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LOW ALTITUDE FLIGHT LOAD SPECTRA FOR LIGHT AIRCRAFT

BY
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LOW ALTITUDE FLIGHT LOAD SPECTRA FOR LIGHT AIRCRAFT

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SUMMARY

An analysis is presented of more than 1,300 hours flight loads records obtained from light aircraft engaged in low altitude terrain-following operations.

It is shown that continuous operation in the average low altitude environment reduces the estimated fatigue life by a factor of 15 to 1 when compared with the normal operating environment, and in the limiting condition imposed by pilot tolerance this factor is increased to 90 to 1.

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1.0 INTRODUCTION

Considerable attention has been directed in recent years to the problem of fatigue of light aircraft engaged in low altitude operations, particularly those that involve terrain-following.

The aircraft under consideration are those of 12,500 lb. gross weight or less, licenced in Canada and the United States in the Normal Category of Fedral Aviation Regulations, Part 23. At the present time, these regulations do not call for a fatigue evaluation of the airframe except in the special case of aircraft having pressurized cabins and, even in this special case, only the fatigue strength of the cabin structure itself must be proved by analysis, tests, or both.

However, amendment of the current regulations is being considered. In Notices of Proposed Rule Making 67-11 and 67-14, the fatigue requirements are extended to include those parts of the wing, wing carry-through, and attaching structure whose failure would be catastrophic, and these requirements, when adopted, will be applicable to all aircraft whether pressurized or not. In the explanation of the proposed change, it is stated that FAR.23 does not require an effective evaluation of the wing and associated structure. Service experience has shown that fatigue effects not adequately covered by present design practice can develop over a period of time.

An extensive program of low altitude flight load recording has been in progress in Canada for the past three years, during which time 1,330 hours of data have been accumulated. Although some of the data presented in this Report have been obtained from aircraft not within the scope of the FAR.23 licencing regulations, the results are considered generally applicable.

2.0 DESCRIPTION OF AIRCRAFT AND OPERATIONS

The types of aircraft used in the load recording program and their operational roles are given below. The first two were licenced under the provisions of Federal Aviation Agency Civil Aeronautics Manual 3 (Normal Category), the regulatory document preceding the current FAR.23; the other two aircraft were military types.

2.1 Aero Commander 680-E

This is a twin-engined (piston) high-wing aircraft of 7,500 lb maximum gross weight. Records totalling 283 hr were obtained from two aircraft, Canadian civil registrations CF-PDA and CF-ULZ. Both were employed on aerial magnetometer survey operations over mountainous terrain, involving contour flying at an altitude not exceeding 1,000 ft above the terrain. These operations were

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conducted over the Yukon Territory using CF-PDA based at Whitehorse, and over southern central British Columbia using CF-ULZ based at Kamloops and Williams Lake. Records for an additional 11 hr were obtained from CF-PDA during flight test operations in the Ottawa area.

2.2 Piper Aztec. PA-23-250

This is a twin-engined (piston) low-wing aircraft of 4,800 lb maximum gross weight. Records totalling 984 hr were obtained from three aircraft, Canadian civil registrations CF-GAS, CF-GAZ, and CF-NVV. All three aircraft were employed on aerial pipeline inspection operations over eastern and central Canada, from Montreal to the Saskatchewan-Alberta border. These operations involved contour flying at a mean altitude of 150 ft above the terrain, and not exceeding 200 ft.

2.3 Canadair Sabre 5

This is a single-engined (jet) low-wing aircraft of 16,500 lb maximum gross weight. Records totalling 43 hr were obtained during low altitude turbulence research operations, involving contour flying at an approximately constant altitude of 500 ft above the terrain. These operations were flown over a triangular course of 260 nautical miles total length, over the Gatineau hills north of Ottawa.

2.4 Lockheed T-33

This is a single-engined (jet) low-wing aircraft of 15,000 lb maximum gross weight. Records totalling 9 hr were obtained during low altitude turbulence research operations similar to those conducted with the Sabre, except that the altitude above terrain was 300 ft.

Basic aerodynamic and operational data for each of the above four aircraft are given in Table I. Details of the operations carried out are given in whole, or in part, in References 1 to 4.

3.0 INSTRUMENTATION

In all cases, records were obtained of vertical (normal) acceleration at, or near, the aircraft centre of gravity. A V-G-H recorder was installed in Aero Commander CF-PDA, and simple counting accelerometers in all other aircraft. Both types of instrument give cumulative counts of the number of times that pre-set vertical acceleration levels are reached or exceeded during flight. The V-G-H recorder gives additional information on indicated airspeed, pressure altitude, and time. This additional information has not been used in the analysis presented in this Report, other than to determine the mean indicated airspeed of the aircraft in which this type of recorder was fitted. Where simple counting accelerometers only were installed, the mean indicated airspeeds during

operations have been abstracted from the pilots' operating notes.

In all cases, manual or automatic switching was installed to ensure that accelerations would be recorded only when the aircraft was airborne.

4.0 OPERATING PROCEDURES

The following explanatory notes refer to general operating procedures.

4.1 Aero Commander

Take-off time on survey operations was restricted to early morning or evening (local time) when convective activity could be expected to be at a minimum. The operation was cancelled if the surface wind speed at take-off was greater than 15 knots. If the terrain over which the survey was to be carried out was more mountainous than the average, the allowable limiting surface wind speed was reduced to five knots. Some operations were abandoned after take-off because of increasing atmospheric turbulence.

All operations were flown under VFR conditions, and in particularly difficult areas both ceiling and visibility were required to be unlimited.

Flight test operations in the Ottawa area were flown during the afternoon and evening, between 1300 and 1700 hr local time.

Records from CF-PDA were obtained during the period May to August 1965, and those from CF-ULZ during April and May 1967.

4.2 Piper Aztec

Whenever possible, take-off times were restricted to early morning to avoid turbulence. Flights eastward from Toronto were somewhat later in the morning, so that the pilot would not be flying into the sun.

Average duration of a single patrol flight was 3 hr, 45 min.

CF-GAS was based at Toronto and covered the pipeline route north to Kapuskasing and east to Montreal, with a branch south to Niagara. CF-GAZ was based at Winnipeg and covered the route west to the Saskatchewan-Alberta border. CF-NVV was based at Fort William and covered the route across northern and central Ontario and west to Winnipeg. Although each aircraft remained generally within the prescribed operating area, a certain amount of overlap was inevitable.

Wind speed on patrol operations varied between zero and 26 knots, with a mean value of 11 knots.

Records from the three aircraft were obtained during the period June 1965 to June 1967.

4.3 Sabre 5 and T-33

Flights with these aircraft were carried out with the specific objective of obtaining information on aircraft response in low altitude continuous turbulence. The terrain was followed as closely as possible while avoiding rapid control movements in order to minimize pilot-induced accelerations.

Sixty-seven flights were made, averaging approximately 40 min. each. The first series of 24 flights was flown with the Sabre between August and October 1960, the second of 30 flights, also with the Sabre, between May and September 1961, and the third series of 13 flights with the T-33 between August 1962 and April 1963.

Take-off times on all flights were between 0900 and 1600 hr local time. Wind speed varied between zero and 18 knots, with a mean value of seven knots.

