defined, the problems of the structural engineer increase tremendously.

Today, one of the greatest problems being faced by structural engineers is the lack of a proper definition of the low-level turbulence-environment. The definition needed is for altitudes between zero and one thousand feet above the terrain. This report, therefore, will be limited to a discussion of low-level turbulence.

Although United States Air Force aircraft have been operating at low altitudes for the last several years, most of their time has been spent in the highest obstacle clearance mode, where the aircraft maintains an altitude of at least 1000 feet above the highest obstacle within a distance of 5 nautical miles. Thus, the average altitude above the terrain is well over 1000 feet, as can be seen in Figure 1(a) (see Appendix). With the advent of advanced radar equipment, the B-52 bomber began to operate in the contour, or terrain avoidance mode, where the aircraft maintains an altitude of 500 feet, or lower, above the terrain in its immediate vicinity. This mode of operation is shown in Figure 1(b).

As more sophisticated radar and flight control systems become available, more and more aircraft will be exposed to the low-level environment for extended periods of time. This would not be particularly disturbing were it not for the fact that the B-52 has experienced structural difficulties while operating in the low-level contour mode.

The B-52 has experienced various degrees of structural damage as a result of excessive loads on the empennage. These loads were caused by severe turbulence generated by high winds over rough terrain. The B-52 is the only large USAF aircraft that has operated in the low-level contour mode, and while the the strength of the empennage was in excess of the original design requirement, it was not sufficient to protect the airplane in the low-level environment.

While data did exist on B-52 low-level contour operations and could be applied properly, to the improved B-52, extension of these data to other aircraft could be subject to error. It is, therefore, imperative that a realistic environmental definition be made for the structural design of any low-level strike aircraft. This definition is required from both fatigue and overload standpoints.

This report outlines a recommended analytical procedure that should be used and the data that are presently available and presents a low-level environmental description that could be used in the design of an aircraft that must operate in the low-level environment.

SECTION II

THE ANALYTICAL PROCEDURE

During the last few years, the power spectral density approach has become widely recognized among aircraft structural engineers as the most realistic method for analyzing aircraft loads in turbulence. This approach has been, and is being, used in the fatigue analysis of several USAF aircraft, and recently it was used to establish the ultimate load requirement in the design of the improved B-52.

The power spectral analysis is based on the premise that atmospheric turbulence can be defined as a continuous random disturbance described by power spectral density functions of the gust velocity time history and the probability distributions of root-mean-square gust velocities (Reference 1).

The selection of a gust power spectral shape to use in the derivation of the turbulence model is important, since the response characteristics of the airplane depend on this function. There is considerable controversy as to just what the power spectral shape should be. Many analysts advocate a power spectrum that decays with increasing frequency by a minus two power law, and others hold that a minus five-thirds power law gives a better fit to the data. The value of the scale parameter, L, is also a matter of controversy. The reader should note that, as L becomes larger, more power is shifted into the lower frequencies of the power spectrum, as can be seen from Equation (1). Scale parameters as low as 200 feet (Reference 2) and as high as 5000 feet (Reference 3) have been mentioned for low-altitude clear-air turbulence. At the present time, no obvious resolution of these two controversies is in sight; however, it seems reasonable that, if a consistent procedure is established with respect to the use of the power spectral density function, any of the spectra derived from measured data should cause no significant errors.

Most of the effort in the analyses of aircraft in the United States has involved the use of the "NACA" (Reference 1) power spectral shape. For low level, the current military specification (Reference 4) requires that a scale parameter, L, of 500 feet should be used with the NACA power spectrum. The parameter L and the NACA power spectrum have been used in this report for low-level turbulence, and the relationship is expressed as

$$\Phi_u(\Omega) = \sigma_u^2 \frac{L}{\pi} \frac{(1+3\Omega^2 L^2)}{(1+\Omega^2 L^2)^2} \qquad (1)$$

The second relation that must be specified to describe the turbulence is the probability density distribution of root-mean-square gust velocities. Reference 5 suggests that this distribution is of the form expressed as

$$f(\sigma_u) = \frac{P_1}{b_1}\sqrt{\frac{2}{\pi}}\, e^{-\sigma_u^2/2b_1^2} + \frac{P_2}{b_2}\sqrt{\frac{2}{\pi}}\, e^{-\sigma_u^2/2b_2^2} \qquad (2)$$

where the subscripts, 1 and 2 represent non-storm and storm turbulence, respectively, the parameter P specifies the percenage of time spent in each type of turbulence, and the parameter b is a measure of the intensity of each type of turbulence. The relationship for $f(\sigma_u)$ specified by Equation (2) indicates that the probability of occurrence of σ_u is the sum of two folded Gaussian distributions. The folding, which merely multiplies the standard expression of the Gaussian probability function by two, is required since root-mean-squares cannot be negative. It is of interest to note that the quantity, b, is the standard deviation of the distribution of root-mean-square gust velocities for each type of turbulence.

