NACA

RESEARCH MEMORANDUM

PRELIMINARY MEASUREMENTS OF ATMOSPHERIC TURBULENCE AT HIGH ALTITUDE AS DETERMINED FROM ACCELERATION MEASUREMENTS ON LOCKHEED U-2 AIRPLANE

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An analysis of a sample of turbulence data obtained from VGH records taken on Lockheed U-2 airplanes during research flight up to 55,000 feet over England and Western Europe has indicated substantial reductions in the number and intensity of gusts with increasing altitude. These results on the variation of atmospheric turbulence over England and Western Europe were found to be in overall agreement with previous turbulence data obtained from airplane- and balloon-borne instruments over the United States.

INTRODUCTION

The collection of detailed information at high altitudes on atmospheric turbulence and other meteorological conditions has, in the past, been largely dependent upon the availability of operational airplanes. As a consequence, the collection of such data has, in general, lagged behind the development of airplane altitude capabilities. To the present time, the available airplane measurements of atmospheric turbulence have been almost entirely limited to flight altitudes below approximately 45,000 feet. For higher altitudes, the only information available is some measurements obtained by means of balloon-borne instruments. (See ref. 1.) These measurements have provided limited information on turbulence variations with altitudes to approximately 60,000 feet. In addition to the altitude limitations of the foregoing investigations, the measurements were also limited in regard to geographic areas and were largely confined to continental United States. This lack of information on high-altitude turbulence conditions around the world has been a handicap in aircraft design studies and in operational analysis, both in regard to aircraft load problems and in regard to stability and control problems.

During the early part of 1956, the National Advisory Committee for Aeronautics, in cooperation with the Air Weather Service of the United States Air Force, initiated a research program aimed at providing detailed meteorological information both at higher altitudes than those covered by present-day operating airplanes and for various geographic areas of the world. The availability of Lockheed U-2 airplanes at the initiation of this program permitted the coverage of flight altitudes to approximately 55,000 feet. The NACA activity in this program has so far been primarily aimed at obtaining information on the amount and intensity of atmospheric turbulence at these higher altitudes. The Air Weather Service has simultaneously provided instrumentation to collect data on humidity, pressure variations, and winds.

The initial research flights of the U-2 airplane were undertaken to cover two geographic areas, the United States and Western Europe. Because of operational difficulties, a statistically significant sample was initially obtained only from the operations over England and Western Europe. For these operations, measurements covering a total of 22,000 flight miles were made and evaluated. Although this sample is small, the initial results appear to be of sufficient interest to warrant publication. Accordingly, these results are presented herein and are compared with the earlier estimates on the variation of atmospheric turbulence with altitude given in reference 1.

INSTRUMENTATION AND SCOPE OF DATA

The flight measurements were obtained during flights of several Lockheed U-2 airplanes for the high-altitude meteorological research program of the NACA in cooperation with the Air Weather Service. The Lockheed U-2 is a subsonic, straight wing, single-engine airplane originally designed for use as a high-altitude test medium for engine and aircraft-component testing. The high-altitude performance and economy of operation of the U-2 airplane were the prime factors affecting its selection for use in the present research program.

The measurements pertinent to this report consisted in time-history records of airspeed, acceleration, and pressure altitude taken with NACA VGH recorders (ref. 2). The time histories were recorded on photographic paper moving at 8 inches per minute. Records were obtained on 17 flights during operations from bases at Lakenheath, England, and Wiesbaden, Germany, between May and September 1956. The flight plans used in the operations consisted in climbing to an altitude of approximately 45,000 feet, cruising initially at approximately 45,000 feet with the altitude gradually increasing to approximately 55,000 as the fuel load decreased, and then descending to the home base. For these initial operations, the flight schedules were based primarily on airplane availability, and no attempt was made to schedule flights to sample turbulence associated with specific meteorological conditions. The turbulence encountered during the present operations was, for the most part, in clear air, and no turbulence in heavy cumulus clouds or thunderstorms is represented in these data.

The scope of the data in terms of miles flown within different altitude intervals is summarized in the following table:

Pressure altitude, ft	Flight miles
20,000 to 30,000	1,548
30,000 to 40,000	3,492
40,000 to 50,000	6,021
50,000 to 55,000	10,461
Total	21,522

Because of the operational procedures used, only a small amount of information was obtained at the lower altitudes; consequently, only the data above an altitude of 20,000 feet are included in this paper.