5.0 BASIC DATA

Acceleration-time histories (hours to reach or exceed one count at a given acceleration level) for each of the four aircraft have been plotted on Figures 1 to 3 as follows:

Figure 1 - Aero Commander: Survey and Flight Test Operations
Figure 2 - Piper Aztec: Normal and Limiting Roughness Flights
Figure 3 - Sabre 5 and T-33: Turbulence Research Operations

In all cases, first-order exponentials have been drawn as best-fit straight lines through the plotted points.

The term "limiting roughness" has been used to describe those pipeline patrol flights with the Aztec aircraft that the pilots had noted as approaching the limit of their tolerance in respect to aircraft response in severe continuous turbulence.

6.0 DATA ANALYSIS

On Figure 4, all the above acceleration-time histories have been plotted together for purposes of direct comparison. The difference in these histories is most marked. However, it is possible to reduce this as explained below.

6.1 Sabre and T-33 Operations

As noted previously, operations with these two aircraft were flown under conditions of minimum pilot input. Such manoeuvres as were necessary in order to follow the terrain were initiated and completed as gently as possible, and the acceleration increments resulting from these deliberate manoeuvres did not exceed an average value of ± 0.25g. Under these conditions, it may justifiably be assumed that all significant vertical accelerations were the result of vertical gust inputs. Equivalent vertical gust velocities may then be computed, using the standard rigid-body discrete-gust method of analysis; the equivalent vertical gust velocity in feet per second, U_e, being given by

$$U_e = \frac{2W \cdot \Delta_n}{\rho_o V_e SKa} \qquad (1)$$

where

W = aircraft weight (lb)

Δ_n = acceleration increment (g units)

ρ_o = density of air at sea level (slugs/ft^3)

V_e = equivalent airspeed (ft/sec)

S = gross wing area (ft^2)

K = gust alleviation factor

a = slope of lift curve/rad

A ramp-type gust, having a constant gradient distance of 100 ft, has been assumed.

Substitution of the appropriate values of the constants into the equivalent gust equation gives

For the Sabre $U_e = 18.6\Delta_n$, and a 10-ft/sec gust causes an acceleration increment of 0.54g

For the T-33 $U_e = 13.5\Delta_n$, and a 10 ft/sec gust causes an acceleration increment of 0.74g

Gust frequencies, in terms of the nautical miles flown to reach or exceed one gust cycle at various equivalent gust velocities, are shown on Figure 5. The term "gust cycle" means one positive (up) gust followed by one negative (down) gust. First-order exponentials have again been drawn as best-fit straight lines through the experimental points. The individual gust spectra shown by the

broken lines are practically coincident, and may conveniently be represented by the single solid line, which is that derived from summation of all results. It will be noted that the distribution of positive and negative gusts is, to all intent, symmetrical. The marked difference in frequency of occurrence of accelerations of the same magnitude results almost entirely from the difference in response of these two aircraft to a gust of the same equivalent velocity.

Although the Sabre and T-33 were flown at different altitudes, the greater part of the records was obtained from the Sabre operating at an altitude of 500 ft. Thus this spectrum is hereafter referred to as a 500-ft gust spectrum.

The above gust spectrum may then be used to determine the vertical acceleration response of a reference aircraft having the following assumed characteristics typical of the category of aircraft considered in this Report.

Wing loading	- 25 lb/ft^2
Slope of lift curve	- 5.00 per rad
Equivalent airspeed	- 130 knots
Gust alleviation factor	- 0.70

This gives $U_e = 27.4\Delta_n$, and a 10-ft/sec gust causes an acceleration increment of 0.36g.

6.2 Aero Commander and Aztec

The nature of the general operations with these two aircraft is such that the recorded accelerations will inevitably contain a relatively large number of counts resulting from deliberate pilot-induced manoeuvres, which cannot be separated from those due to vertical gust input. Nevertheless, the frequency of occurrence of recorded accelerations, whether resulting from manoeuvres or from turbulence, is properly considered as space-dependent rather than time-dependent. Therefore, this variable is represented more accurately by plotting frequency of occurrence in terms of nautical miles flown to reach or exceed one count, against magnitude of the normal acceleration. This eliminates the effect of differences in equivalent airspeed.

The transformed acceleration spectra derived from the Aero Commander and Aztec records have been plotted on Figure 6, together with that derived from the 500-ft gust spectrum of Figure 5 applied to the typical reference aircraft.

This completes the basic data analysis.

7.0 DERIVED GUST SPECTRA

As noted in paragraph 6.1 above, the gust spectrum derived from the

combined Sabre and T-33 records, and shown by the solid line of Figure 5, is considered representative of the turbulence characteristics at an altitude of 500 ft above terrain. Gust spectra at altitudes of 150 ft and 1,000 ft above terrain may be derived from the negative acceleration records obtained during the Aztec limiting roughness flights and the Aero Commander flight test operations. The assumption that these records will not contain any significant numbers of counts resulting from deliberate pilot input is justified from the following considerations.

(a) During the Aztec limiting roughness flights, it was confirmed by one of the pilots that deliberate manoeuvres involving significant negative accelerations would not be induced while flying in continuous turbulence at such a low altitude.

(b) It is known that the Aero Commander flight test operations that are considered here were flown with minimum negative acceleration input from the pilot.

Positive acceleration records from the Aztec and Aero Commander aircraft during the operations detailed in (a) and (b) above have not been considered, as it is assumed with some certainty that these will contain a significant number of counts resulting from pilot input.

Substitution of the appropriate constants for these two aircraft into the equivalent gust equation gives

For the Aztec $U_e = 29.9\Delta_n$, and a 10-ft/sec gust causes an acceleration increment of 0.33g

For the Aero Commander $U_e = 29.2\Delta_n$, and a 10-ft/sec gust causes an acceleration increment of 0.34g

The symmetrical distribution of positive and negative gusts established from the Sabre and T-33 records in the 500-ft case is assumed to apply also at altitudes of 150 ft and 1,000 ft.

The resulting spectra at altitudes of 150, 500, and 1,000 ft above terrain are shown on Figure 7, in terms of the nautical miles flown to reach or exceed one positive or negative gust of given velocity. It must be noted that this is one-half the distance flown per gust cycle.

The equality of slope of the three lines indicates that the relative frequency of occurrence of gusts of different velocities does not change with increasing altitude up to an altitude of 1,000 ft above terrain.

8.0 DISCUSSION

8.1 Combined Gust and Manoeuvre Spectra

Records from the flight test operations with the Aero Commander and the limiting roughness flights with the Aztec, while being of interest, are not sufficiently large samples to be statistically significant, since the number of hours of records obtained in each case was only 3.7 and 2.6 percent of the respective totals. However, it is worth noting that approximately 12 percent of all pipeline patrol flights exhibited acceleration frequencies of occurrence between the average and the most severe case defined by the limiting roughness spectrum.

For the purpose of establishing a combined gust and manoeuvre spectrum representative of average low altitude terrain-following operations, which may be used for fatigue life estimation, records from general operations with the Aero Commander and Aztec aircraft may be combined. This spectrum is shown on Figure 8, and identified as the "low altitude - average case". The "low altitude - most severe case" spectrum derived from the Aztec limiting roughness flights is shown for comparison.

