NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4129

ANALYSIS OF OPERATIONAL AIRLINE DATA TO SHOW THE EFFECTS OF AIRBORNE WEATHER RADAR ON THE GUST LOADS AND OPERATING PRACTICES OF TWIN-ENGINE SHORT-HAUL TRANSPORT AIRPLANES

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SUMMARY

Samples of airspeed, altitude, and acceleration measurements obtained from transport operations utilizing airborne weather radar have been evaluated to determine the effects of radar storm detection on the magnitudes of the gust velocities, gust loads, and operating airspeeds. The data samples were obtained with NACA V-G and VGH recorders installed in twin-engine short-haul commercial transports.

The results indicate that the magnitudes of the largest gust velocities and gust accelerations experienced for a given number of flight miles during operations with airborne radar were approximately 25 percent less than those experienced before the radar equipment was installed. However, airborne radar appeared to have no appreciable effect upon the frequency of occurrence of the smaller repeated gust loads. Inasmuch as the airspeed practices in rough air were not affected by the use of airborne radar, the reduction in the magnitudes of the largest gust accelerations appeared to be due mainly to the avoidance of storm areas which were detected by the radar.

INTRODUCTION

The development of airborne weather radar has provided a useful means of locating thunderstorm rain areas. Inasmuch as these rain areas are normally severely turbulent, weather radar thus provides a means of locating and avoiding such turbulent areas. Flight tests with radar-equipped airplanes have indicated that storm avoidance through the use of airborne radar could result in a reduction in gust loads and improved passenger comfort. (See, for example, refs. 1 to 4.) As a result of these and other possible benefits, a number of airlines have recently installed airborne weather radar in their airplanes. However, no quantitative information has, as yet, been obtained on the magnitudes of the effects of airborne weather radar on the gust loads in actual airline operations.

In order to assess the effects of airborne radar on the gust loads and operating practices of commercial airlines, the National Advisory Committee for Aeronautics has initiated a program with the cooperation of the airlines to obtain measurements of the gust loads experienced by transports both with and without radar equipment. The procedure followed in carrying out the program has been to install NACA V-G and VGH recorders in transport airplanes scheduled to receive airborne weather mapping radar at some future date so that samples of airspeed, altitude, and acceleration data could be obtained before the radar was installed. Similar data were obtained subsequent to the installation of the airborne radar. To date, data from this program have been obtained from three airplanes of the same type flown by one airline.

The data for operations both with and without radar installed have been analyzed and the results are presented in this paper. Although these results are of limited extent, they provide a basis for an early examination of any trends in the gust loads and associated operating practices which might be attributed to the use of radar.

INSTRUMENTATION AND SCOPE OF DATA

The data were collected with one NACA VGH recorder and three NACA V-G recorders which are described in detail in references 5 and 6, respectively. The VGH recorder yields a time-history record of indicated airspeed, pressure altitude, and normal acceleration. The V-G recorder supplies an envelope type of record which represents only the maximum accelerations that occur throughout the airspeed range for the time covered by the record. The VGH records are used primarily for detailed studies of the load history of the airplane and its associated operating practices; whereas, estimates of the large and relatively infrequent gust accelerations, gust velocities, and airspeeds are made by obtaining considerably larger samples of V-G data.

The present data were obtained from three twin-engine airplanes; two of the airplanes were equipped with NACA V-G recorders, and the third airplane was equipped with both an NACA V-G and an NACA VGH recorder. The airplane characteristics pertinent to the evaluation of the data are as follows:

Design gross weight, W, lb	47,000
Wing area, S, sq ft	920
Span, b, ft	105.3
Aspect ratio, A	12
Mean geometric chord, c, ft	8.7
Slope of lift curve, m, per radian $\left(\text{computed from } \frac{6A}{A + 2}, \text{ see ref. 7}\right)$	5.14
Design speed for maximum gust intensity (indicated), V_B, mph (computed according to ref. 8)	185
Design cruising speed (indicated), V_c (also manufacturer's design maximum level-flight speed, V_L), mph	325
Design never-exceed speed (indicated), V_{NE}, mph	338
Normal acceleration corresponding to the design limit-gust-load-factor increment, $a_{n,LLF}$, g units (computed according to ref. 8)	2.03

