C.P. No. 419
(20,563)
A.R.C. Technical Report

C.P. No. 419
(20,563)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Distribution of Gusts in the Atmosphere. An Integration of U.K. and U.S. Data

by

N. I. Bullen

LONDON: HER MAJESTY'S STATIONERY OFFICE

1959

FOUR SHILLINGS NET

C.P. No. 419

U.D.C. No. 533.6.048.5(.083.6)(42):533.6.048.5(.083.6)(73)

Technical Note No. Structures 244

June, 1958

ROYAL AIRCRAFT ESTABLISHMENT

THE DISTRIBUTION OF GUSTS IN THE ATMOSPHERE AN INTEGRATION OF U.K. AND U.S. DATA

by

N. I. Bullen

SUMMARY

Information on gust frequencies in the British papers is derived from counting accelerometer records, and in the U.S. work from the V.g.h. recorder. The methods of deriving the gust velocity from aircraft acceleration are first compared. The relative frequencies of gusts of differing magnitudes are then examined, and finally the absolute frequencies at varying heights are compared. In general there is good agreement between the two sets of data.

LIST OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1 INTRODUCTION

British data on the effect of atmospheric gusts on aircraft are derived from the records of counting accelerometers[1] carried in the aircraft. The counting accelerometer is an instrument which records automatically the number of times a given series of normal accelerations are exceeded. The lowest acceleration recorded is usually about 0.2g. The aircraft accelerations are converted to gust velocities by the method of Zbrozek[2,3] which is based on the assumption of a discrete gust of given profile (i.e., a given velocity-space relation). Results of such analysis are given by Heath-Smith[4,5,6,7] and J.E. Aplin[8] and are collected and summarized by Bullen[9].

United States data on gust accelerations of aircraft are obtained from the N.A.C.A. V.g.h. recorder[10]. This gives a time history type of record of indicated airspeed, normal acceleration and altitude. From this record it is the usual practice to calculate the gust velocity corresponding to each acceleration of more than 0.3g upwards or downwards. It will be noted that this figure is somewhat higher than the lowest level on the counting accelerometer and leads to the omission of more of the lower velocity gusts. The effect of this can be seen on some of the cumulative frequency curves (e.g. Fig.4). The procedure with the counting accelerometer data is to ensure that the lowest gust velocity quoted always falls above the lowest acceleration level; the corresponding gust frequency is then found by interpolation and this leads to more reliable estimates at the lower gust velocities. There is, in fact, evidence that the gust frequency distribution continues to show the same general trend to much lower values of gust velocity[19].

Results from V.g.h. records are given in Refs.13-18. For interpreting the aircraft acceleration in terms of gust velocity use is again made of the discrete gust assumption. In Ref.13 an early method of conversion is employed which is not based on the mass parameter. It assumes a sharp edged gust and uses the gust alleviation factors given by Rhode and Donely[12]. The remainder, however (Refs.14-18) give results based on the method of Pratt and Walker[11]. Here the gust profile is defined in terms of the aircraft wing chord. This has the advantage of reducing by one the number of parameters on which the gust alleviation factor is based, although it is perhaps somewhat illogical to define a property of the atmosphere in terms of the dimensions of a particular aircraft. However, the question cannot be dismissed lightly. Donely[20] gives some evidence in justification of the U.S. method and considers that:-

> "...... airplane size might be a significant parameter, as in the case of boats where waves of small wave length that are of no concern to a large boat cause the small boat considerable difficulty."

Pratt and Walker further reduce the number of parameters by making no allowance for aspect ratio and are thus able to express the gust alleviation factor in terms of the mass parameter only.

A comparison of the two sets of data is made, firstly to examine the relative frequencies of gusts of different velocities, and secondly to compare the absolute frequency per mile of flight of gusts of a velocity greater than some standard magnitude.

2 THE RELATIVE FREQUENCIES OF GUSTS OF DIFFERENT MAGNITUDES

The relevant British data are summarised in Ref.9. The U.S. data are extracted from Refs.15-18 and also include gust frequencies based on a re-assessment* of the original data of Ref.13. Data from Ref.14 are omitted, as the high value of the gust velocity corresponding to 0.3g under certain operating conditions makes the estimates of the gust frequencies for low velocities very unreliable. This is clearly shown in Fig.4. Since also the frequencies are given for a different set of values of gust velocities interpolation would, in any case, be necessary.

For a direct comparison allowance should be made for differences in the gust alleviation factor used in the calculations. Accordingly, for each aircraft and operating condition in the U.S. papers the gust alleviation factors estimated by each method have been compared. It is found that the ratio K_z/K_p ranges between about 1.04 and 1.12 with a mean of 1.075,

where K_z is the gust alleviation factor estimated by Zbrozek's method, and

K_p is the gust alleviation factor estimated by the method of Pratt and Walker.

It is considered that for the comparison of relative frequencies it is sufficiently accurate to decrease the values of gust velocities given in the U.S. work by the factor 1.075.

The two sets of data are tabulated in Tables 1 and 2 and are shown plotted in Fig. 1. In the U.S. data a large number of gusts between 8 and 12 ft/sec have been excluded by the method of analysis so that the value given for the number of gusts greater than 8 ft/sec is too low. Apart from this, the distributions show the same general form, with, however, a small difference in slope. The two distributions are each readily fitted by the sum of two exponential terms, the exponents being the same in each case**. The formula for the British data has been fitted to agree with the observed total number of gusts of more than 10 ft/sec. The corresponding figure for the U.S. data is 11.16 ft/sec. For the British data:-

$$N = 631{,}800 \, e^{-0.4301 \, v} + 106{,}900 \, e^{-0.2595 \, v} \qquad (1)$$

and for the U.S. data:-

$$N = 1{,}553{,}000 \, e^{-0.4301 v} + 128{,}500 \, e^{-0.2595 \, v} \; . \qquad (2)$$

If the hypothesis is accepted that the two terms in the expression represent two distinct conditions of turbulence, then the difference between the two distributions is easily explained by assuming that the U.S. aircraft encounter a lower percentage of the more intense turbulence. This is in agreement with the fact that the Comet and Hermes routes include tropical regions of high convective activity with which the high intensity turbulence is considered to be associated.

---

*Unpublished communication.

**The exponents have been modified from the values given in Ref.9 in the light of the U.S. data and more recent estimates in this country. The values of these parameters are not particularly critical as a change of slope of the curve can be effected either by changing the exponents or by changing the ratio between the two terms.

3 THE VARIATION OF GUST FREQUENCY WITH ALTITUDE

In order to investigate the variation of gust frequency with altitude, a standard gust velocity of 10 ft/sec is chosen. The information obtained from counting accelerometer data has been summarised by Bullen[9] and Fig. 2 is reproduced from his paper.