Figure 8 also shows a third spectrum, identified as the "normal operating case". This has been derived from point-to-point ferry flights with both Aero Commander aircraft between Ottawa and the bases from which the survey operations were conducted, and may be considered as representative of the flight loads imposed on this category of aircraft in what may be termed the "normal design operating case". Mean cruise altitude during these flights was 8,000 ft. Although the records obtained from the Aero Commander aircraft totalled only 42 hr, the data are confirmed by additional records totalling 119 hr, obtained during scheduled operations with a large military transport aircraft over generally similar terrain and routes, also at a mean cruise altitude of 8,000 ft.

The equations of the straight-line spectra of Figure 8 have the general form

$$D = A \cdot \exp(kG) \qquad (2)$$

where D = distance flown to reach or exceed one count of given magnitude (nautical miles)

A, k = constants

G = value of the normal acceleration (g units)

For the purpose of fatigue life estimation, the cumulative number of counts in 100 hr of operation at any given acceleration level is

$$N = \frac{100V}{A \cdot \exp(kG)} \qquad (3)$$

where V = mean aircraft speed (knots)

Values of the constants are

		A	k
Normal Operating Case	Positive	5.9123×10^{-6}	11.2489
	Negative	1.3864×10^{5}	-12.4086
Low Altitude - Average Case	Positive	2.4232×10^{-5}	8.0443
	Negative	3.1243×10^{3}	-10.2357
Low Altitude - Most Severe Case	Positive	5.4413×10^{-5}	6.4112
	Negative	3.2902×10^{2}	-9.9927

Certain reservations should be made concerning use of the above spectra.

For the class of aircraft considered, changes in lift curve slope and gust alleviation factor from one type to another will be small. Then, if the effect of these changes is neglected, the response of an aircraft to a vertical gust, in terms of the acceleration increment experienced, is directly proportional to airspeed and inversely proportional to wing loading. However, it is generally true that small aircraft having a low cruising speed also have a low wing loading and, as the size and cruising speed increase, the wing loading also increases. Thus, these effects tend to cancel out.

If a given flight path is followed during operations involving contour flying, then, other things being equal, the acceleration increment will be proportional to the square of the airspeed.

In the analysis of flight load spectra, it is frequently assumed that negative acceleration increments result entirely from vertical gust input, and the positive manoeuvre load spectrum is derived by subtraction on the further assumption that the positive and negative gust distributions are symmetrical.

During general low altitude operations of the nature described in this Report, the assumption that all negative acceleration increments result from vertical gust input is not valid. For example, it has been calculated that accurate terrain-following of some of the contours depicted in Reference 1, at an airspeed of 120 knots, would produce acceleration increments of the order of ± 0.60g.

In this connection, it has been noted previously that terrain-following flights with the Sabre and T-33 aircraft were conducted under controlled conditions in which the average acceleration increment resulting from pilot input was of the order of ± 0.25g. This corresponds to an average equivalent vertical gust velocity of ± 4 ft/sec, which, when applied to the typical reference aircraft considered representative of the FAR.23 Normal Category (see para. 6.1), produces an acceleration increment of ± 0.14g. This is below the cut-off point of any practical spectrum that may be used to simulate the fatigue loading of this category of aircraft.

As far as the low altitude operations are concerned, there is no rational basis on which the gust and manoeuvre loads may be separated, and it is therefore impossible to make any allowance for changes in the magnitude of the acceleration increments due to (a) gusts, and (b) manoeuvres that may result from changes in airspeed.

While the manoeuvre loads associated with following a given terrain profile at a given airspeed may be considered invariant, the gust loads contribution to the combined spectrum will be highly dependent upon meteorological conditions and time of day. The survey and pipeline inspection operations described herein were flown under generally favourable meteorological conditions and at times of day when convective activity was at a minimum.

The low altitude-average case spectrum of Figure 8 should therefore be considered representative of the average conditions to be expected for the type of operations described. It should be noted that the flight loads records from which this spectrum has been derived include those from the Aztec "limiting roughness" flights. As stated earlier, flights in this latter category form only a small percentage of the whole, and it has been checked that their exclusion from the total makes no significant difference.

The low altitude - most severe case spectrum represents conditions that may be encountered for approximately 2.5 percent of the total flight time. Any marked increase in the percentage total flight time spent in the "limiting roughness" condition (for example, to 10 percent) has a significant effect upon the overall load spectrum, and this should be taken into account.

8.2 Gust Spectra up to 1,000 Feet

The variation of 10-ft/sec gust frequency with altitude derived from the low altitude operations described in this Report is shown on Figure 9, and compared with similar data extracted from References 5 and 6.

Climb and descent points for civil transport operations have been taken from Table I of Reference 6, and those for operations over flat and hilly desert from Table III of the same reference.

At all altitudes up to 1,000 ft above terrain, the mean frequency of

occurrence of gusts equalling or exceeding an equivalent velocity of ± 10 ft/sec from the present analysis is approximately four times more severe than that obtained from Reference 5, and from two to four times more severe than that obtained from the desert operations described in Reference 6.

The curve of Reference 5 was derived almost exclusively from operations with civil transport aircraft on scheduled routes in Europe. The three points at 200 ft, 400 ft, and 600 ft, for operations over flat and hilly desert, were obtained from three aircraft flying almost simultaneously at these heights. However, it should be noted that the ground referred to as "hilly desert" was more in the nature of an eroded plateau than of a rolling, hilly character.

Figure 10 shows the cumulative relative frequency distributions of gusts of different velocities for each of the four general categories given on Figure 9, in all cases normalized with respect to 1,000 gusts at an equivalent vertical velocity of 10 ft/sec. The frequency distribution of gusts derived from the present analysis is practically coincident with that given in Reference 5 up to a gust velocity of 25 ft/sec, and the following formula, given in this Reference, may be used in combination with Figure 9 for determination of the number of miles per gust at velocities other than 10 ft/sec

$$N = 27800 \exp(-0.3441 U_e) + 878.2 \exp(-0.2081 U_e) \qquad (4)$$

where U_e = equivalent gust velocity (ft/sec)

and $N = 1000$ at $U_e = 10$ ft/sec

8.3 Gust Spectra at 8,000 Feet

Figure 11 shows the gust spectrum derived from ferry and transport operations in Canada compared with the 8,000-ft spectrum derived from Reference 5.

It will be observed that the frequency of occurrence of gusts of the same velocity is somewhat lower than that of Reference 5. The major factor contributing to this is the effect of the longer average stage length in the Canadian operations, this being from one-and-one-half times to twice as long as the European stage length.

9.0 PILOT RESPONSE IN CONTINUOUS TURBULENCE

During pipeline patrol operations described by the Aztec pilots as approaching the limit of their tolerance, accelerations having an amplitude of 0.70g about a mean of 1.10g were encountered at a frequency of 20 cycles per

hour, with maximum positive and negative loads of 2.67g and -0.10g respectively. During the Sabre flights, accelerations of the same amplitude about a mean of 1.00g were encountered at a frequency of 160 cycles per hour, with maximum positive and negative loads of 2.83g and -0.74g respectively.