If we use the equations derived by Rice (Reference 6) and the procedure of Reference 1, the relationship between any response parameter, y of the airplane, and the turbulence environment can be expressed

$$M(y) = N_0 \int_0^{\infty} f(\sigma_u) e^{-y^2/2A^2\sigma_u^2} \, d\sigma_u \tag{3}$$

in which M(y) is the average number of cycles per second of flight exceeding y. The quantity denoted by N_0 is the characteristic frequency of the specified response, y, and is expressed

$$N_0 = \frac{V}{2\pi} \left[\frac{\int_0^{\infty} \Omega^2 \Phi_y(\Omega) \, d\Omega}{\int_0^{\infty} \Phi_y(\Omega) \, d\Omega} \right]^{\frac{1}{2}} \tag{4}$$

The quantity, A, is essentially the integrated transfer function between turbulence input and response and is expressed

$$A = \frac{\sigma_y}{\sigma_u} = \frac{1}{\sigma_u} \left[\int_0^{\infty} \Phi_u(\Omega) T^2(\Omega) \, d\Omega \right]^{\frac{1}{2}} \tag{5}$$

By substituting Equation (2) into Equation (3) and carrying out the integration, the probability of equaling or exceeding the response parameter, y, can be expressed

$$\frac{M(y)}{N_0} = P_1 e^{-y/Ab_1} + P_2 e^{-y/Ab_2} \tag{6}$$

The reader should note that $M(y)/N_0$ is the probability of reaching or exceeding any response parameter, y, and y/A is a true gust velocity whose wavelength is the most probable value as determined by the power spectrum used to compute A. Thus, by assuming that the spectral shape and b are, on an average, the same as for the measured atmosphere, gust probability data based on peak counts of actual gust time histories may be directly used as response probability data. For the purposes of this paper y/A and U_T are used interchangeably, i.e.,

$$\frac{M(y)}{N_0} = F(U_T) = P_1 e^{-y/Ab_1} + P_2 e^{-y\,Ab_2} = P_1 e^{-U_T/b_1} + P_2 e^{-U_T/b_2} \tag{7}$$

With the procedure presented thus far in this section, the data that have been collected on low-level turbulence can be examined and converted into a form useful for design by specifying the parameters P and b.

SECTION III

DATA PRESENTLY AVAILABLE

There are several sources of data available for low-altitude turbulence. Only those d that have been converted into the power spectral form and actual, measured, true gust velociti have been considered. Table I (see Appendix) shows some of these sources of data that ha been generated in the United States. As can be seen, these sources do not agree in the description of the environment at low altitude. It would be beneficial to examine each of the data sources in order to assess their applicability to the problem.

The low-altitude data from NACA Technical Note 4332 (Reference 5) is based on domest transport operations between zero and two thousand feet. It is believed that this type of oper tion is not representative of the low-level military mission. In addition, the single degree-o freedom dynamic analysis used to establish the transfer function, A, and thus the scale param eter in the probability density distribution, b, appears to underestimate the actual value of For example, the value of A computed from the single degree-of-freedom dynamic analys has been shown to be from one-half to two-thirds of the value of A computed from a B- 16 degree-of-freedom dynamic analysis and a B-58 dynamic response flight test for the flig conditions examined. There is some evidence that this underestimation of A could be ev greater for other flight conditions. Even though the configurations of transports are conside ably different from those of the B-52 and B-58, a significant error can occur when the A fro the single degree-of-freedom dynamic analysis is used to convert operational data to spect form. An underestimation of A will make the operational data look more severe than wou be the case if a more realistic value of A were used. One further limitation to the TN 4332 da is that no lateral gusts were considered.

The current USAF specification, MIL-A-8866, (Reference 4) for a low-level turbulence inp is based on TN 4332 (Reference 5) with the following exceptions:

a. The scale parameter (scale of turbulence) in the power spectrum equation was decreas to 500 feet for altitudes between zero and one thousand feet.

b. Turbulence of some magnitude exists 100 percent of the time at these altitud

c. There is no "storm" or severe turbulence at these altitudes.