These values were obtained from the manufacturer's design data unless otherwise indicated in the table. As previously indicated, all the airplanes were of a similar type flown by the same airline. The instrumentation was installed prior to the airborne radar in order to obtain samples of operations without radar installed. The data obtained without radar installed as well as the data obtained with radar installed were obtained from short-haul flights over both transcontinental and Pacific Coast routes. The operating conditions covered by the data and the sample size from each operation are summarized in the following table:

	Operations without radar installed	Operations with radar installed
Dates of record collection	Oct. 1955 to April 1956	April 1956 to May 1957
VGH record hours evaluated	267	325
V-G record hours evaluated	2,717	6,126
Average indicated airspeed, mph	198	190
Average cruising pressure altitude, ft	8,900	9,300
Average length of flight, hr	0.86	0.91

The radar equipment used consisted of production models of a 5.5-cm (C-band) airborne weather mapping radar. A significant feature of this weather radar is that it includes isoecho contour circuitry which permits the mapping of different levels of rainfall intensity (ref. 2).

EVALUATION OF DATA AND RESULTS

Gust Accelerations

The procedures used in evaluating the VGH records are described in reference 9. Briefly, the evaluation consisted of reading positive and negative gust accelerations a_n above a threshold of 0.3g from the VGH records by using the steady-flight position of the acceleration trace as a reference. These data were formed into combined (positive and negative) frequency distributions of gust accelerations and are given in table I(a) for operations both with and without radar installed. The flight miles represented by each distribution are shown also in table I(a).

A detailed description of the procedures used in evaluating the V-G records is given in reference 10. The values read from each V-G record were the maximum positive and negative acceleration $a_{n,max}$ occurring at speeds above 160 miles per hour, the indicated airspeed V_o for each maximum acceleration, and the maximum indicated airspeed V_{max}. The acceleration increments below 160 miles per hour were not read in order to exclude the effects of maneuvers during take-off and approach and impact shocks during landing. Combined frequency distributions of the maximum positive and negative gust accelerations obtained from the V-G records are given in table I(b) for the operations both with and without radar installed. The flight miles represented by each distribution are also indicated in table I(b).

The distributions of tables I(a) and I(b) for operations both with and without radar installed are shown in figure 1 in terms of the average number of accelerations greater than a given value per mile of flight. In order to obtain an indication of the overall gust-acceleration histories for each operation, a curve (solid line) was faired through the lower values of the VGH gust-acceleration data obtained without radar installed and then extended to match the higher values of the V-G gust-acceleration data obtained without radar installed. Another curve (dashed line) was faired in a similar manner through the VGH and V-G data obtained with radar installed. The process of synthesizing the two types of data shown in figure 1 is necessary due to limitations in the data obtained from the VGH as well as the V-G recorder. The higher values of the VGH data were not considered in the fairing since considerably larger samples of VGH data would be required to obtain reliable estimates of their frequency of occurrence. (See, for example, ref. 11.) The lower values of the V-G data cannot be used, on the other hand, since they underestimate the frequency of occurrence of the smaller acceleration values. These tendencies in the data are attributed to the nature of the V-G records and the evaluation procedures used (two readings per record).

In order to illustrate the characteristics of the V-G records obtained, composite acceleration envelopes from V-G records representing all of the data evaluated are shown in figure 2 for the operations both with and without radar installed. The envelope type of record shown indicates the maximum accelerations experienced throughout the range of operating airspeeds.

Gust Velocities

Derived gust velocities were calculated for each gust acceleration peak by means of the revised gust-load formula (ref. 12) by using the corresponding indicated airspeed and pressure altitude obtained from the VGH records:

$$U_{de} = \frac{2Wa_n}{K_g \rho_o V_e m S}$$

where

U_{de}	derived gust velocity, fps
W	airplane weight, lb
a_n	normal acceleration, g units
K_g	gust factor
ρ_o	air density at sea level, slugs/cu ft
V_e	equivalent airspeed, fps
m	slope of lift curve per radian
S	wing area, sq ft

The value for the gust factor K_g was based on the mass parameter of the airplane computed for the flight altitude at which the gust was encountered. Since detailed information on the operating weight at the time of gust encounters was not available, an assumed average operating weight of 0.85 design weight was used in determining the values of K_g and in computing the gust velocities.

The resulting combined (positive and negative) frequency distributions of gust velocities for the operations without radar installed are presented in table II(a) in class intervals of 4 feet per second. A similar distribution is also presented in the table for the operations with radar installed.