In order to estimate the corresponding frequencies from the U.S. V.g.h. data, the tabulated frequencies of Refs. 13-18 have been plotted, after converting the velocities quoted to those based on Zbrozek's gust alleviation factor. In this conversion the correct factor for each case, rather than a mean value, has been used. The results are shown in Figs. 3-8. The majority of these curves give indications of the falling off at low gust velocities already mentioned. Acceleration increments smaller in magnitude that 0.3g are neglected in the analysis, and as for certain flight conditions the corresponding gust velocities are as high as 15 ft/sec, the lowest two or three frequencies are affected in some cases. The curves are therefore extrapolated along the general trend in order to obtain a reading at 10 ft/sec. This occasionally involves extrapolation for a considerable distance, as for example in Fig.4, but it is considered that on the whole, the errors involved are reasonably small. The gust frequencies obtained in this way are given in Table 3.

The values from Table 3 are grouped into height ranges and the average distance flown to encounter a gust of velocity more than 10 ft/sec is calculated. A few minor adjustments have been made to the heights. Flying over the Rocky Mountain routes at mean pressure altitudes of 5,000 ft and 9,600 ft has been included in the lowest altitude range as the heights above the ground are considerably less than these figures. The data for the 10,000 ft to 20,000 ft range from Ref.5 have been included in the 10,000 ft to 15,000 ft range as it is probable that most of the flying took place in the lower part of the range. The 20,000 ft to 25,000 ft data from Ref.6 are not considered representative of this altitude which is above the normal cruising height, and give indications of being obtained only in adverse conditions. For this reason, the sample, which is small, is included in the lower altitude range.

The results are summarised in Table 4 and shown plotted in Fig. 9. Also shown in this Figure are the relations given in Ref.9 for cruise and climb and descent. It is not feasible to divide the U.S. data in this way, but cruise conditions predominate and the figure shows that there is good agreement with the British figures for cruising. The small difference in slope is explained by the fact that in the case of the U.S. data the lower altitude bands contain a higher percentage of climb and descent conditions than the higher bands and this makes the conditions at the lower altitudes appear relatively more severe. Averaging the British data in a similar way indicates that the overall conditions gave about 50% more gusts at 10 ft per sec than the conditions experienced by the U.S. aircraft. This is probably due to the fact that the British data include a higher percentage of flying in tropical regions than the U.S. data which are based almost entirely on flying in temperate zones.

4 CONCLUSIONS

In general, there is good agreement between the two sets of data. The frequency distributions for gusts of different velocities show some difference but this can be explained on the assumption that the British data contain a higher proportion of turbulence of the type associated with thunderstorm activity. The agreement in absolute frequencies for gusts of 10 ft/sec or greater is remarkably good, indicating that there is little difference in the average conditions under which the two sets of data were obtained and that a degree of reliance can be placed in the results. It is also encouraging that the two different types of instrument give results that are in such good agreement.

LIST OF REFERENCES

No.	Author(s)	Title, etc.
1	Taylor, J.	Design and use of counting accelerometers. R. & M. 2812 June, 1950.
*2	Zbrozek, J.	Gust alleviation factor. May, 1951.
*3	Zbrozek, J.	Compressibility effect on gust loads. August, 1953.
4	Heath-Smith, J.R.	Turbulence encountered by Comet I aircraft. Current Paper No. 248. May, 1955.
5	Heath-Smith, J.R.	Atmospheric Turbulence encountered by Hermes aircraft. Current Paper No. 334. January, 1957.
6	Heath-Smith, J.R.	Turbulence encountered by Viking aircraft over Europe. Current Paper No. 311. July, 1956.
7	Heath-Smith, J.R.	Unpublished work.
8	Aplin, J.E.	Unpublished work.
9	Bullen, N.I.	The variation of gust frequency with gust velocity and altitude. Current Paper No. 324. October, 1956.
10	Richardson, N.R.	N.A.C.A. V.g.h. recorder. N.A.C.A. T.N. 2265, 1951.
11	Pratt, K.G. Walker, W.G.	A revised gust-load formula and a re-evaluation of V-g data taken on civil transport airplanes from 1933 to 1950 N.A.C.A. Report 1206, 1954.

---

*Refs. 2 and 3 have now been combined with another paper in the R. & M. Series. The title of the R. & M. is:-

Gust alleviation factor. Part I. Incompressible flow. Part II. Compressibility effect. Part III. Gust loads on swept wings (based on N.A.C.A. gust-tunnel tests).- J. Zbrozek. R. & M. 2970. August, 1953.

LIST OF REFERENCES (Cont'd)

No.	Author(s)	Title, etc.
12	Rhode, R.V. Donely, P.	Frequency of occurrence of atmospheric gust and of related loads on airplane structures. N.A.C.A. A.R.R.L. 4121, 1944.
13	Press, H. McDougal, R.L.	The gust and gust-load experience of a twin-engine low-altitude transport airplane in operation on a northern transcontinental route. N.A.C.A. T.N. 2663. April, 1952.
14	Coleman, T.L. Copp, M.R. Walker, W.G. Engel, J. N.	An analysis of acceleration, airspeeds and gust velocities from three commercial operations of one type of medium-altitude transport airplane. N.A.C.A. T.N. 3365. March, 1955.
15	Coleman, T.L. Walker, W.G.	Analysis of accelerations, gust velocities, and airspeeds from operations of a twin-engine transport airplane on a trans-continental route from 1950 to 1952. N.A.C.A. T.N. 3371. February, 1955.
16	Coop, M.R. Coleman, T.L.	An analysis of acceleration, airspeed and gust velocity data from one type of four-engine transport airplane operated over two domestic routes. N.A.C.A. T.N. 3475. October, 1955.
17	Coleman, T.L. Fetner, M.W.	Anaanalysis of acceleration, airspeed and gust velocity data from a four-engine transport airplane in operations on an eastern United States route. N.A.C.A. T.N. 3483. September, 1955.
18	Copp, M.R. Fetner, M.W.	An analysis of airspeed, altitude and acceleration data obtained from a twin-engine transport airplane operated over a feeder-line route in the Rocky Mountains. N.A.C.A. T.N. 37500. October, 1956.
19	Coleman, T.L. Funk, J.	Preliminary measurements of atmospheric turbulence at high altitude as determined from acceleration measurements on Lockheed U-2 airplane. N.A.C.A. R.M.L.57.A.11. March, 1957.
20	Donely, P.	Summary of information relating to gust loads on airplanes. N.A.C.A. T.N. 1976. November, 1949.