Aside from tiredness after two trips in one day, the Sabre pilots experienced no serious physiological problems and were able to maintain complete control of the aircraft at all times.

The marked difference of opinion between the Aztec and Sabre pilots as to the nature of a "rough ride" is thought to reflect the psychological and physiological differences between the two operations. The Aztec pilots were subjected to continuous severe turbulence for periods in excess of three hours, whereas the Sabre flights were of 40-minute duration only. On pipeline patrol, the Aztec pilots were confronted with two major tasks at a clearance altitude of 150 ft - the Sabre pilots with one only at a clearance altitude of 500 ft. Furthermore, an excursion to 2.67g with the Aztec represents 60 percent of limit load, whereas an excursion to 2.83g with the Sabre is only 29 percent of limit load.

It is of interest to note that, during one flight with the T-33, maximum positive and negative loads of 3.20g and -1.37g were attained, and during the same flight, accelerations having an amplitude of 0.70g were encountered at a frequency of 1,300 cycles per hour. This gives a mean spacing between 10 ft/sec gusts of approximately 0.16 nautical miles and less than two seconds in time. The pilot reported that it was very rough, and on the boundary of controllability. Normal navigational tasks were impossible. Lateral "snaking" in side gusts was also encountered. Although the gust spacing during this flight was approximately equal in distance to that encountered in the limiting roughness Aztec operations, the time spacing differed by a factor of 4.5 to 1.

10.0 EFFECT OF LOW ALTITUDE OPERATIONS ON FATIGUE LIFE

Estimates of aircraft fatigue life have been made based on the three load spectra of Figure 8, assuming various mean stresses in the wing main spar and appropriate stress increments per "g". An aircraft speed of 100 knots has been assumed in all cases.

Fatigue lives have been estimated, using the Miner-Palmgren hypothesis of cumulative damage, together with the basic S-N curves for aluminum alloy wings and tailplanes of Reference 7. These are reproduced on Figure 12.

Figure 13 shows typical 100-hr damage curves for a mean stress of 10,000 lb/in^2 for each of the three operational cases, and Figure 14 shows the estimated unfactored fatigue life in hours plotted against stress per "g", again for each of the three operational cases. Comparison of these curves with those previously published in Reference 8 shows a slight decrease in estimated fatigue life in all cases and for all stress levels. In the previous analysis, a 1.0g stress

increment had been assumed equal to the mean stress. This assumption is strictly valid for symmetrical load spectra only. All load spectra of Figure 8 have a positive bias, in that the mean load is not constant and is not equal to 1. 0g. For example, in the low altitude average case, the mean load over a range of load amplitudes between 0. 20g and 2. 00g varies between 1. 04g and 1. 27g.

The 100-hr proportional damage has been re-calculated for bandwidths of 1,000 lb/in^2, in each operational case assuming a constant mean load that is, in effect, the average of the means in each bandwidth. The corresponding stress per "g" has been taken as the assumed mean stress divided by the mean load. Figure 15 shows the effect of variation in stress per "g" on estimated fatigue life for a constant mean stress.

In Reference 8, it was stated that exposure to the average low altitude spectrum reduced the fatigue life by a factor of approximately 10 to 1 when compared with the normal operating case, and in the most severe case, this factor increased to approximately 50 to 1. As a result of the damage re-calculations, these factors are now increased to approximately 15 to 1 and 90 to 1 respectively.

11. 0 CONCLUDING OBSERVATIONS

The low altitude average case (combined gust and manoeuvre spectrum shown on Fig. 8) has been derived from low altitude terrain-following operations totalling 1,270 flight hours and 158,000 nautical miles, and is considered to be statistically representative of the flight loads to be expected during such operations.

The limiting roughness spectrum, although derived from analysis of less than 30 hr of data, is probably representative of the most severe conditions likely to be encountered during low altitude operations of the nature described in this Report.

The low altitude gust spectrum of Figure 9 is also considered representative of the most severe conditions likely to be encountered in continuous turbulence. This may be used to determine the response of an aircraft in terms of the normal acceleration increment resulting from vertical gust input, to which manoeuvre loads may, or may not, be added as dictated by the operating requirements.

The normal operating spectrum of Figure 8 is considered representative of the flight loads to be expected in the normal operational role of aircraft licenced in the Normal Category of FAR.23 - that is, unscheduled short and medium haul passenger and cargo transport operations.

Although there is wide variation in the aerodynamic and operating characteristics of aircraft in this category, the acceleration response to a given vertical gust input remains virtually constant over the whole range. Taking the

Cessna 172 and the De Havilland Twin Otter as representing the extremes of the range (Cessna 172: 2,500 lb gross weight, 102 mph cruising speed; Twin Otter: 11,000 lb gross weight, 156 mph cruising speed), it has been calculated that the acceleration increments resulting from a 10 ft/sec gust will be 0.39g for the Cessna and 0.37g for the Twin Otter.

The very large reduction in comparative fatigue life of an aircraft engaged in low altitude terrain-following operations is to be particularly noted, and emphasizes the need of using realistic spectra in fatigue life estimates.

However, fatigue life prediction is at best an art, and the estimates given in this Report are subject to a number of inaccuracies, prime amongst which is the assumption that the S-N curves used are regarded as representative of so-called "typical structures". Furthermore, the estimates made are based on flight loads only, and do not take into account the effect of loads imposed upon the structure during the ground-air-ground cycle.

12.0 RECOMMENDATIONS

In spite of the limitations inherent in fatigue life prediction, it is recommended that the three load spectra shown on Figure 8 should be used in estimating the average unfactored fatigue life of unpressurized light aircraft licenced in the Normal Category of FAR. 23.

Consideration must be paid to the estimated percentage total operating time spent in each of the three operational roles.

The curves of estimated unfactored fatigue life shown in Figure 14 assume 100 percent utilization in each role for a constant mean airspeed of 100 knots. If the percentage utilization in each role is known, or can be estimated, together with the corresponding mean airspeeds, and if the maximum stress per "g" in the wing main spar is also known, these curves may be used to arrive at preliminary estimates of the percentage fatigue life remaining after any given number of hours total operating time.

For example, if in 1,000 hr total operations, the utilization and mean airspeed in each of the three roles is:

Normal operating case	- 55 percent at speed V_1
Low altitude average case	- 30 percent at speed V_2
Low altitude most severe case	- 15 percent at speed V_3

then the percentage fatigue life remaining at the end of 1,000 hr operations is

$$100 \left\{ 1 - \left[\frac{5.5V_1}{A} + \frac{3.0V_2}{B} + \frac{1.5V_3}{C} \right] \right\}$$

where A, B, and C are the 100 percent utilization estimated fatigue lives at 100 knots from Figure 14 for the respective operational roles at the measured or design maximum stress per "g".

At the utilization given, assuming a maximum stress per "g" of 10,000 lb/in^2 and V_1, V_2, and V_3 equal to 145, 125, and 110 knots respectively, it will be found that the fatigue life remaining after 1,000 hr total operations is 60.5 percent.