The maximum positive and negative derived gust velocities were computed for each V-G record by using the maximum positive and negative acceleration values and the respective values of airspeed V_o in the gust-velocity formula previously discussed. The value of the gust factor K_g used for evaluating the gust velocities from the V-G data was based on an average operating altitude of 9,000 feet and an assumed average operating weight of 0.85 design weight. Combined frequency distributions of the maximum positive and negative derived gust velocities obtained from the V-G records are given in table II(b) for operations both with and without radar installed.

The VGH and V-G gust-velocity distributions of table II are shown in figure 3 for each operation. The ordinate scale is in terms of the average number of gust velocities greater than a given value per mile of flight. As in figure 1, faired curves were drawn through the V-G and VGH data points of each operation in order to obtain an indication of the overall gust-velocity histories.

Operating Airspeeds

The indicated airspeed and pressure altitude were read from the VGH records for each 1-minute interval of flight in order to define the operating altitudes and airspeeds for the operations both with and without radar installed. Average values of airspeed were obtained from the 1-minute readings for climb, en-route, and descent flight conditions and for the total samples of data obtained with and without radar installed. These values are shown in table III(a).

The airspeed data were further evaluated to determine whether significant reductions in airspeed were made upon encountering rough air. For this evaluation, any portion of the VGH record was considered to represent rough air if the acceleration trace contained gust-acceleration peaks of at least 0.3g. The remainder of the record was accordingly classified as representing smooth air. The 1-minute airspeed readings were then identified as being read during either rough- or smooth-air conditions and were sorted into separate distributions. Average airspeed values in rough and smooth air were computed from these distributions for each flight condition and for the total samples of each operation. These values are listed in table III(a).

As a further means of comparing the airspeed practices of both operations, average values of the airspeed V_o at the time of maximum acceleration and the maximum airspeed on the record V_{max} were obtained from the V-G records and are given in table III(b).

PRECISION AND RELIABILITY OF RESULTS

The inherent errors in the NACA VGH recorder and the installation errors are discussed in detail in reference 5. Since the installation requirements given in reference 5 were met, the effects of installation errors upon the present VGH data are negligible. Instrument errors, which are discussed in detail in reference 11, are not considered to be of sufficient magnitude to affect the reliability of the results. Reading errors, although estimated to be small, of the order of 0.05g, can seriously affect the number of accelerations exceeding given values. The effect of such errors on the reliability of the actual distributions is difficult to evaluate. Experimental checks have indicated that for individual records the counts above 0.3g are, at best, only reliable to ±30 percent. As the number of records increase, errors from this source should balance out. For the present sample, it is estimated that the values for the cumulative frequency per mile given in figures 1 and 3 are reliable to within ±20 percent.

The inherent errors in the V-G recorder are less than ±0.1g and approximately ±5 miles per hour. Errors incurred in reading the V-G records are considered to be negligible.

In an analysis of limited samples of data, such as the V-G and VGH data in figures 1 and 3, questions arise as to whether the observed differences between the data are truly representative of the conditions encountered or whether they are due to sampling variations. Simple statistical tests have been applied to the V-G and VGH data of table I. These tests have indicated that the observed differences in figures 1 and 3 between the two samples at larger acceleration levels and gust velocities were clearly statistically significant. Statistical tests were also applied to the VGH data in order to test the statistical significance of the observed differences at the lower levels of gust acceleration and gust velocity. These tests indicated that the observed differences were not statistically significant and thus may not be real but rather the result of sampling error.

DISCUSSION

Gust Accelerations

An inspection of figure 1 indicates that considerable differences exist in the magnitudes and frequencies of occurrence of the larger gust accelerations $\left(a_n \gtrless 1.0g\right)$ obtained with the V-G recorders during operations with and without radar installed. The magnitudes and frequencies of occurrence of gust accelerations evaluated from the VGH records, however, were approximately similar for both operations. With the airborne radar in operation, it appears that the magnitudes of the larger gust accelerations experienced per mile of flight were reduced by approximately 25 percent. On the other hand, the use of airborne weather radar appeared to have no significant effect upon the frequency of occurrence of the smaller repeated loads $\left(a_n \lesseqgtr 0.5g\right)$ which are important to the fatigue life of the airplane structure.