All except the latter assumption appear reasonable. Based on the B-52 and F-106 experienc turbulence associated with high winds over rough terrain can be every bit as severe as thunde storm turbulence. Since MIL-A-8866 was based on TN 4332 data, the "non-storm" or "norm turbulence model appears to overestimate the actual situation. Again, lateral gusts were n considered.

The low-level turbulence data of ASD TDR 61-235* is based primarily on B-58 true gust velo ities taken from 200 to 1000 feet. This data source (TR 61-235) is probably the best availab but it too seems to underestimate severe low-level turbulence, and lateral gusts were not co sidered.

A recent United States Air Force publication (Reference 10) is based on B-52 low-lev contour statistical loads (Vgh) data and severe turbulence encounters on B-52 aircraft. T data include maneuvers for terrain avoidance and combine Vgh data (vertical) with the B- severe turbulence encounters (lateral). These data were considered acceptable for use for t improved B-52, but extension to other aircraft is open to question.

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*Reference 8

The B-66 low-level gust study data (Reference 7), while limited in sample size (32.5 Hours), is about the only source of low-level turbulence data taken with a gust boom that covers a wide variety of meteorological and topographical conditions. These data were taken at altitudes between 200 and 1000 feet and covered several locations in the United States. The severe component of low-level turbulence due to high winds over rough terrain was not noted, because of the limited data runs that were made on this program. The B-66 program is believed to be quite valuable, however, in identifying the non-storm or normal low-level turbulence. Lateral and longitudinal turbulence data are available, also, which increases the value of the program.

The F-106 low-level high-intensity gust program* was conducted in the Sangre de Cristo mountain range of Colorado and New Mexico during March and April of 1964. The purpose of the program was to identify the severe component of low-level turbulence that was not noted in the B-66 program. The aircraft was equipped with a gust boom to measure true gust velocities. The data from this program are probably the most significant data on low-level turbulence that have been collected in the last several years.

The subsequent section of this report will review the results of the B-66 and F-106 programs in conjunction with the B-52 operational experience to establish a low-level turbulence model that can be used in design.

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*Reference 9

SECTION IV

RECOMMENDED TURBULENCE MODEL

Due to the limitations of all of the available data on low-level turbulence outlined in the preceding sections, it is obvious that more data are required for a better assessment of low-level turbulence design criteria and that there is an immediate need for specifying these criteria. For these reasons, an assessment must be made of the limited data available at the present time, and a low-level turbulence model must be established based on these data. To this end, we have used the B-66 and F-106 gust data and the B-52 service experience data.

Primary peak count data from the B-66 program are shown in Figure 2. In order to increase the sample size, we added longitudinal and lateral peak counts to establish the lateral data points shown in Figure 2. The lateral gusts are more severe than the vertical gusts by a factor of about 15 percent. The straight lines of slope = 2.7 for vertical gusts and 3.1 for lateral gusts give a good fit to the measured data, except at large values of gust velocity where the sample size is quite small.

Primary peak count data for gusts over 40 ft/sec from the F-106 program are shown in Figure 3. Again, the lateral gusts are more severe than the vertical gusts, but the factor is a bit higher than in the "normal" turbulence case, i.e., the lateral turbulence is 30 percent more severe than the vertical turbulence. The straight lines give a reasonable fit to the data with slope = 10.65 for the vertical gusts and slope = 14.06 for the lateral case.

Table II represents the best estimate of the spectral gust velocities encountered by the B-52 aircraft in low-level contour operation. The total low-level contour exposure time was converted into $M(y)/N_0$ form to allow these gust encounters to be plotted on a spectral exceedance curve (Reference 11). Since the B-52 gust encounters were lateral, these encounters have been used in establishing the lateral turbulence model.

The procedure used in constructing the low-level turbulence model is similar to that used in Reference 5, i.e., low-level turbulence is broken down into two types, — "normal" turbulence that is due to convective action and mechanical turbulence under moderate wind conditions, and "severe" turbulence that is due to high winds over rough terrain. This is analogous to the non-storm and storm turbulence used in Reference 5.