EVALUATION OF DATA

The VGH records were evaluated to obtain the vertical gust velocities, the percent of rough air at various altitudes, and the horizontal extent of the turbulent areas encountered. The evaluation procedures are similar to the procedures used in reference 1 and are discussed briefly in the following paragraphs.

The vertical gust velocities were derived from simultaneous readings of acceleration, airspeed, and altitude through the use of the gust equation which is given in reference 3 as

$$U_{de} = \frac{2a_nW}{m\rho_oK_gV_eS}$$

where

U_{de} derived gust velocity, fps

a_n peak normal acceleration, g units

W airplane weight, lb

S	wing area, sq ft
K_g	gust factor
V_e	equivalent airspeed, fps
m	wing lift-curve slope, per radian
ρ_o	air density at sea level, slugs/cu ft

In evaluating the records, the accelerations were read to a threshold sufficiently low to yield complete frequency counts of all gust velocities greater than 2 feet per second. Values of airspeed and pressure altitude were obtained from the records for each acceleration evaluated. The in-flight weight loss was accounted for in determining the values of wing loading W/S for use in the equation. Appropriate values of the gust factor K_g were computed for each part of the record where rough air was encountered. The values of the lift-curve slope m used in deriving the gust velocities were based on data from the airplane manufacturer.

The gust-velocity values presented herein may be open to some question because of effects of airplane flexibility and stability on the accelerations from which the gust velocities were computed. The magnitude of these effects is not known at present, and additional work is required before their influence on the gust-velocity values can be assessed.

In addition to determining the gust velocities, the VGH records were evaluated to obtain the horizontal extent of turbulent areas and the percent of rough air at the different altitudes. For the purpose of determining the horizontal extent of the turbulent areas, the airplane was considered to be in rough air whenever the accelerometer trace was continuously disturbed and contained accelerations corresponding to gust velocities greater than 2 feet per second; this threshold corresponds to that used in previous gust studies such as reference 1. The length of each turbulent area was found simply by multiplying the true airspeed by the time spent in the rough air. The summation of the lengths of the individual areas of rough air was divided by the total flight distance for given altitude intervals in order to obtain the percent of rough air for that interval.

RESULTS AND DISCUSSION

Overall Gust Distributions

The gust velocities derived from the acceleration and airspeed data are presented as frequency distributions in table I for four altitude intervals between 20,000 and 55,000 feet and are shown in figure 1 as cumulative frequency distributions per mile of total flight for each altitude interval. The cumulative distributions give the average number of gusts per mile of total flight which exceeded given values of gust velocity. Inspection of the results of this investigation in figure 1 shows that, over the altitude range covered, variations on the order of 10 to 1 exist in the frequency with which given gust velocities were encountered. In general, the distributions depict a consistent decrease in gust frequency with increasing altitude. The data for the altitudes of 30,000 to 40,000 feet deviate from this pattern to some extent, however, and indicate a lower frequency for the higher gust velocities than would be expected from the general pattern. Because of the limited sample size, this deviation from the general pattern may not be real, but due to a sampling error.

For comparison with the present data, the cumulative frequency distributions of gust velocity were determined from the results of reference 1 and these distributions are also shown in figure 1. These distributions are based on the basic distribution of non-thunderstorm turbulence and the variation of gust intensity with altitude given in figures 5 and 1, respectively, of reference 1. Comparison of the two sets of distributions in figure 1 shows that the slopes of the two sets of distributions are about the same but that, in general, the data of this investigation indicate somewhat lower gust frequencies than those obtained from reference 1. One possible reason for the lighter level of turbulence for the present data is the limited seasonal coverage, the present data covering only the summer months; whereas the results from reference 1 represent average turbulence conditions for operations throughout the year. More severe clear-air turbulence may be anticipated during seasons of the year other than summer and particularly during the winter months when the winds at high altitude are likely to be the strongest.