TABLE 1

Cumulative distribution of gusts. British data

Gust velocity v ft/sec	Number of gusts exceeding v ft/sec				Observed totals	Totals calculated from (1)
	1	2	3	4		
10	5,544	5,312	5,167	520	16,543	16,540
15	1,093	1,405	687	29	3,214	3,177
20	251	355	109	6	721	711.7
25	74	75	18		167	176.2
30	17	21	3		41	46.0
35	2	11			13	12.3
40	1	1			2	3.3
45	1	1			2	0.9

The original sources of the gust distributions in the numbered columns together with aircraft type and route are as follows:-

1 Refs. 4 and 7. These gust frequencies were obtained from Comet aircraft during about 2,000 hours on routine passenger service between London and Johannesburg, Colombo, Singapore and Tokyo, and about 40 hours low level test flying.

2 Ref. 5. Hermes aircraft on routine passenger service between London and Africa.

3 Ref. 6. Viking aircraft on routine passenger service on European routes based on London.

4 Ref. 8. Bristol 170 aircraft operated on general routes over Nigeria and the Gold Coast.

Expression 1 is repeated here for convenience.

$$N = 631{,}800\ e^{-0.4301\ v} + 106{,}900\ e^{-0.2595\ v} .$$

TABLE 2

Cumulative distribution of gusts. U.S. Data

Gust velocity ft/sec		No. of gusts exceeding v ft/sec					Observed totals	Totals calculated from (2)
v_p	v_z	1	2	3	4	5		
8	7.44	8,490	5,593	3,626	3,200	47,045	67,954	81,870
12	11.16	3,536	3,641	3,130	3,068	6,487	19,862	19,860
16	14.88	837	936	1,393	1,077	975	5,218	5,277
20	18.60	198	273	523	336	179	1,509	1,548
24	22.33	58	72	184	120	37	471	496.6
28	26.05	20	34	71	41	10	176	170.3
32	29.77	5	9	30	19	2	65	61.0
36	33.49		2	10	7		19	22.5
40	37.21		1	3	2		6	8.4
44	40.93		1	2			3	3.2
48	44.65		1				1	1.2

In Table 2, v_p is the gust velocity calculated by the method of Pratt and Walker and v_z is the value adjusted to approximate to the corresponding value using Zbrozek's method. The original sources of the gust distributions in the numbered columns, together with aircraft type and route are as follows:-

1 A re-assessment of the data of Ref. 13 (unpublished). A twin-engined low altitude transport airplane on a northern trans-continental route of the U.S.

2 Ref. 15. A twin-engined transport airplane used on short haul passenger operations between New York and Los Angeles.

3 Ref. 16. A four-engined transport airplane used on two U.S. routes.

4 Ref. 17. A four-engined transport airplane used on an eastern U.S. route.

5 Ref. 18. A twin-engined transport airplane used on a feeder-line route in the Rocky Mountains.

Expression 2 is repeated here for convenience.

$$N = 1,553,000 \; e^{-0.4301 \, v} + 128,500 \; e^{-0.2595 \, v} .$$

In substituting for v, the values of v_z should be used.

TABLE 3

Summary of U.S. data on gusts exceeding 10 ft/sec

Source N.A.C.A. T.N.	Route	Height in feet	Miles flown	No. of gusts exceeding 10 ft/sec
2663	Trans-northern U.S.A.	0- 5,000 5,000-10,000	77,600 35,400	1,980 510
3365	New York to Europe and South America	12,700 Mean	284,000	1,890
	Los Angeles to Honolulu and San Francisco	12,400 Mean	488,000	4,550
	Trans-northern U.S.A.	13,500 Mean	235,000	2,450
3371	New York to Los Angeles	0- 5,000 5,000-10,000 10,000-20,000	59,800 58,800 16,600	4,200 1,610 320
3475	Trans-U.S.A. routes	0- 5,000 5,000-10,000 10,000-15,000 15,000-20,000 20,000-25,000	51,000 86,000 132,000 214,000 16,700	2,580 2,070 528 588 88
3483	Eastern U.S.A. routes	0- 5,000 5,000-10,000 10,000-15,000 15,000-20,000	48,000 63,000 81,000 40,000	2,910 950 656 65
3750	Feeder line routes in Rocky Mountains, U.S.A.	9,600 Mean 5,000 Mean	99,000 113,000	5,500 7,400

TABLE 4

Variation of gust frequency with altitude
U.S. data for gusts greater than 10 ft/sec

Mean altitude	Miles per gust
2,500 ft	18.2
7,500 ft	47.3
12,500 ft	119
17,800 ft	365