The B-66 data were used to represent the normal type of low-level turbulence described by b_1, and the F-106 data were used to represent the severe type described by b_2. The proportion of time spent in severe turbulence during the F-106 program cannot be used, because the purpose of that operation was to find the severe turbulence as frequently as possible. The B-66 program indicated the presence of <u>some</u> turbulence 100 percent of the time, thus $P_1 + P_2 = 1.0$. To determine the percent of time spent in severe low-level turbulence (P_2), we can turn to the B-52 severe gust encounters. This portion of the curve is defined by using the severe lateral turbulence slope, b_2, from the F-106 program and fitting a new severe lateral turbulence exceedance curve through the B-52 lateral gust encounters. Since the percent of time in turbulence (P_2) must be the same vertically and laterally, the F-106 vertical gust exceedance curve must pass through the same intercept, P_2. The construction of this curve is shown in Figure 4. When the normal and severe turbulence environments are considered together with the above derived values of P_1, P_2, b_1, and b_2 shown in Table III, the final low-level exceedance curves result as shown in Figure 5. These are the recommended design curves for a low-level aircraft.

SECTION V

CONCLUSIONS

At the present time, low-level turbulence is not well defined, particularly in regard to the lateral component. A recommended low-level exceedance curve has been derived, based on B-66 and F-106 data in conjunction with B-52 gust encounters. The curve indicates that lateral turbulence can be from 15 to 30 percent more severe than vertical turbulence at low level.

Additional work is required, particularly in the flight test area, to re-inforce or modify the recommended low-level turbulence model. Further investigations of turbulence data should be made as a function of meteorological and topographical conditions.

As aircraft are entering this new environment, much more intensive effort is required to give the designer an accurate, usable set of design criteria that will insure the desired level of structural reliability and insure that the aircraft has the maximum capability to fulfill its mission.

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APPENDIX

TABLES
AND
ILLUSTRATIONS

TABLE I

SOURCES FOR LOW-LEVEL TURBULENCE DATA

DATA SOURCE AND TYPE OF DATA	P_1	b_1	P_2	b_2	L (feet)	SPECTRUM
NACA TN 4332 0-2000 ft	0.34	4.6	0.00025	9.4	1000	NACA (Reference 1)
MIL-A-8866 0-1000 ft	1.0	3.9	0	-	500	" "
ASD-TR-61-235 0-1000 ft	1.0	2.72	0.01	5.44	500	" "
SEG-TDR 64-24 low level contour	0.9974	3.62	0.0026	7.62	1000	" "
B-66, vertical peak count	1.0	2.7	-	-	*	*
B-66, lateral peak count	1.0	3.1	-	-	*	*
F-106, vertical peak count	-	-	0.068	10.65	*	*
F-106, lateral peak count	-	-	0.068	14.06	*	*

*Assumed NACA Power Spectrum, L = 500 ft

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TABLE II

B-52 HIGH LATERAL GUST LOAD OCCURRENCES*

Gross Weight (lbs)	Speed (Knots)	$M(y)/N_O$	y/A (feet per second)
330,000	325	2.5×10^{-7}	53
275,000	390	1.8×10^{-7}	55
361,000	350	1.2×10^{-7}	63
348,000	280	6.0×10^{-8}	71

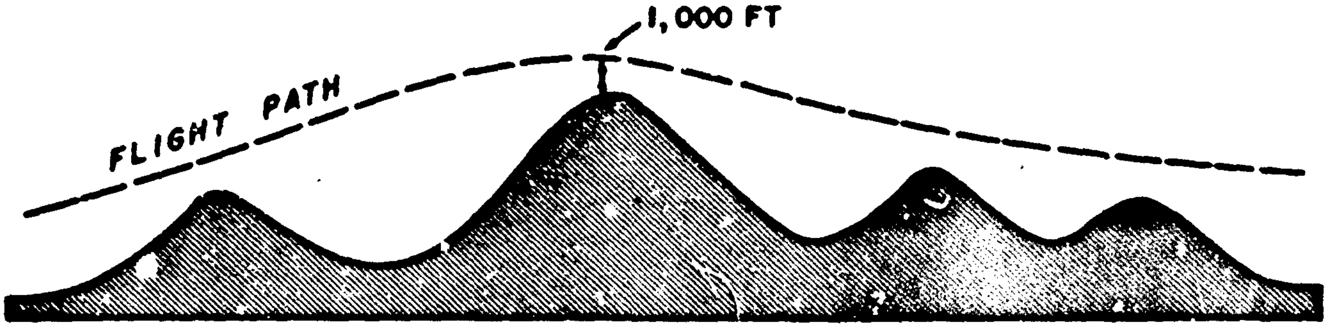
*Accidents and Incidents due to lateral loads. All occurred in the presence of high winds over rough terrain.