Intensity of Turbulence

In order to compare in further detail the gust measurements of this investigation with the results from reference 1, it is helpful to consider separately the variations in the intensity and in the amount of rough air with altitude. As an indication of the severity of the rough air alone, the cumulative frequency distributions of gust velocity per mile of flight in rough air are plotted in figure 2 for the different altitude intervals. For comparison, the corresponding gust distributions for non-thunderstorm turbulence were calculated from reference 1 and are also shown in the figure. Inspection of the present data in figure 2 shows that, in general, the gust frequency per mile of rough air also decreased with increasing altitude. However, again, the data for the altitudes of 30,000 to 40,000 feet do not follow this pattern and, in this case, indicate a lower frequency than is shown for the other altitudes. Examination of the time-history records revealed that this low gust frequency resulted mainly from two long (30 to 50 miles) areas of turbulence of low intensity. In view of the peculiarity of the data for the altitudes of 30,000 to 40,000 feet, the present indication of a low gust frequency for this altitude interval is open to question.

Comparison of the results of this investigation on the gust intensity, based on miles of flight in rough air, with the corresponding results from reference 1 shows not only that the two sets of distributions have approximately the same slopes but also that the gust intensity is considerably lower for the present data. (See fig. 2.) For a given frequency of occurrence, the gust velocities shown by the present data are, in general, only about 75 percent as large as the gust velocities given by the results from reference 1 for the same altitude interval. For the altitude of 30,000 to 40,000 feet, the percent is even lower, it being about 50 percent. Thus, in general, the intensity of the rough air for the data of this investigation is substantially lower than that given by reference 1.

In addition to the direct comparison of the gust intensities given in the preceding paragraph, it is of interest to compare the relative variations of the gust intensities with altitude for the two sets of gust distributions. In figure 3, the variations of the gust intensity with altitude for the present results and the results based on reference 1 are given in terms of the ratio of the maximum gust velocity expected in a given flight distance in rough air at the lower altitude interval (20,000 to 30,000 feet) to the maximum gust velocity for the same flight distance in rough air at higher altitudes. The data in figure 3 were obtained by determining from the gust distributions of figure 2 the maximum gust velocity expected in a given flight distance in rough air at different altitudes for each sample of data. For this purpose, a gust frequency of 0.05 per mile in figure 2 was selected as being through the more reliable range of the present distributions. The values of maximum gust velocity obtained from figure 2 for each set of distributions were then normalized to the gust velocity for the lower altitude interval in order to obtain the gust-velocity ratios plotted in figure 3.

Figure 3 shows that the relative variation of the gust intensity with altitude for the present data is in good agreement with the results from reference 1 except for the data for the altitudes of 30,000 to 40,000 feet. As previously noted, however, the reliability of the data at this altitude is open to some question. The comparison presented in figure 3 implies that the variation in gust intensity with altitude over Western Europe, at least for the summer season, is similar to that indicated in reference 1 for this country.

Amount of Turbulence

The percent of the flight distance within each altitude interval which was in rough air is presented in figure 4. Similar results, based on airplane and telemeter data from reference 1, are also given in the figure for comparison. Figure 4 shows that the results of this investigation are in good agreement with the results from reference 1 for altitudes above 35,000 feet. Below this altitude, the present data indicate slightly higher percentages of rough air than do the data from reference 1. The high percentage of rough air for the altitudes of 30,000 to 35,000 feet resulted from the two areas of 30 to 50 miles of turbulence of low intensity that were mentioned previously. Thus, in general, the amount of rough air at the various altitudes is fairly close to that given in reference 1, with the principal difference between the present results and those from reference 1 being associated with the less severe intensity of the turbulence noted previously.

Size of Turbulent Areas

The distribution of the horizontal extents or lengths of the turbulent areas, determined from the acceleration records, is given in figure 5 as the percent of the total number of areas within class intervals of 10 miles. The distribution is based on 115 turbulent areas encountered during the present operations between 20,000 and 55,000 feet. The distribution of turbulent areas given in reference 1 is also shown in the figure for comparison. For the present data, approximately 75 percent of the turbulent areas were less than 10 miles in length and less than 2 percent of the rough areas exceeded a length of 40 miles. Additional analysis of the data indicated that the distributions of the lengths of turbulent areas did not vary significantly with altitude for altitudes between 20,000 and 55,000 feet. Figure 5 shows that, on the average, the sizes of the turbulent areas for the present data appear to be somewhat smaller than those given by the results of reference 1. The smaller sizes for the present turbulent areas may also be associated with the limited seasonal coverage of the data of this investigation.