WT.2078.C.P.419.K3 - Printed in Great Britain

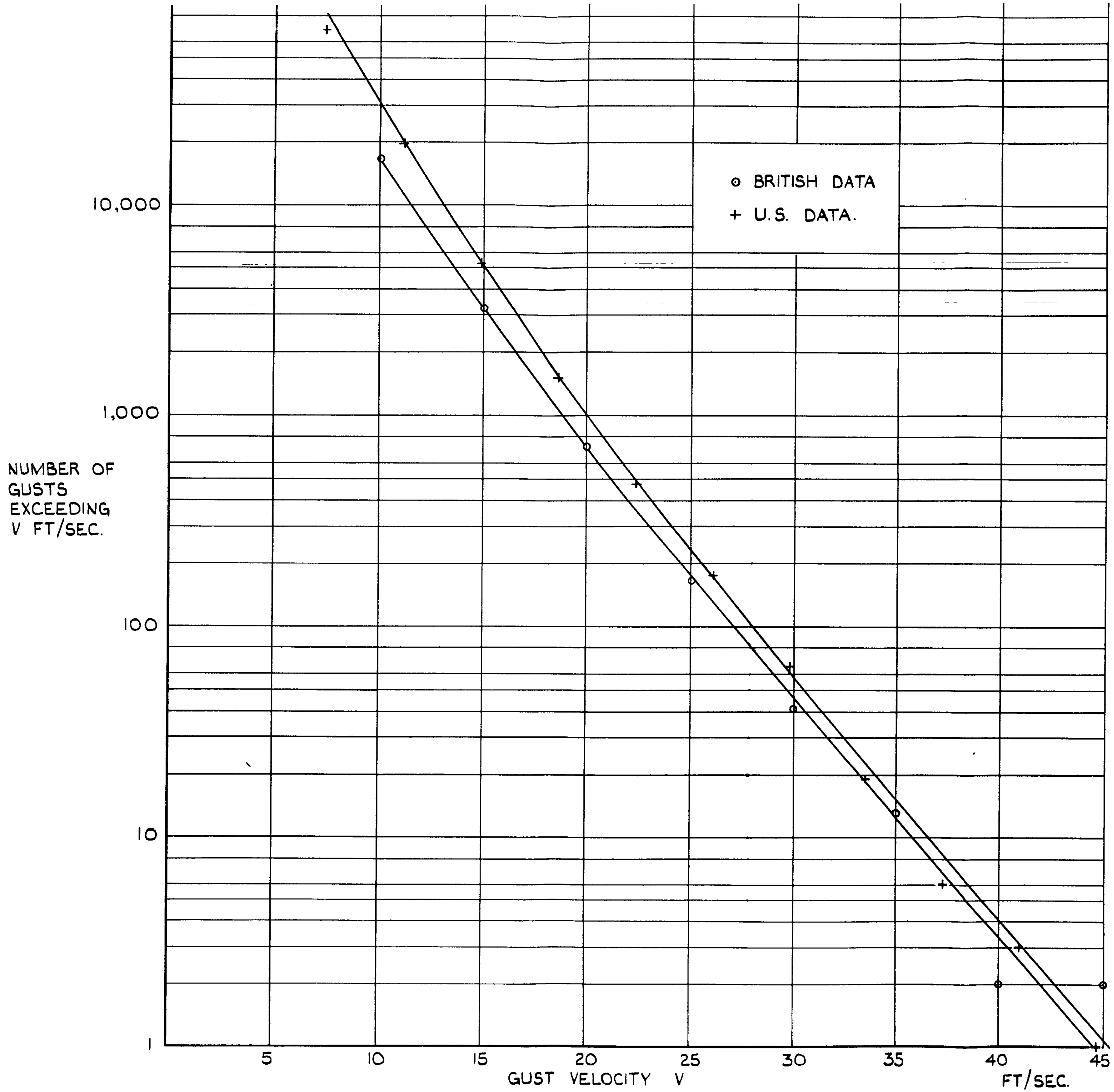
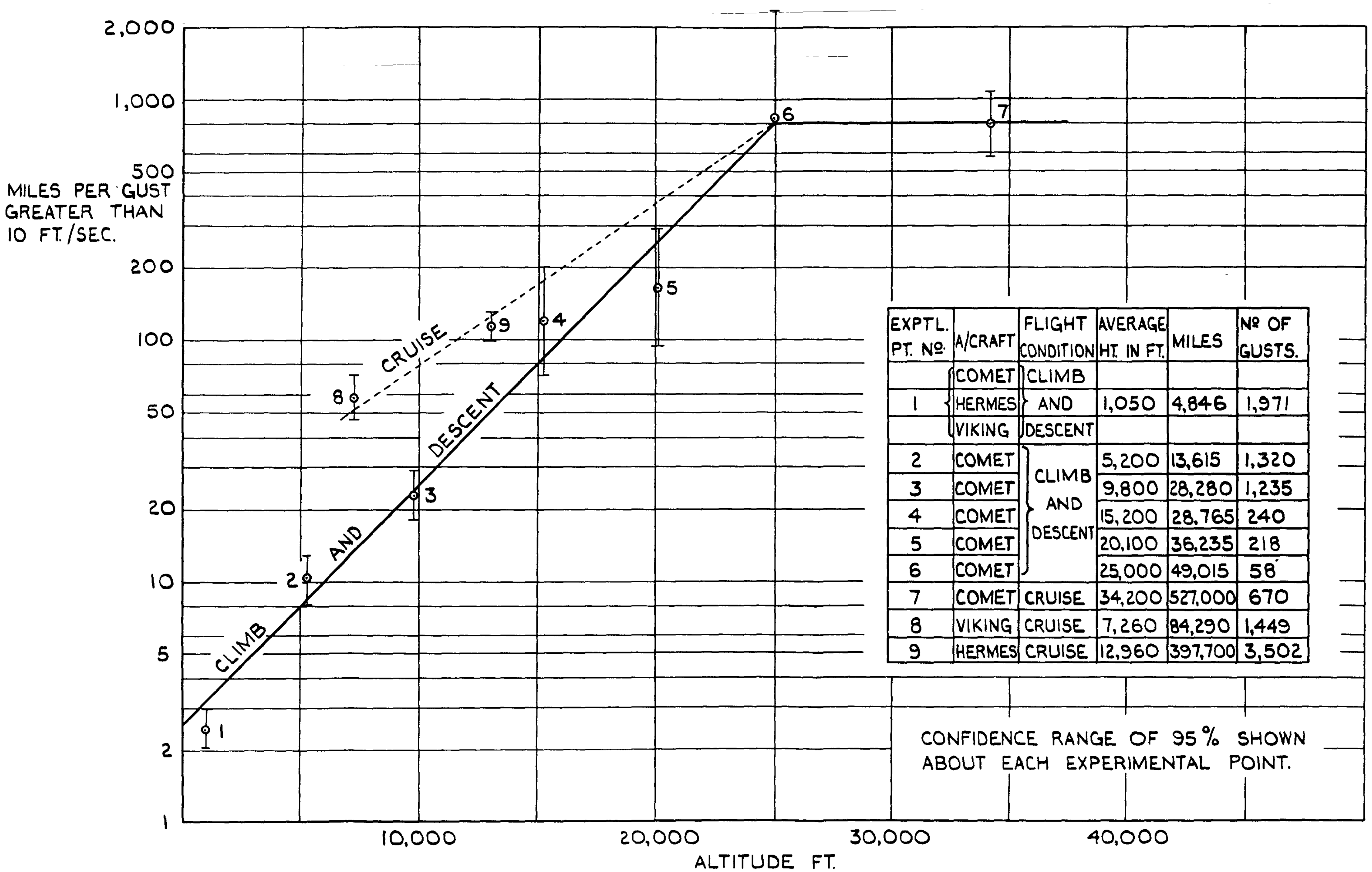


FIG. 1. CUMULATIVE DISTRIBUTIONS OF GUSTS.



EXPTL. PT. Nº	A/CRAFT	FLIGHT CONDITION	AVERAGE HT. IN FT.	MILES	Nº OF GUSTS.
1	COMET HERMES VIKING	CLIMB AND DESCENT	1,050	4,846	1,971
2	COMET	CLIMB AND DESCENT	5,200	13,615	1,320
3	COMET	CLIMB AND DESCENT	9,800	28,280	1,235
4	COMET	CLIMB AND DESCENT	15,200	28,765	240
5	COMET	CLIMB AND DESCENT	20,100	36,235	218
6	COMET	CLIMB AND DESCENT	25,000	49,015	58
7	COMET	CRUISE	34,200	527,000	670
8	VIKING	CRUISE	7,260	84,290	1,449
9	HERMES	CRUISE	12,960	397,700	3,502

FIG. 2. FREQUENCY OF OCCURRENCE OF GUSTS OF MAGNITUDE GREATER THAN 10 FT./SEC. AT DIFFERENT HEIGHTS.