TABLE III

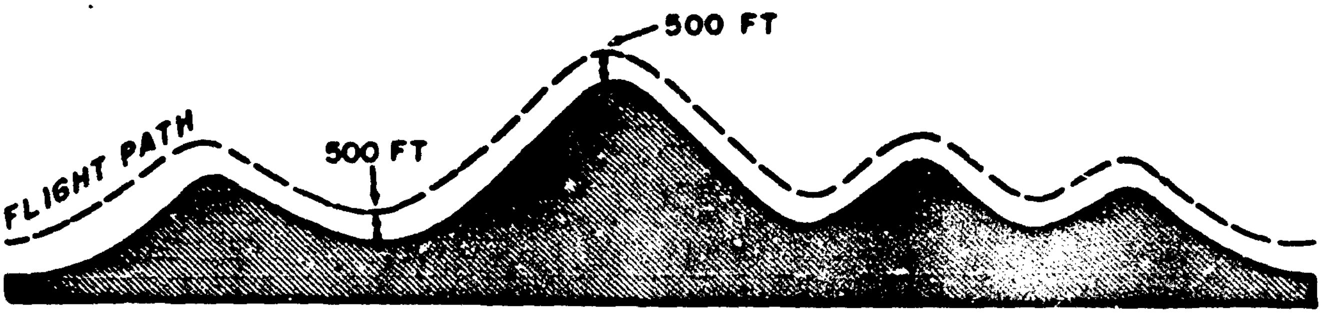
LOW-LEVEL TURBULENCE PARAMETERS

	P_1	b_1	P_2	b_2	L* (feet)
Vertical Gust	0.99999	2.7	0.00001	10.65	500
Lateral Gust	0.99999	3.1	0.00001	14.06	500