13.0 ACKNOWLEDGEMENTS

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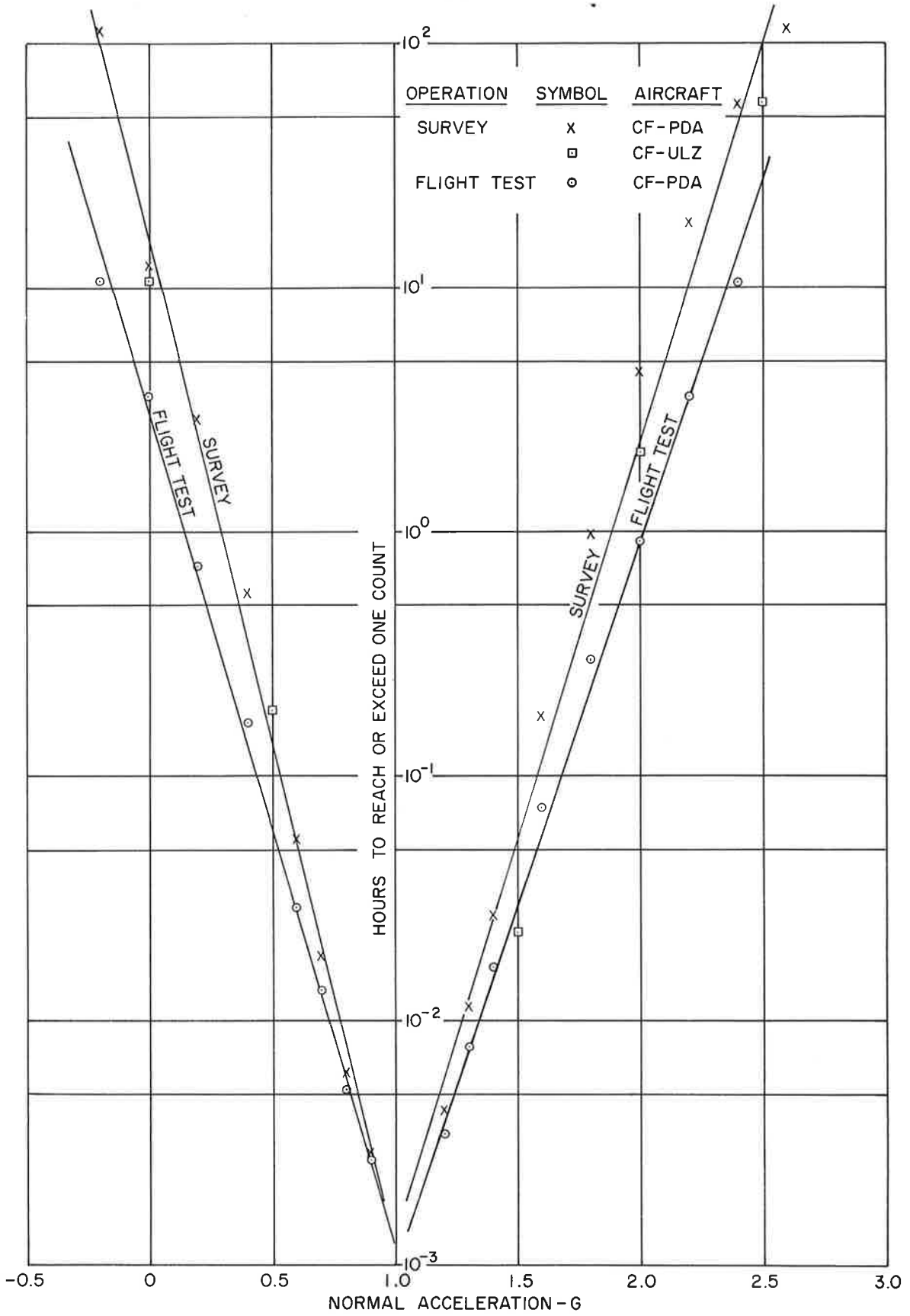
TABLE I

BASIC AERODYNAMIC AND OPERATING DATA

Aircraft	Mean Operating Weight (lb)	Gross Wing Area	Mean Aerodynamic Chord (ft)	Slope of Lift Curve Per Rad	Aspect Ratio	Mean Operating Speed (kt)	Mean Operating Altitude (ft)
Aero Commander	7000	255.0	5.84	4.96	9.45	140	1000
Aztec	4500	207.6	5.58	4.90	6.80	115	150
Sabre V	13830	302.3	8.50	4.02	4.56	400	500
T-33	12500	234.8	6.72	6.73	6.00	400	300

Notes: Aero Commander operating weight and speed given are for survey operations. During flight test operations, these were 6,700 lb and 134 knots respectively.

All operating altitudes are above terrain.