Further indications on the nature of the overall reductions in the larger loads are evident from a comparison of the composite acceleration envelopes from V-G records shown in figure 2. The acceleration envelope representing operations with radar installed is, in general, smaller than the envelope representing operations without radar installed even though the sample size of data obtained with radar installed is more than twice as large as the data sample obtained without radar installed. These tendencies in the data confirm previous estimates made in reference 4 that significant reductions may be realized in the larger loads through the use of airborne radar but that little if any reduction would be achieved for the smaller loads.

Gust Velocities

Considerable differences are apparent in the magnitude and frequency of occurrence of the larger gust velocities represented by the V-G data for the operations with and without radar installed (fig. 3). The results, as indicated by the faired curves, show a reduction in the magnitudes of the largest gust velocities encountered per mile of flight by about 25 percent subsequent to the installation of airborne radar equipment. As in figure 1, little differences are indicated in the frequency of occurrence of the smaller values of gust velocity which were calculated from the VGH data.

Airspeed Practices

A comparison of the average values of airspeed in rough air $(a_n \gtrless 0.3g)$ and in smooth air for each flight condition of operations both with and without radar installed (table III(a)) indicates no appreciable slowing down upon encountering turbulence. Average values of V_o and V_{max} obtained from the V-G records (table III(b)) indicate also that the airborne radar had no apparent effect upon the airspeed practices.

It appears from these results that the reductions in the larger gust accelerations (fig. 1) are due mainly to the avoidance of severe turbulence in thunderstorm areas which were detected by the airborne radar.

Estimated Loads History in Non-Thunderstorm Turbulence

In an effort to provide a measure of the overall efficiency of the radar in reducing gust accelerations for the present operations, the gust accelerations that would be expected on the assumption that all thunderstorm turbulence was widely avoided were calculated for comparison with the present data. The calculated distribution of gust accelerations experienced in non-thunderstorm turbulence is shown in figure 1 and was computed by the method described in reference 13. The non-thunderstorm distribution as used in this report includes only clear air and stratus-type turbulence. Turbulence associated with convective clouds is excluded. The basic gust velocity distribution of non-thunderstorm turbulence (sea level to 10,000 feet) used in the calculations was obtained from the data of table I and figure 5 of reference 13 and is shown in figure 3.

On the basis of the calculated loads distribution in figure 1 and the gust velocity distribution in non-thunderstorm turbulence shown in figure 3, it would appear that all convective turbulence along the routes is not being avoided. In actual airline use, it may, of course, be impractical because of other operational considerations to avoid all the thunderstorms and convective cloud areas which may be detected by the radar. In addition, many of the smaller convective clouds are not detected by the airborne radar.

CONCLUSIONS

An analysis of the effects of airborne weather radar on the gust loads and operating practices of twin-engine transport airplanes operated over a short-haul domestic route has indicated the following results:

1. The magnitude of the largest gust velocities and gust accelerations experienced for a given number of flight miles during operations with airborne radar were approximately 25 percent less than those experienced during operations without radar installed.

2. Airborne radar appeared to have no significant effect upon the frequency of occurrence of the smaller repeated loads (normal acceleration equal to or less than 0.5g) and thus could not appear to affect the fatigue life of the airplane structure.

3. The use of airborne radar had no apparent effect upon the airspeed practices of the present operations.

4. It appears that the reduction in the magnitudes of the largest gust accelerations is due mainly to the avoidance of storm areas which were detected by radar.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 7, 1957.

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TABLE I - FREQUENCY DISTRIBUTIONS OF GUST ACCELERATIONS

(a) VGH data

Acceleration (positive and negative), a_n, g units	Frequency distribution for -	
	Operations without radar installed	Operations with radar installed
0.3 to 0.4	2,399	5,258
.4 to .5	280	738
.5 to .6	74	171
.6 to .7	13	37
.7 to .8	8	5
.8 to .9	1	1
.9 to 1.0	1	1
1.0 to 1.1	1	2
Total	2,777	6,213
Flight miles	5.9×10^4	6.9×10^4

(b) V-G data

Maximum acceleration (positive and negative), $a_{n,max}$, g units	Frequency distribution for -	
	Operations without radar installed	Operations with radar installed
0.5 to 0.6	-	1
.6 to .7	-	10
.7 to .8	-	11
.8 to .9	-	11
.9 to 1.0	-	13
1.0 to 1.1	1	5
1.1 to 1.2	1	6
1.2 to 1.3	8	3
1.3 to 1.4	9	1
1.4 to 1.5	4	1
1.5 to 1.6	2	2
1.6 to 1.7	5	1
1.7 to 1.8	3	0
1.8 to 1.9	1	1
1.9 to 2.0	1	-
2.0 to 2.1	1	-
Total	36	66
Flight miles	6.0×10^5	13.6×10^5