CONCLUDING REMARKS

An analysis of a small sample of turbulence data obtained from NACA VGH recorders during research flights of the Lockheed U-2 airplanes to attitudes of 55,000 feet over England and Western Europe during the summer of 1956 has indicated substantial reductions in the number and intensity of gusts with increasing altitude. The results indicated that the length of turbulent areas was less than 10 miles for about 75 percent of the areas encountered and that less than about 2 percent of the areas of rough air extended more than 40 miles. These results on the intensity, amount, and extent of atmospheric turbulence were found to be in overall agreement with the results given in NACA RM L53G15a for operations over the United States. The principal difference between the results of the two investigations was the indication that, on the whole, the turbulence encountered during the surveys over England and Western Europe was about 25 percent less severe than that for operations over the United States.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 17, 1956.

REFERENCES

1. McDougal, Robert L., Coleman, Thomas L., and Smith, Philip L.: The Variation of Atmospheric Turbulence With Altitude and Its Effect on Airplane Gust Loads. NACA RM L53G15a, 1953.

2. Richardson, Norman R.: NACA VGH Recorder. NACA TN 2265, 1951.

3. Pratt, Kermit G., and Walker, Walter G.: A Revised Gust-Load Formula and a Re-Evaluation of V-G Data Taken on Civil Transport Airplanes From 1933 to 1950. NACA Rep. 1206, 1954. (Supersedes NACA TN's 2964 by Kermit G. Pratt and 3041 by Walter G. Walker.)

TABLE I.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY BY ALTITUDE

Gust velocity, U_{de}, fps	Frequency distribution for altitudes, ft, of -			
	20,000 to 30,000	30,000 to 40,000	40,000 to 50,000	50,000 to 55,000
2 to 2.9	94	84	70	74
3 to 3.9	44	42	51	28
4 to 4.9	21	10	12	12
5 to 5.9	8	4	5	3
6 to 6.9	4	1	4	3
7 to 7.9	2	--	--	--
8 to 8.9	2	--	1	1
9 to 9.9	--	--	--	--
10 to 10.9	1	--	1	--
Total	176	141	144	121