*"NACA" Power Spectrum



(a) HIGHEST OBSTACLE CLEARANCE



(b) CONTOUR OR TERRAIN AVOIDANCE

Figure 1. Modes of Low-Level Operation

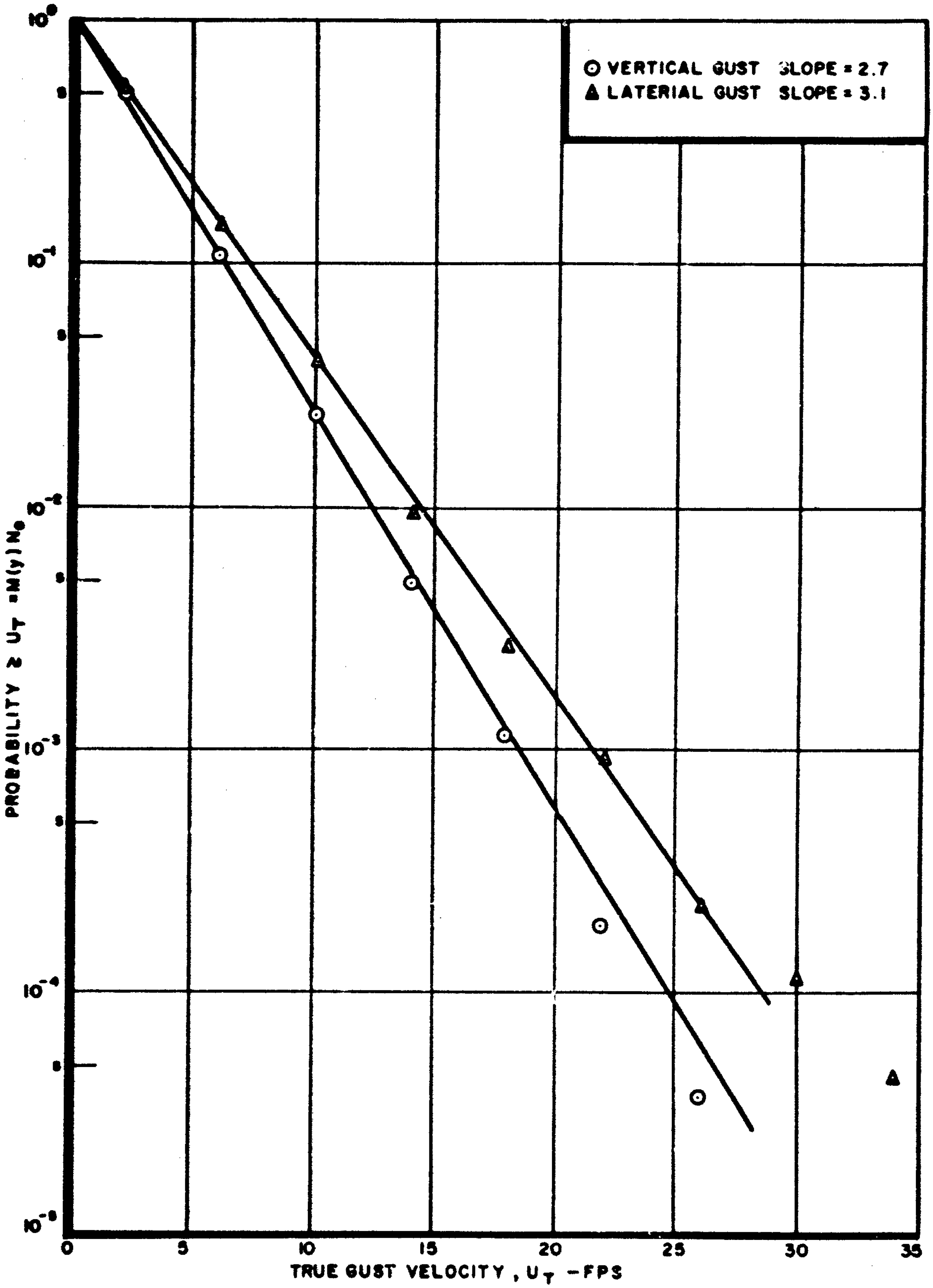