ACCELERATION - TIME HISTORIES
AERO COMMANDER

FIG. 1

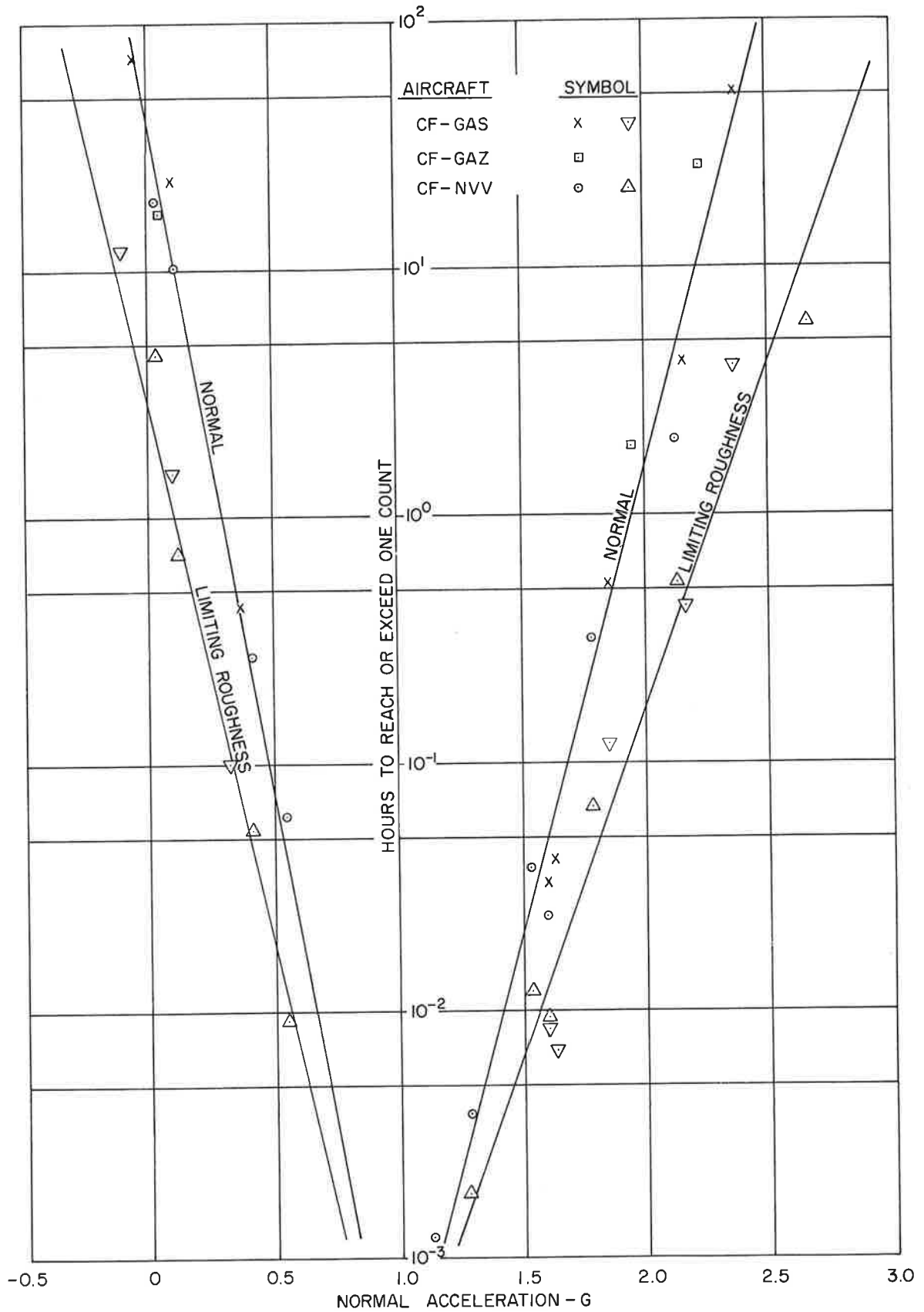


FIG. 2

ACCELERATION - TIME HISTORIES
PIPER AZTEC

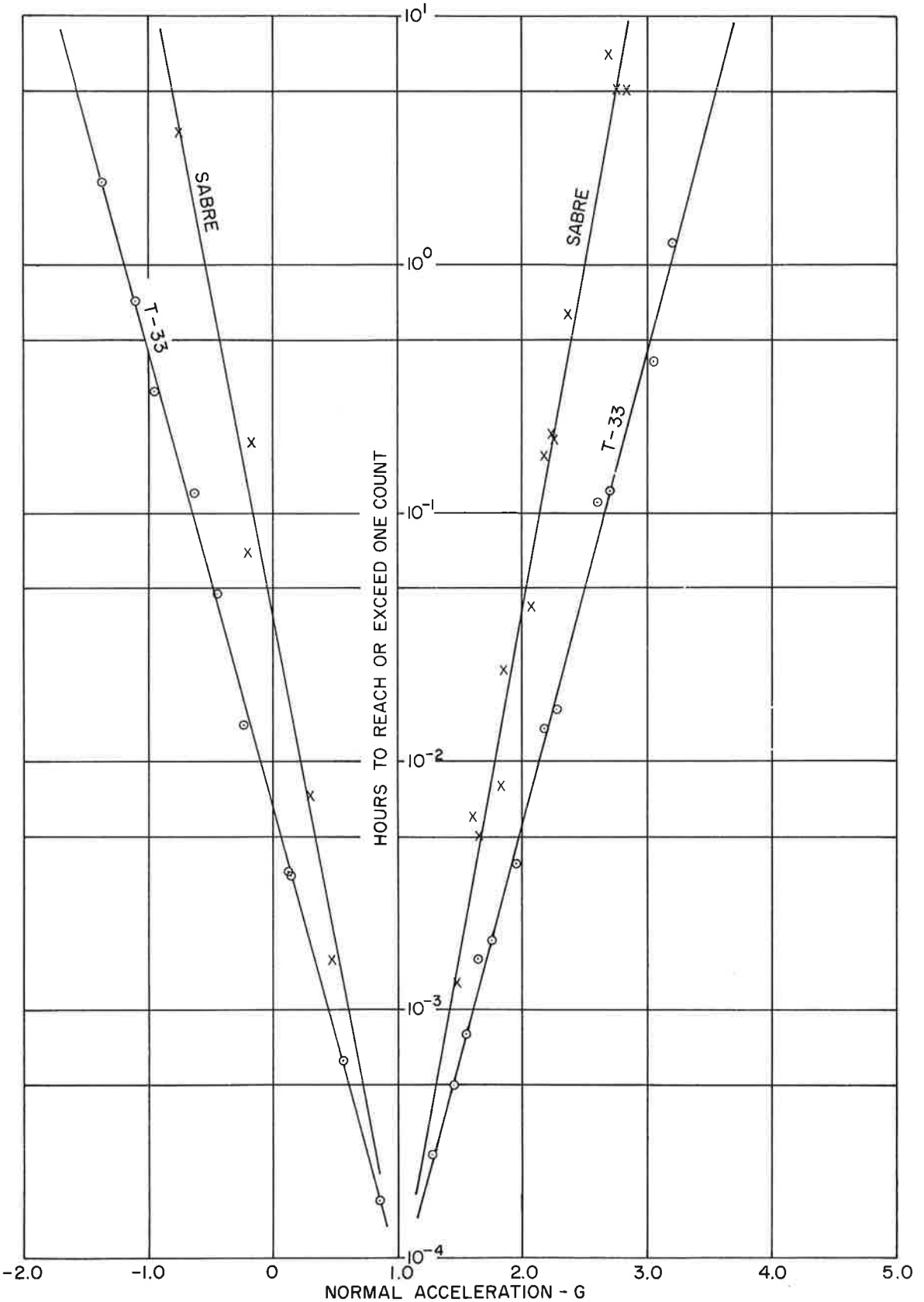