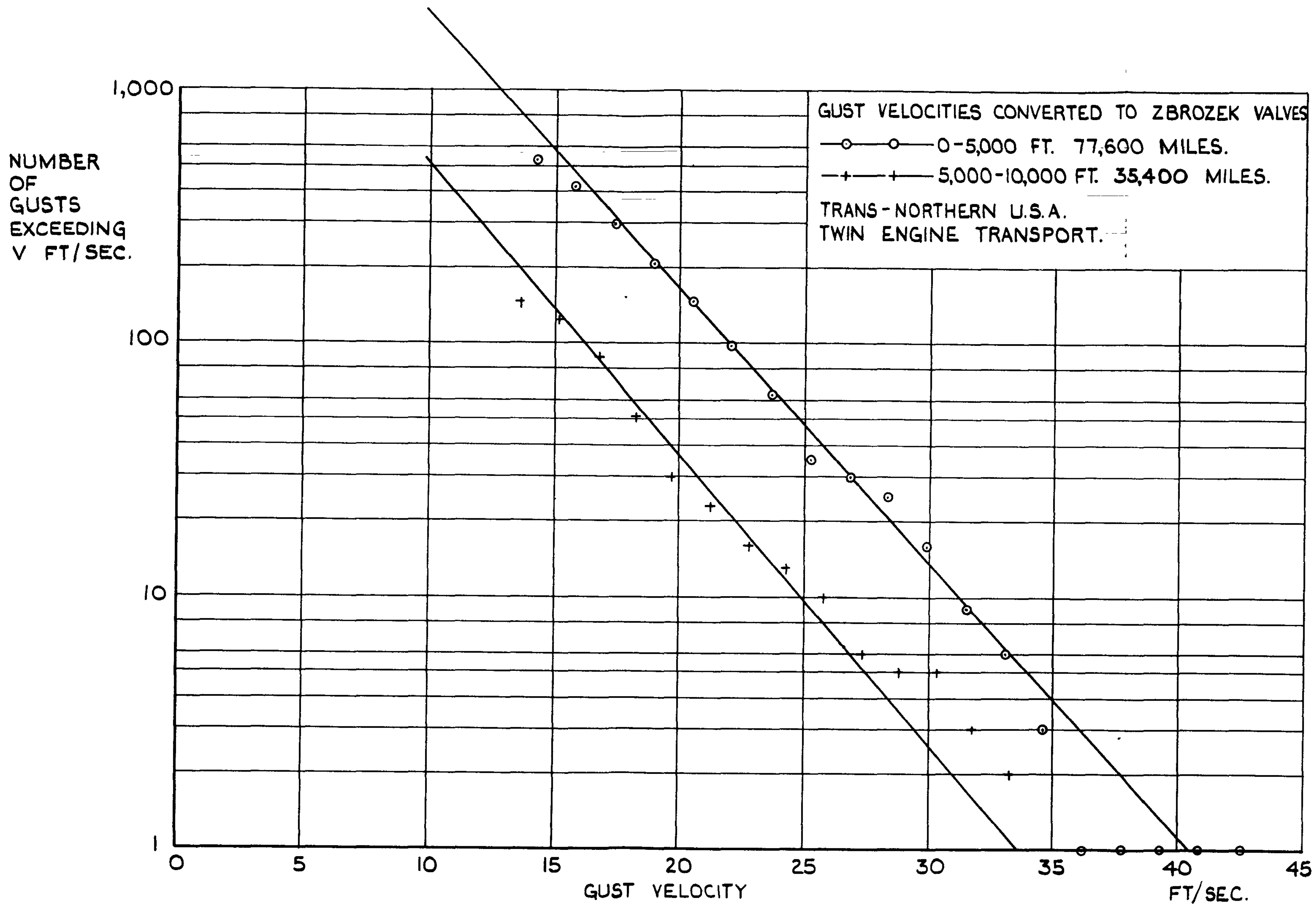


FIG. 3. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 2663.

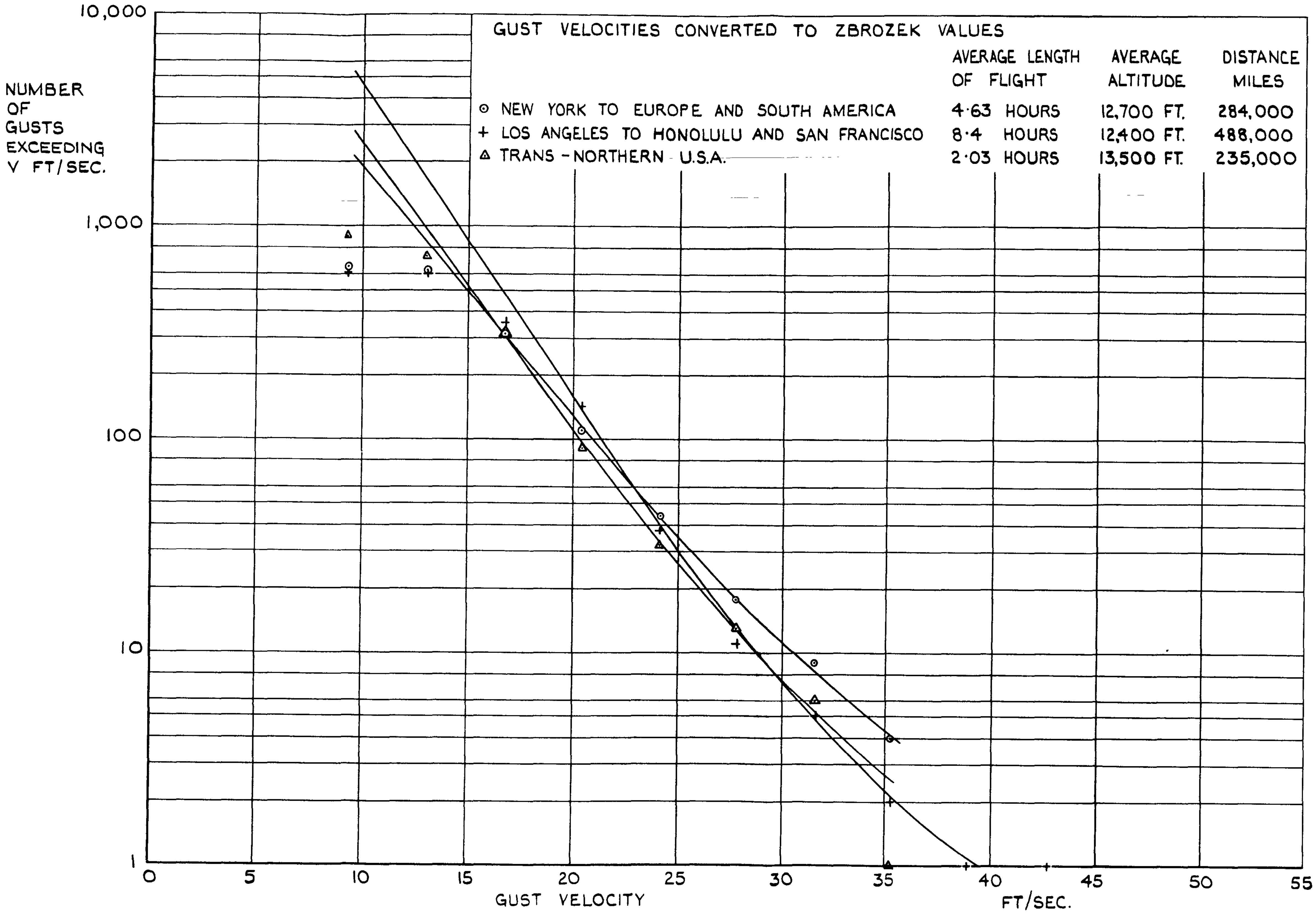


FIG. 4. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 3365.