Figure 2. B-66 Low-Level Gust Study 42 Data Runs

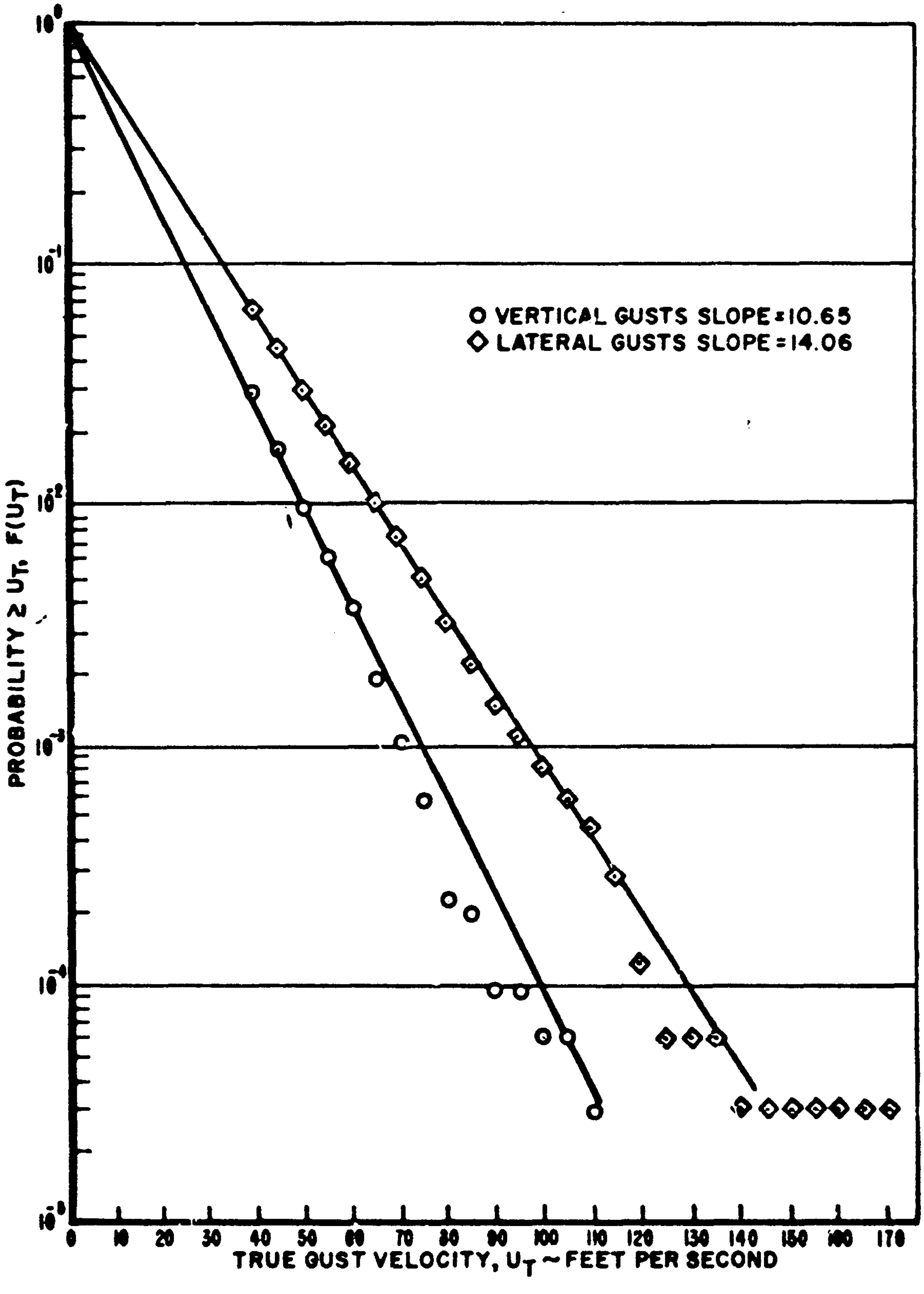


Figure 3. Gusts Over 40 Feet per Second With F-106; Based on High-Intensity Gust Investigation During 32.15 Hours