TABLE II - FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITIES

(a) VGH data

Derived gust velocity (positive and negative), U_{de}, fps	Frequency distribution for -	
	Operations without radar installed	Operations with radar installed
8 to 12	992	2,178
12 to 16	1,350	2,973
16 to 20	358	839
20 to 24	57	178
24 to 28	11	33
28 to 32	8	8
32 to 36	1	2
36 to 40	-	1
40 to 44	-	1
Total	2,777	6,213
Flight miles	5.9×10^4	6.9×10^4

(b) V-G data

Maximum derived gust velocity (positive and negative), $U_{de,max}$, fps	Frequency distribution for -	
	Operations without radar installed	Operations with radar installed
16 to 20	-	1
20 to 24	-	12
24 to 28	-	13
28 to 32	-	11
32 to 36	1	14
36 to 40	7	6
40 to 44	9	4
44 to 48	7	2
48 to 52	3	1
52 to 56	6	2
56 to 60	1	-
60 to 64	1	-
64 to 68	0	-
68 to 72	1	-
Total	36	66
Flight miles	6.0×10^5	13.6×10^5

TABLE III - AIRSPEED PRACTICES

(a) VGH data

Operation	Average indicated airspeed, mph; for -				Turbulence level
	Climb	En route	Descent	Total	
Without radar installed	169 167 168	205 200 205	202 184 197	200 182 198	Smooth air Rough air Total
With radar installed	162 160 161	196 197 196	199 179 194	191 180 190	Smooth air Rough air Total

(b) V-G data

Operation	Average indicated airspeed for $a_{n,max}$, $\overline{V}_o$, mph	Average maximum airspeed on record, $\overline{V}_{max}$, mph
Without radar installed	206	308
With radar installed	202	310