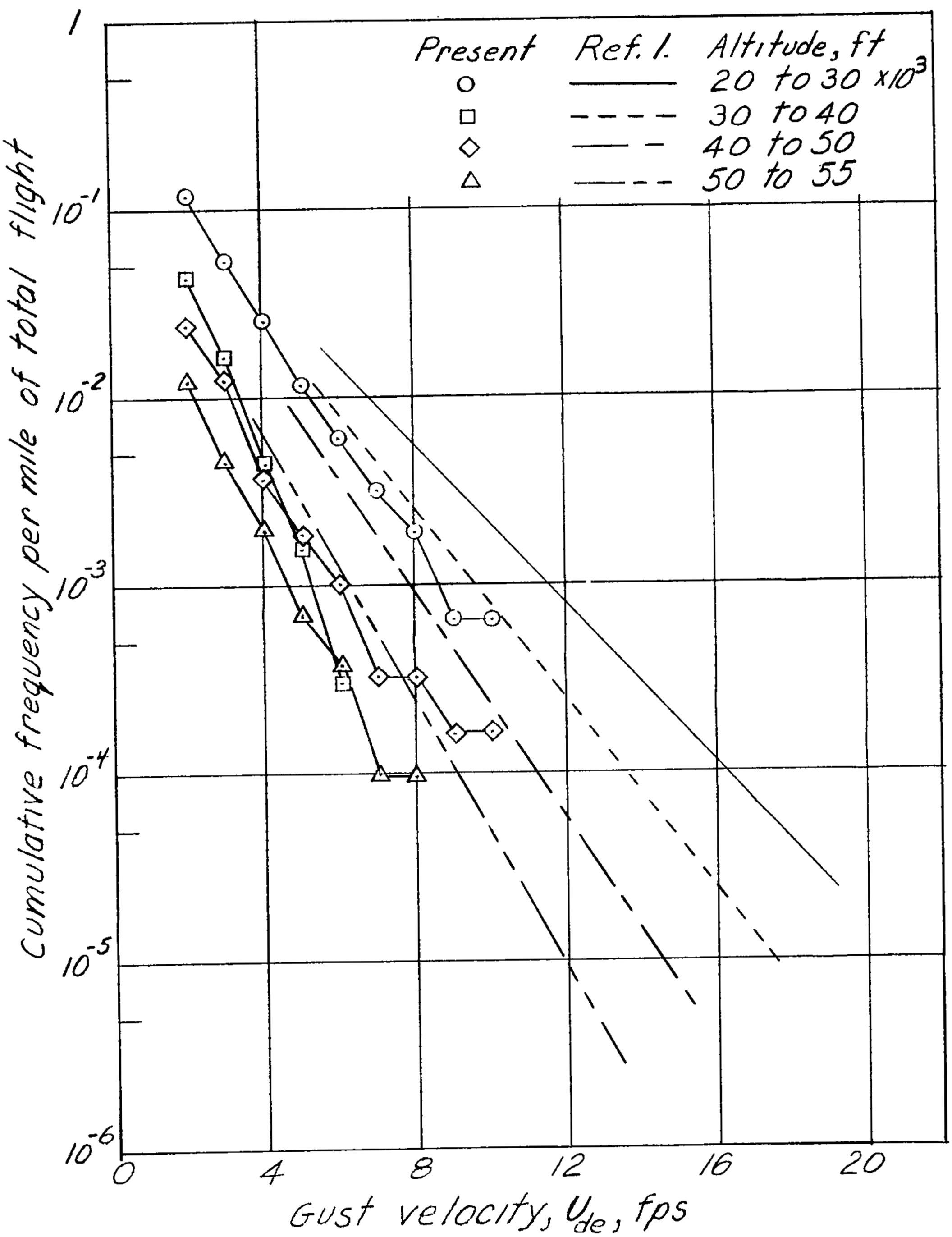

Figure 1.- Comparison of present results on the frequency of exceeding given values of gust velocity per mile of total flight with results from reference 1.