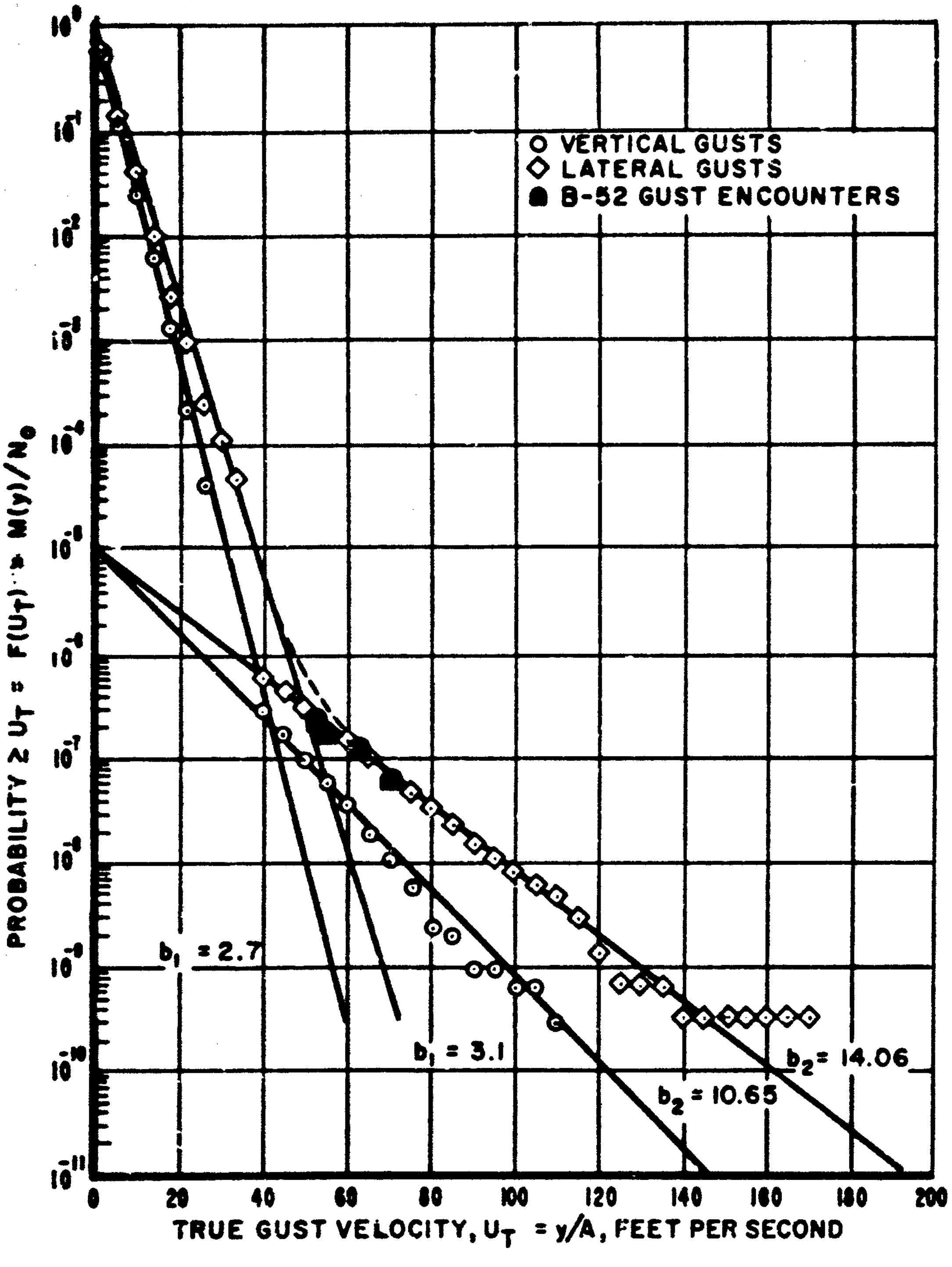


Figure 4. Vertical and Lateral Exceedance Curves for Low-Level Flight

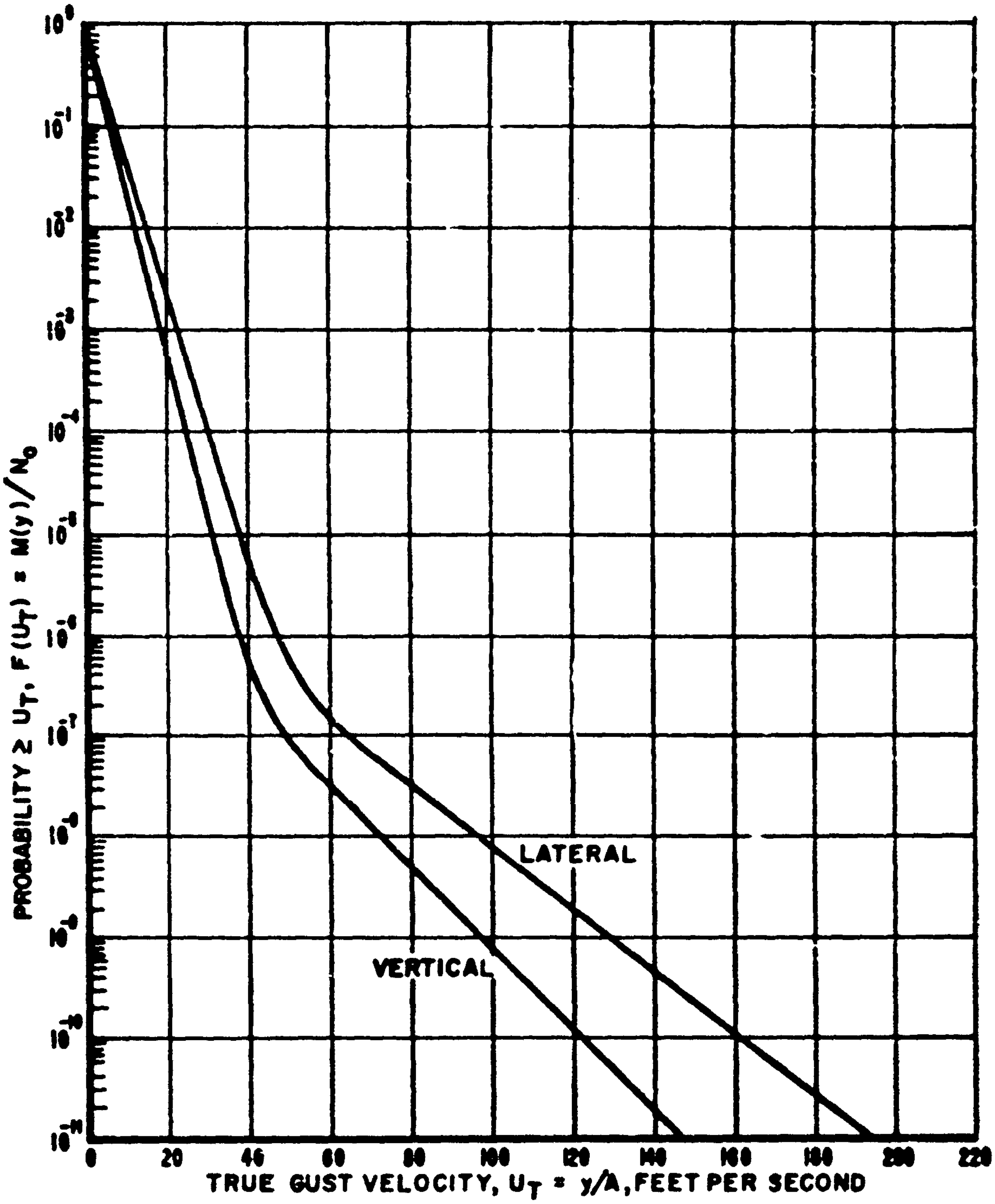


Figure 5. Final Exceedance Curves

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13. ABSTRACT

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