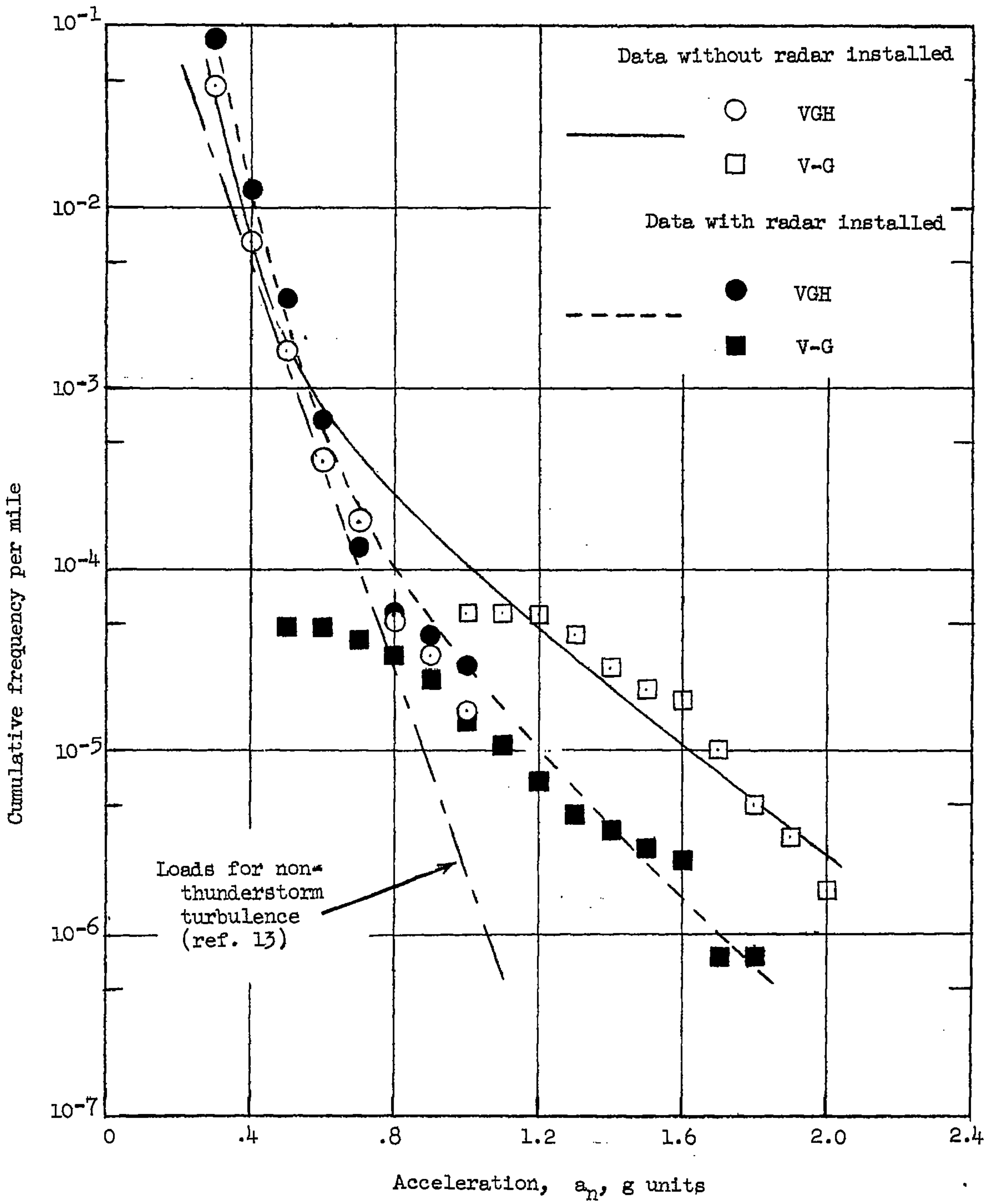

Figure 1.- Comparison of frequency of exceeding given values of gust acceleration per mile of flight.

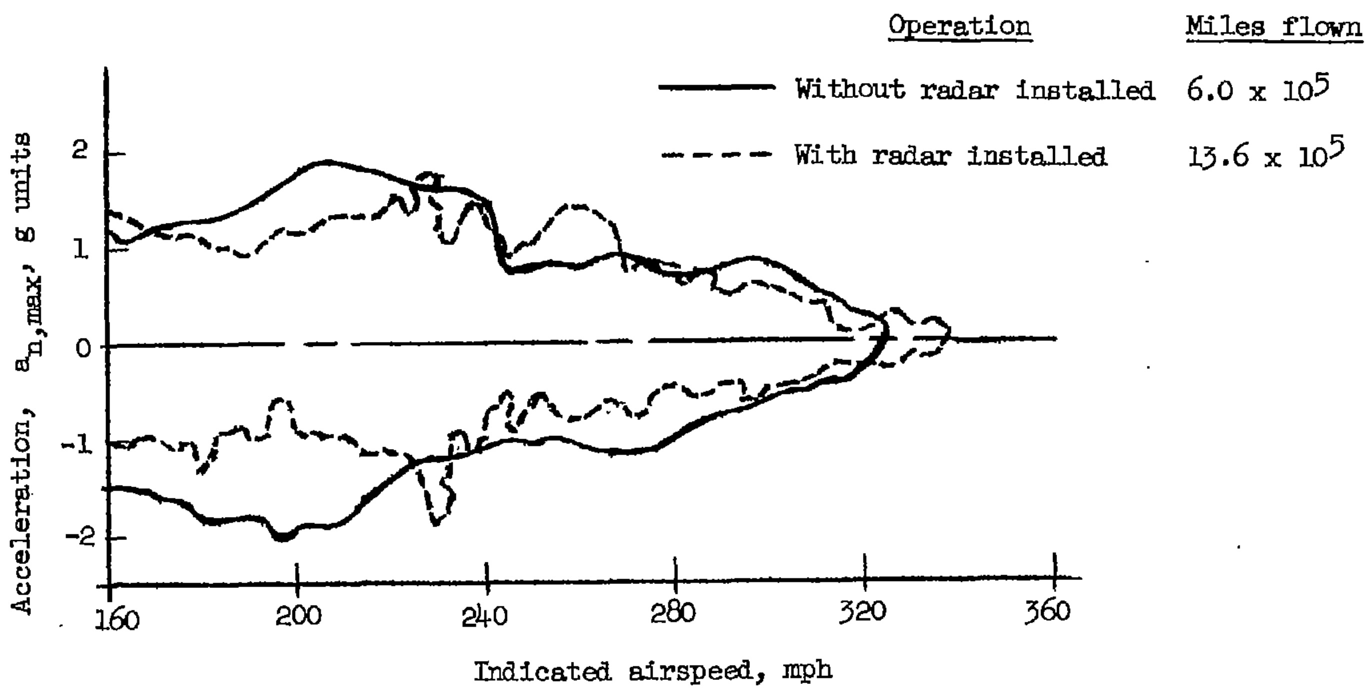

Figure 2.- Comparison of composite acceleration envelopes from V-G records obtained during operations with and without radar installed.