FIG. 3

ACCELERATION - TIME HISTORIES
SABRE AND T-33

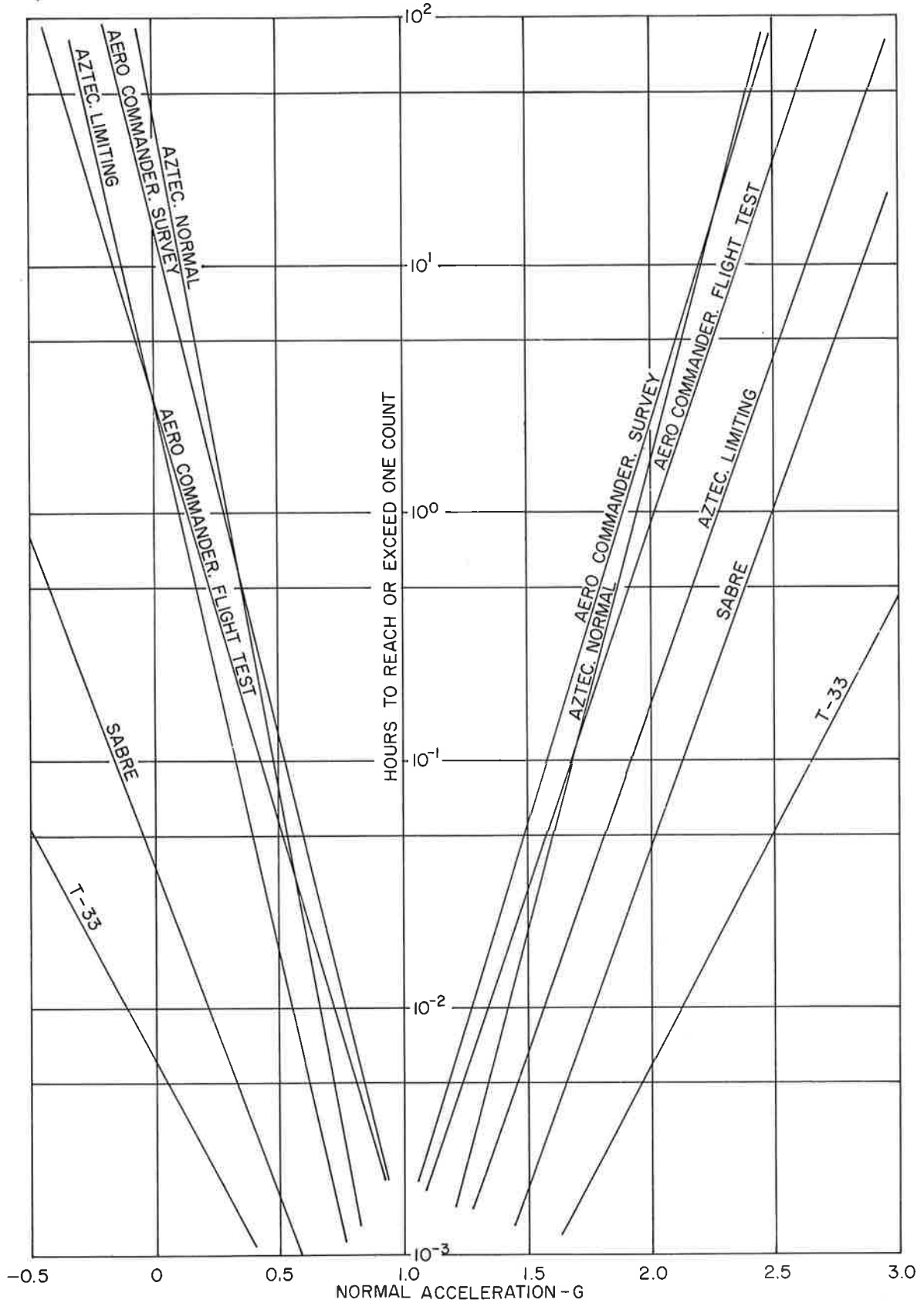


FIG. 4

ACCELERATION – TIME HISTORIES
ALL AIRCRAFT

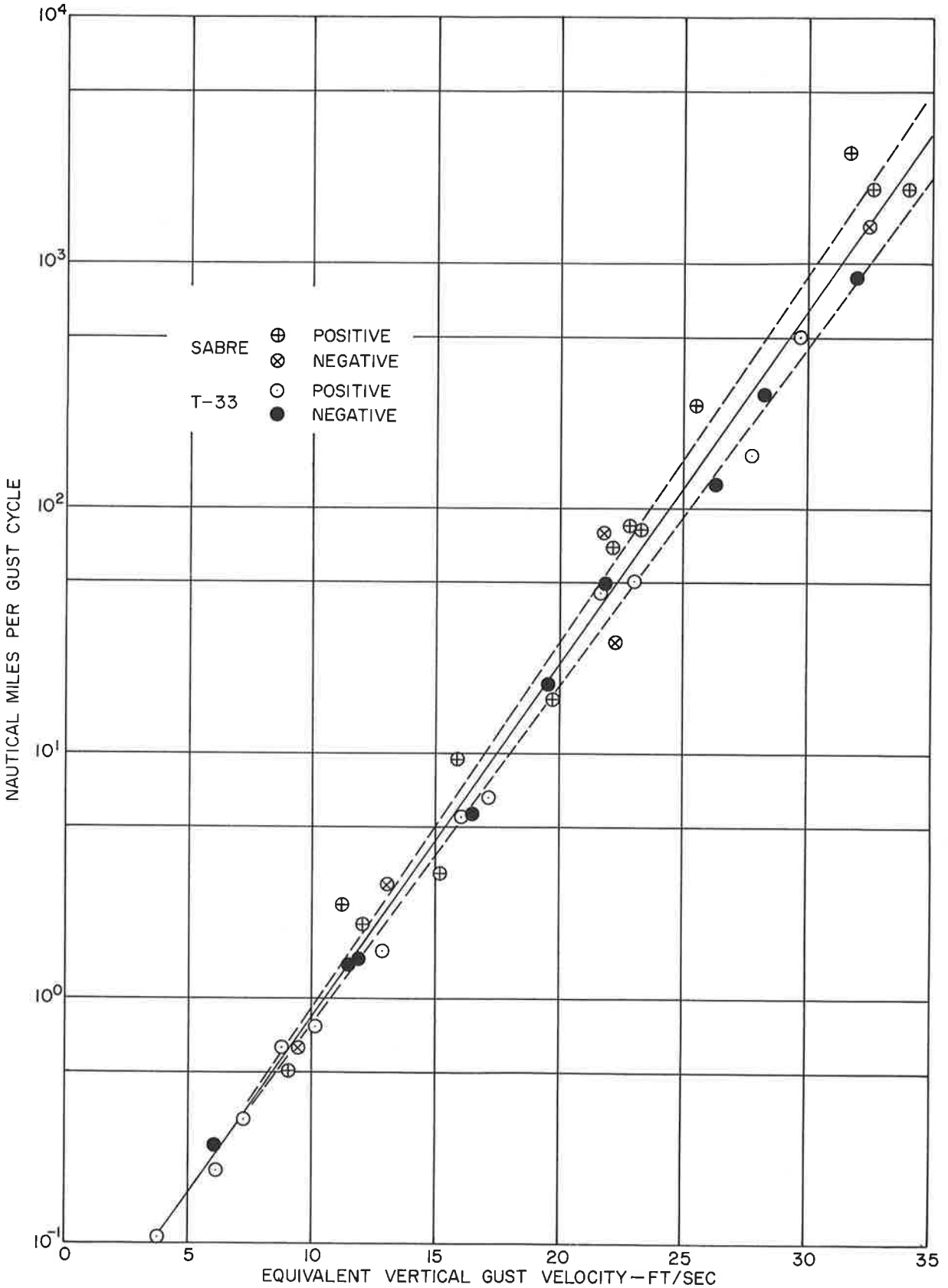