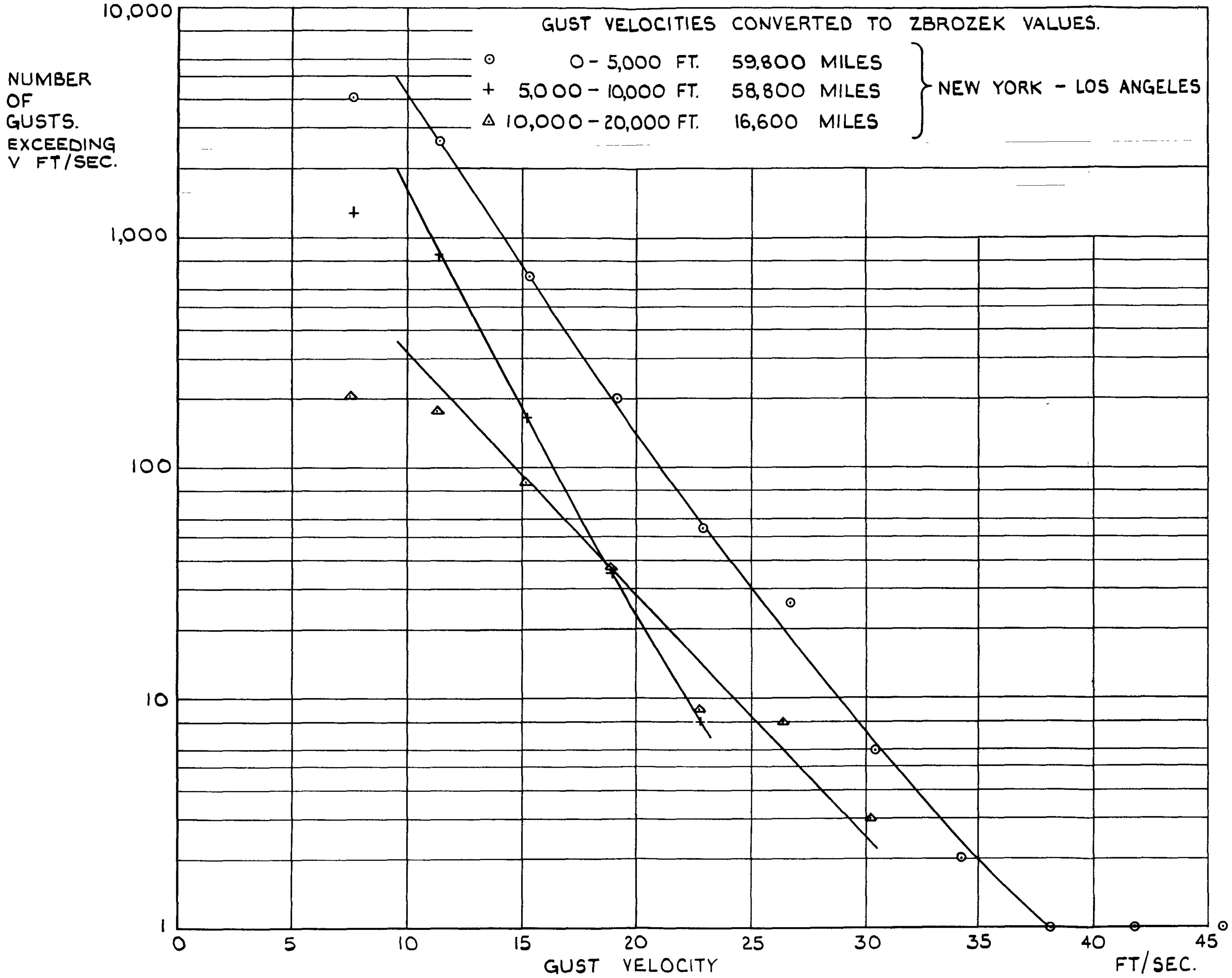


FIG. 5. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 3371.