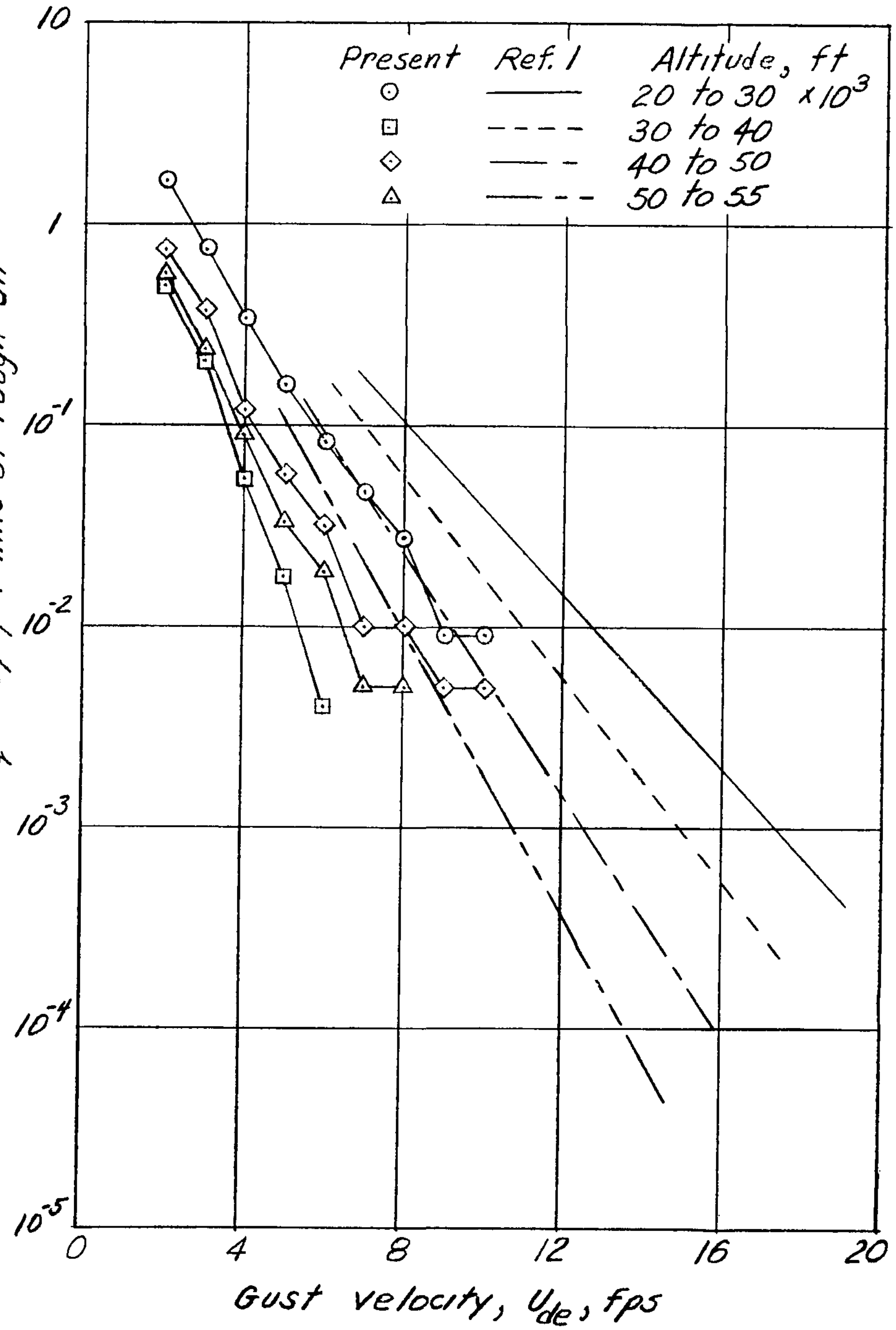

Figure 2.- Comparison of present results on the frequency of exceeding given values of gust velocity per mile of rough air with results from reference 1.