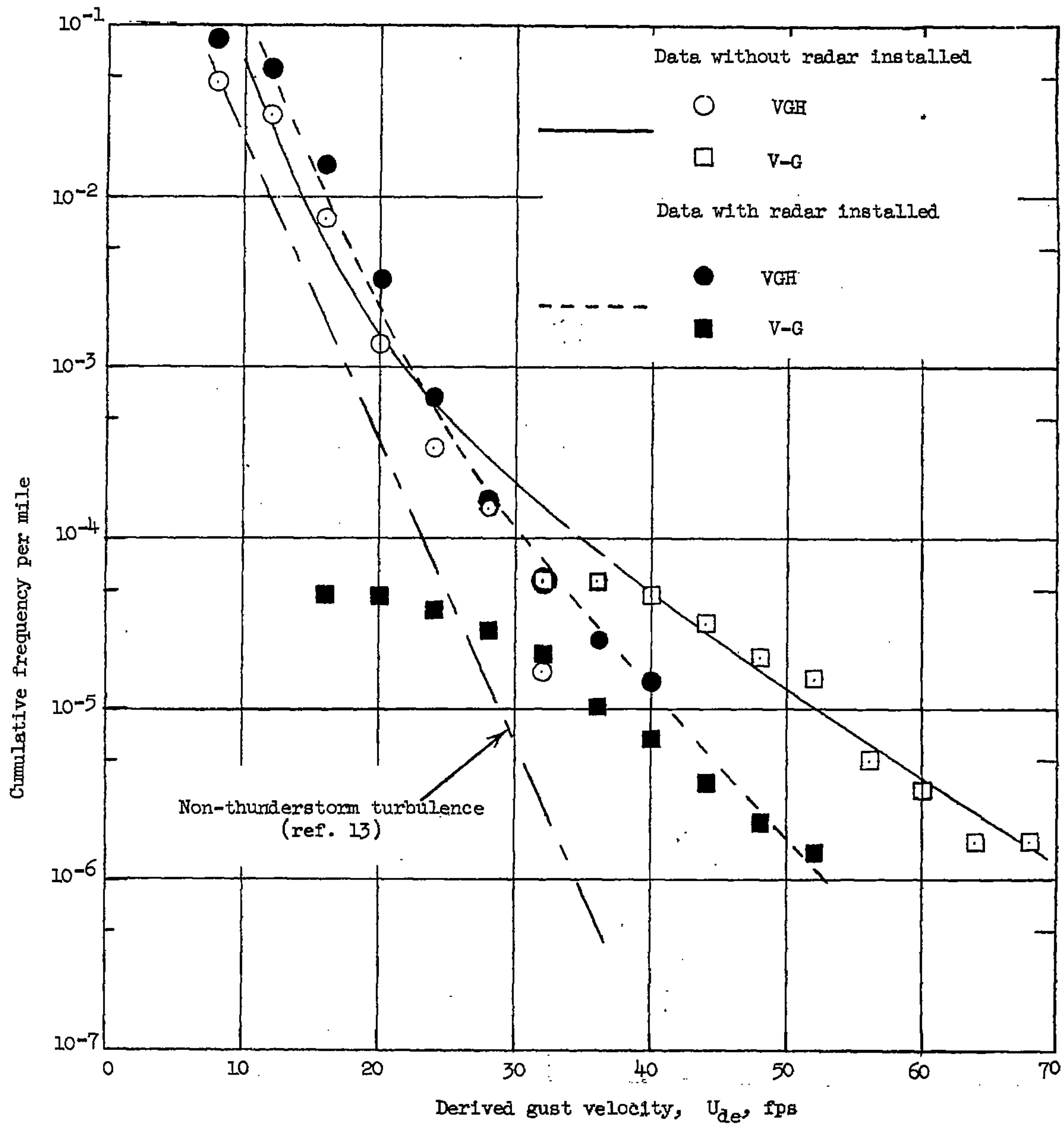

Figure 3.- Comparison of frequency of exceeding given values of gust velocity per mile of flight.