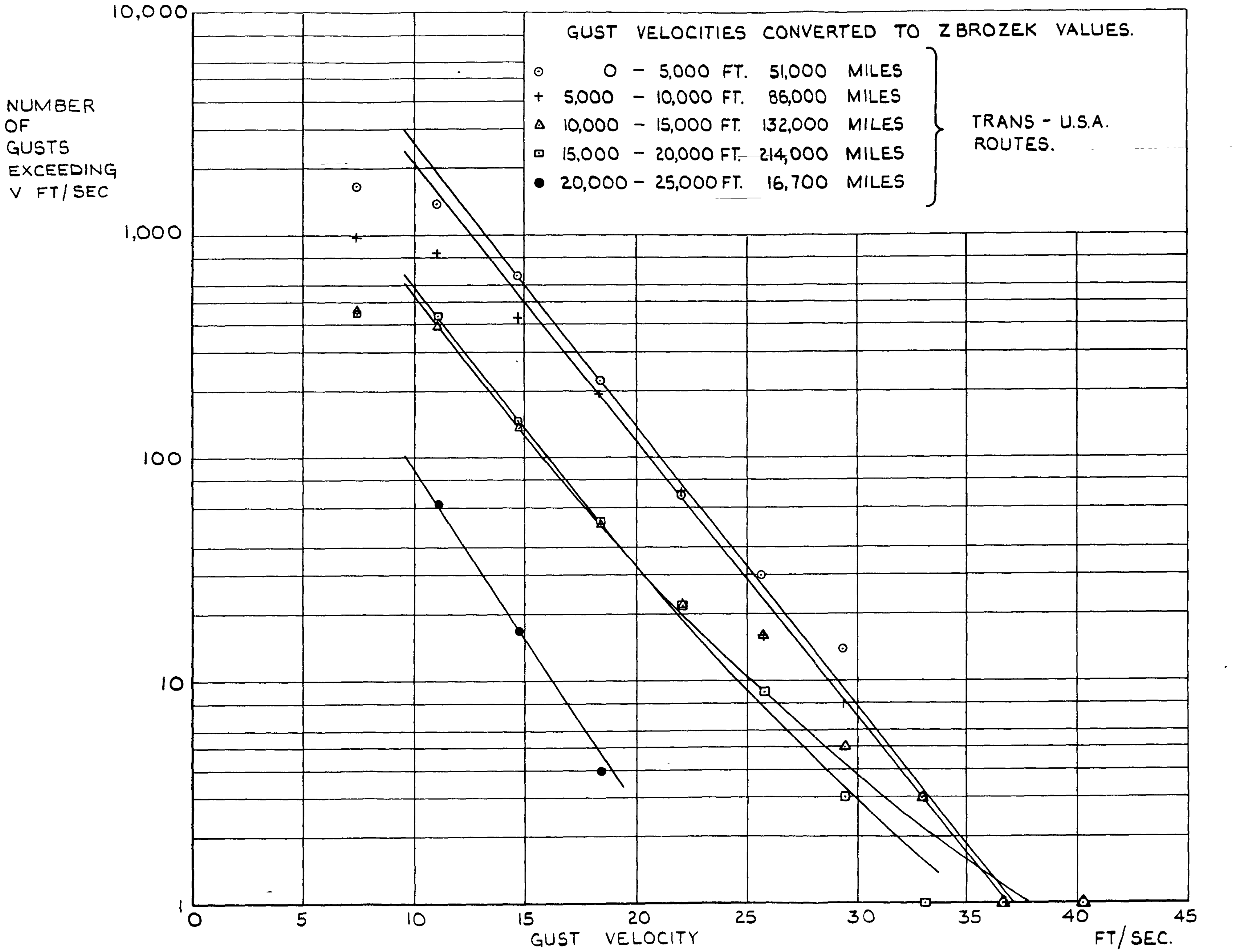


FIG. 6. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 3475

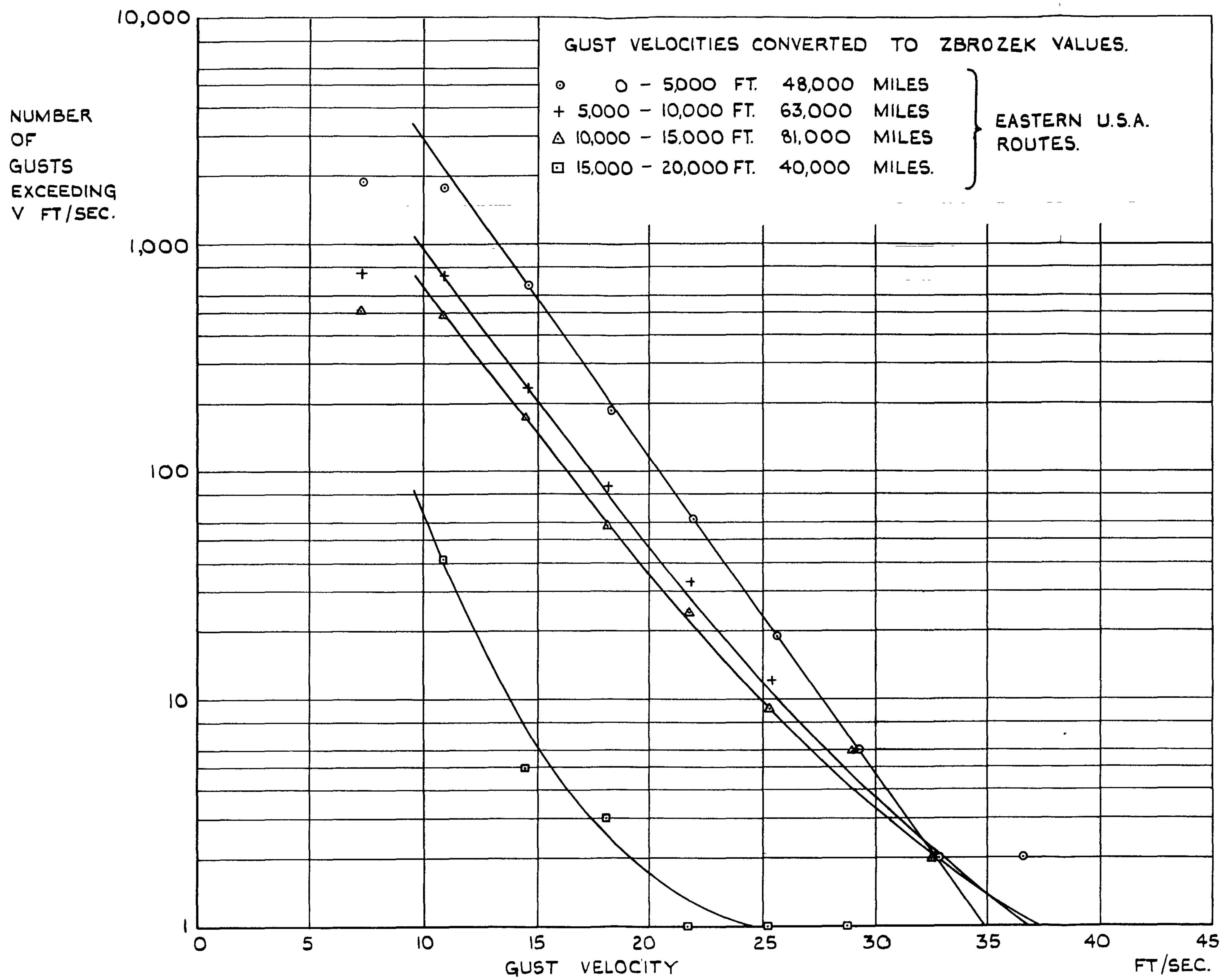


FIG. 7. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 3483.