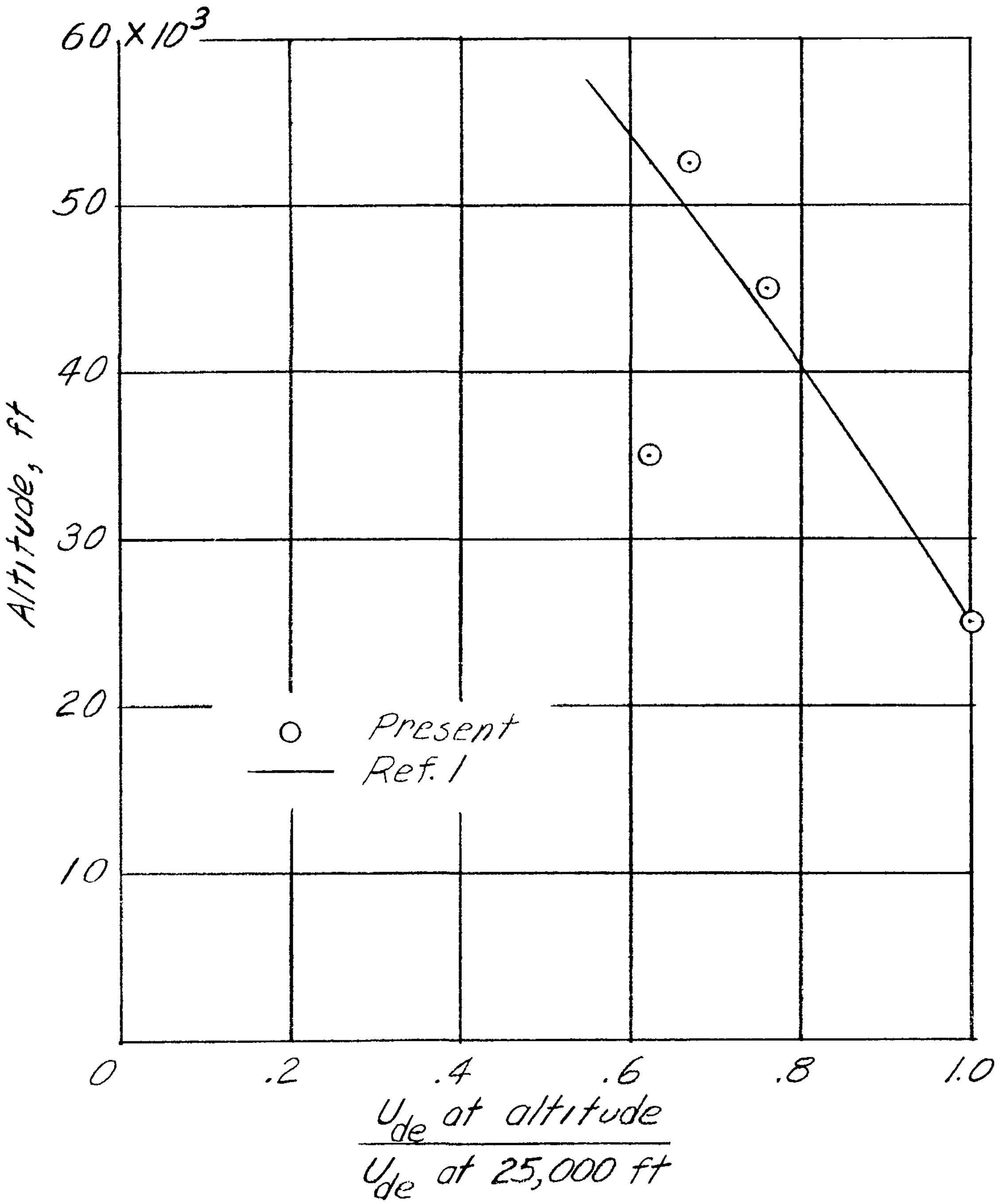

Figure 3.- Variation in relative gust velocities with altitude.

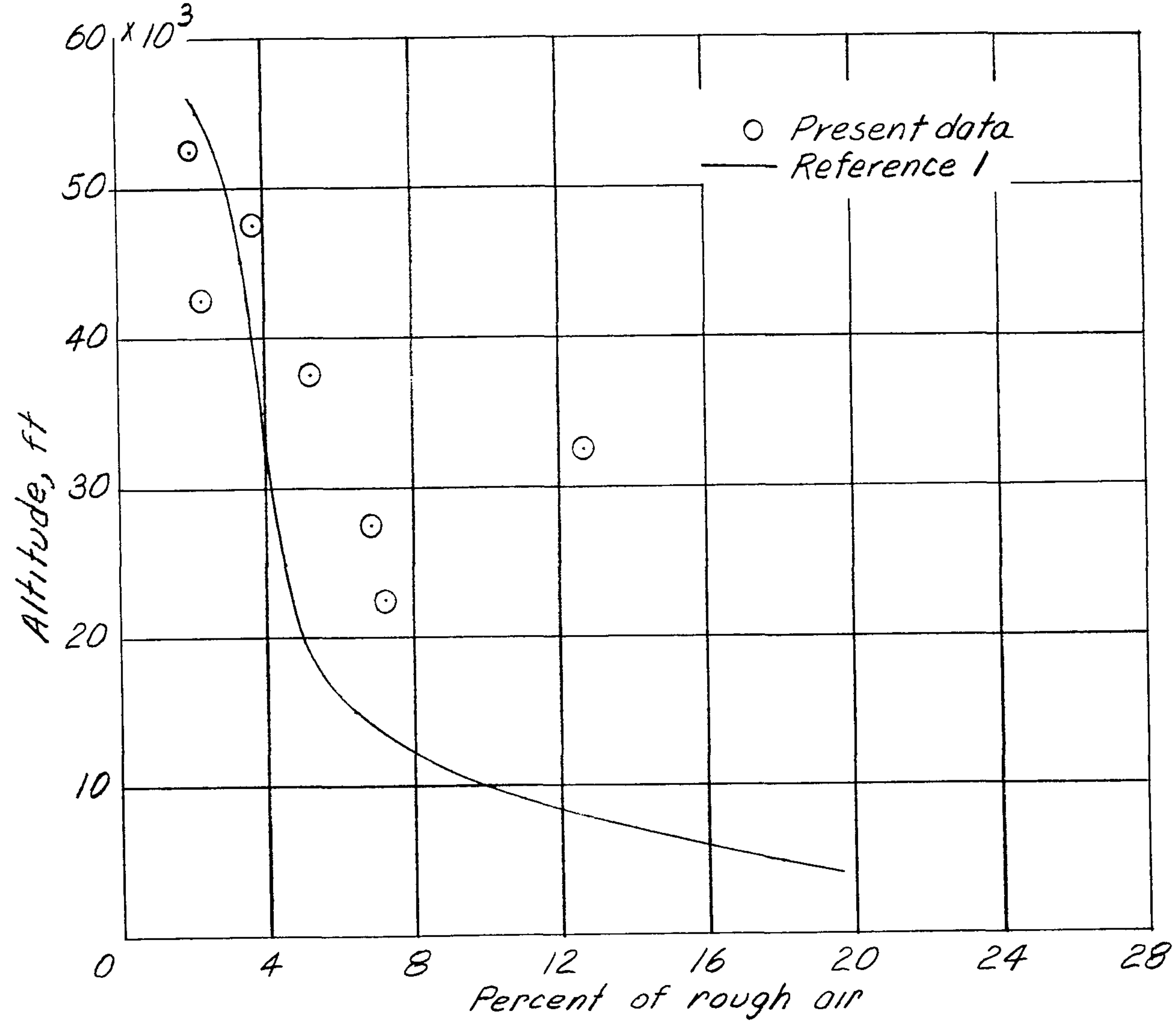

Figure 4.- Variation in percent of turbulent air with altitude.

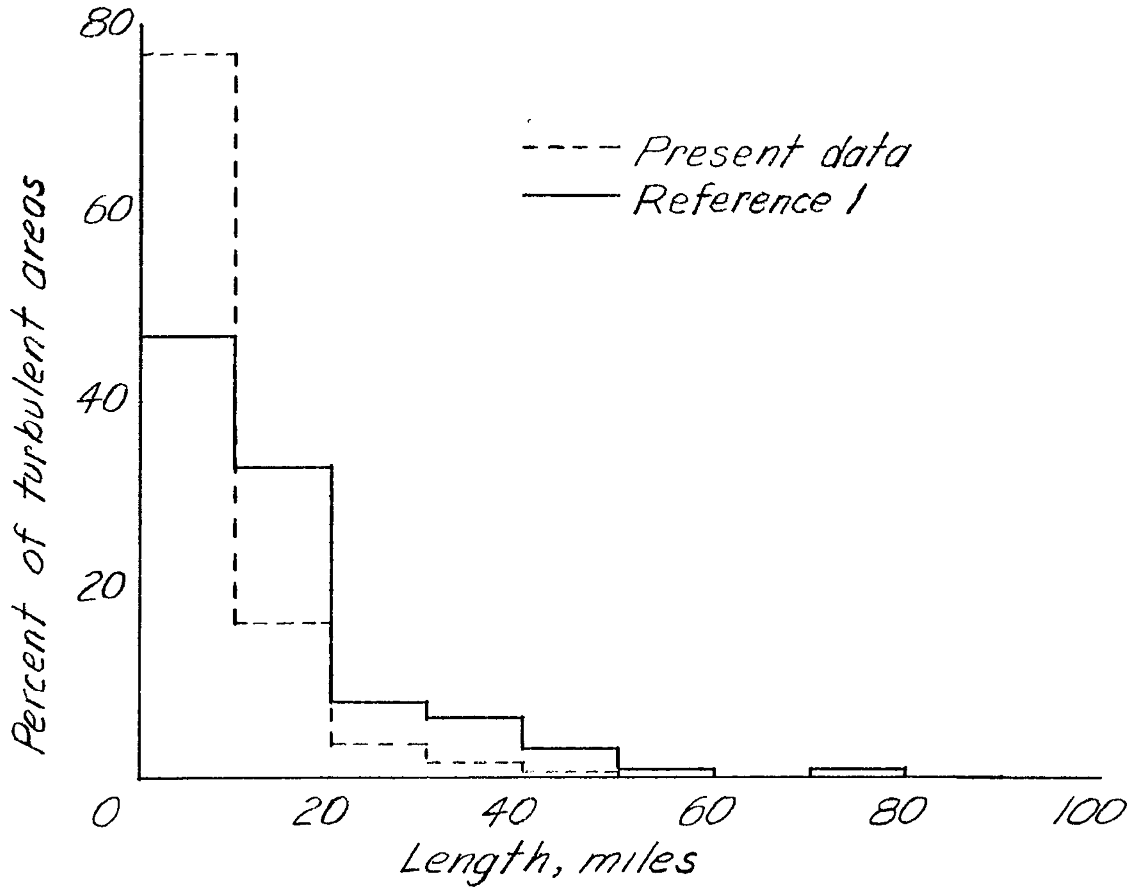

Figure 5.- Distribution of the lengths of turbulent areas for altitudes between 20,000 and 55,000 feet.