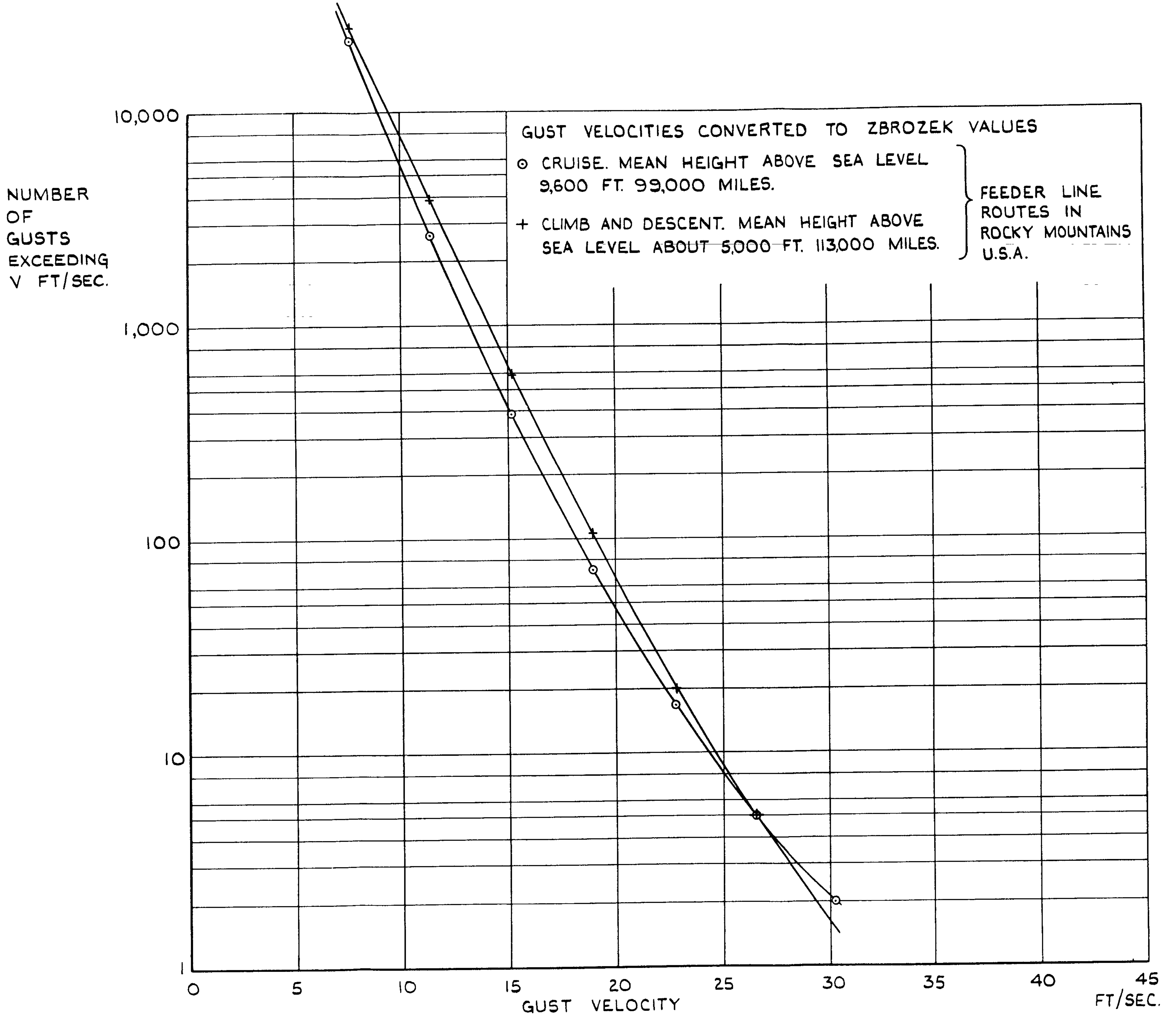


FIG. 8. CUMULATIVE DISTRIBUTION OF GUSTS, DERIVED FROM N.A.C.A.T.N. 3750.

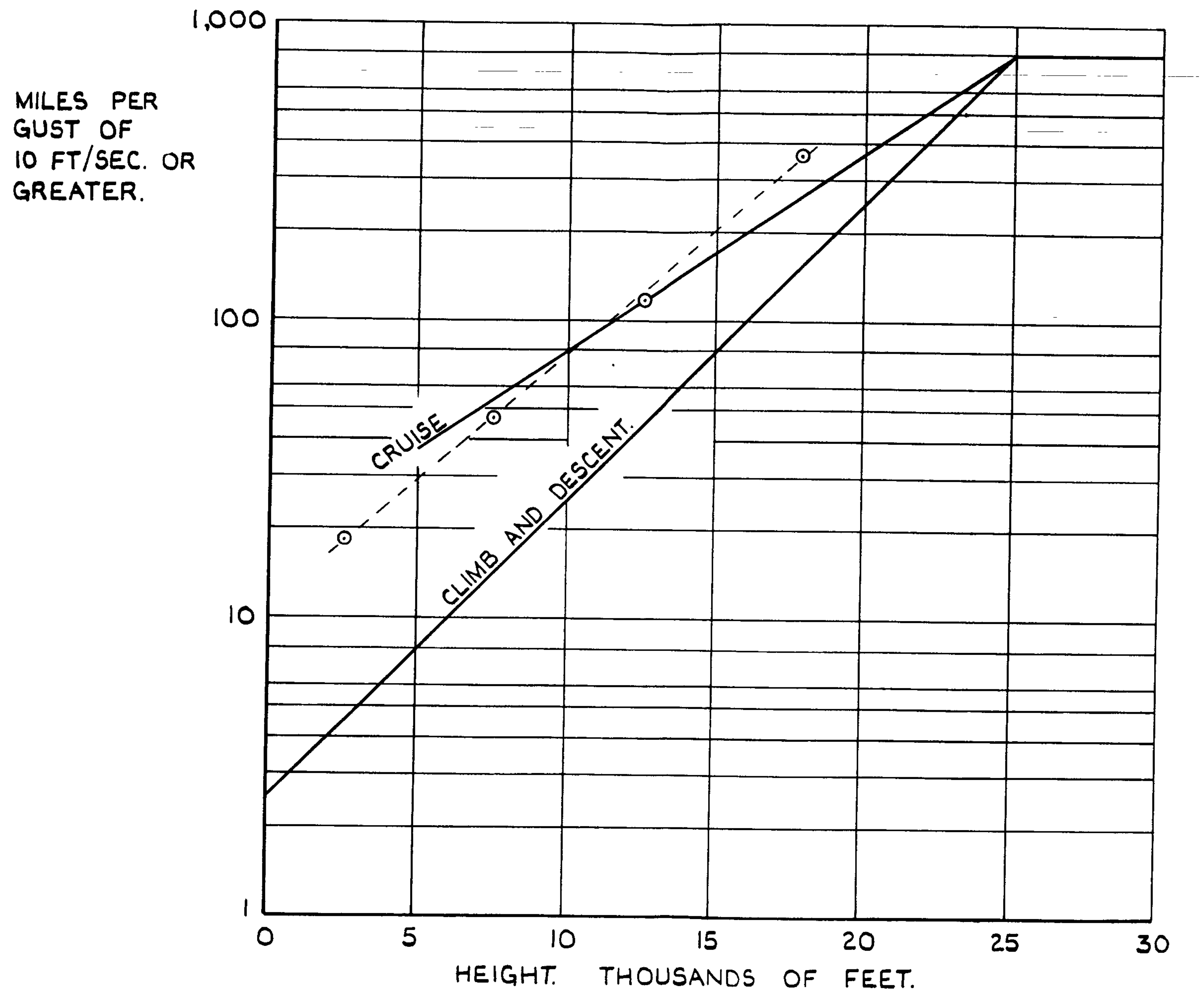


FIG. 9. A COMPARISON OF GUST FREQUENCIES DERIVED FROM U.S. DATA WITH THE RELATION GIVEN IN A.R.C.C.P. 324.

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London W.C.2
423 Oxford Street, London W.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
Tower Lane, Bristol 1
2 Edmund Street, Birmingham 3
80 Chichester Street, Belfast
or through any bookseller

Printed in Great Britain

S.O. Code No. 23-9011-19