FIG. 5 SABRE AND T-33 GUST SPECTRA

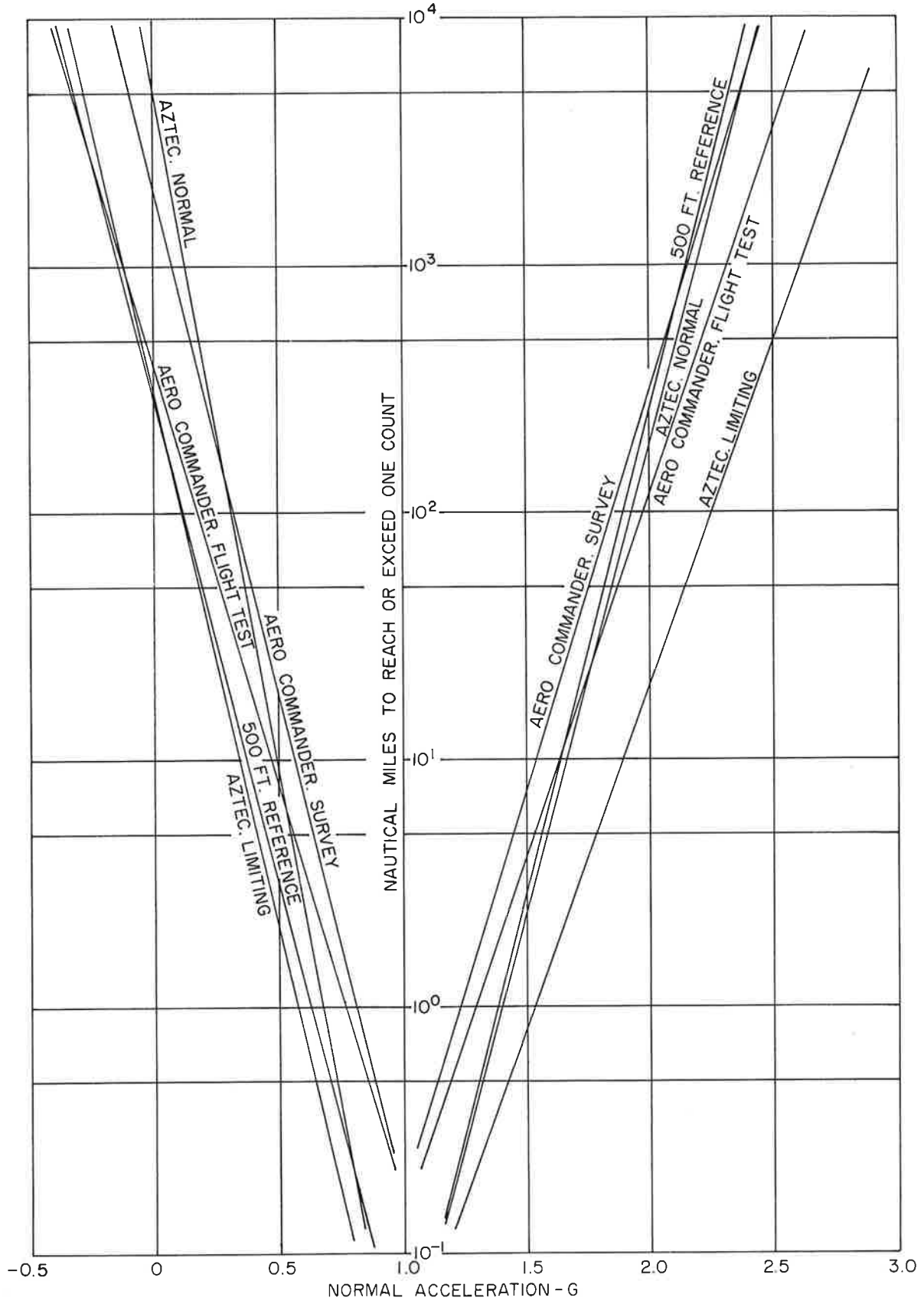


FIG. 6 TRANSFORMED SPECTRA

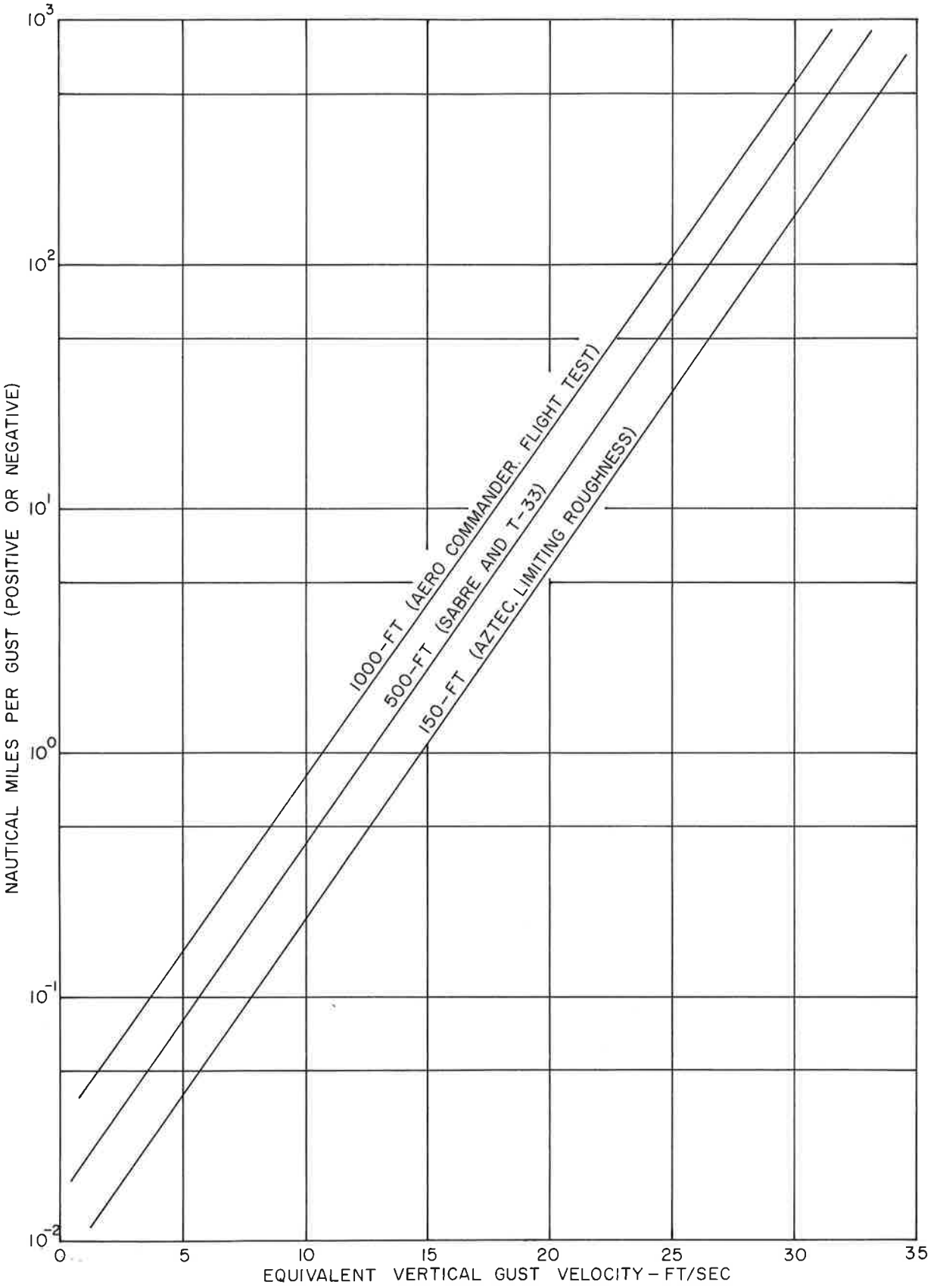


FIG. 7 DERIVED GUST SPECTRA FOR THREE ALTITUDES

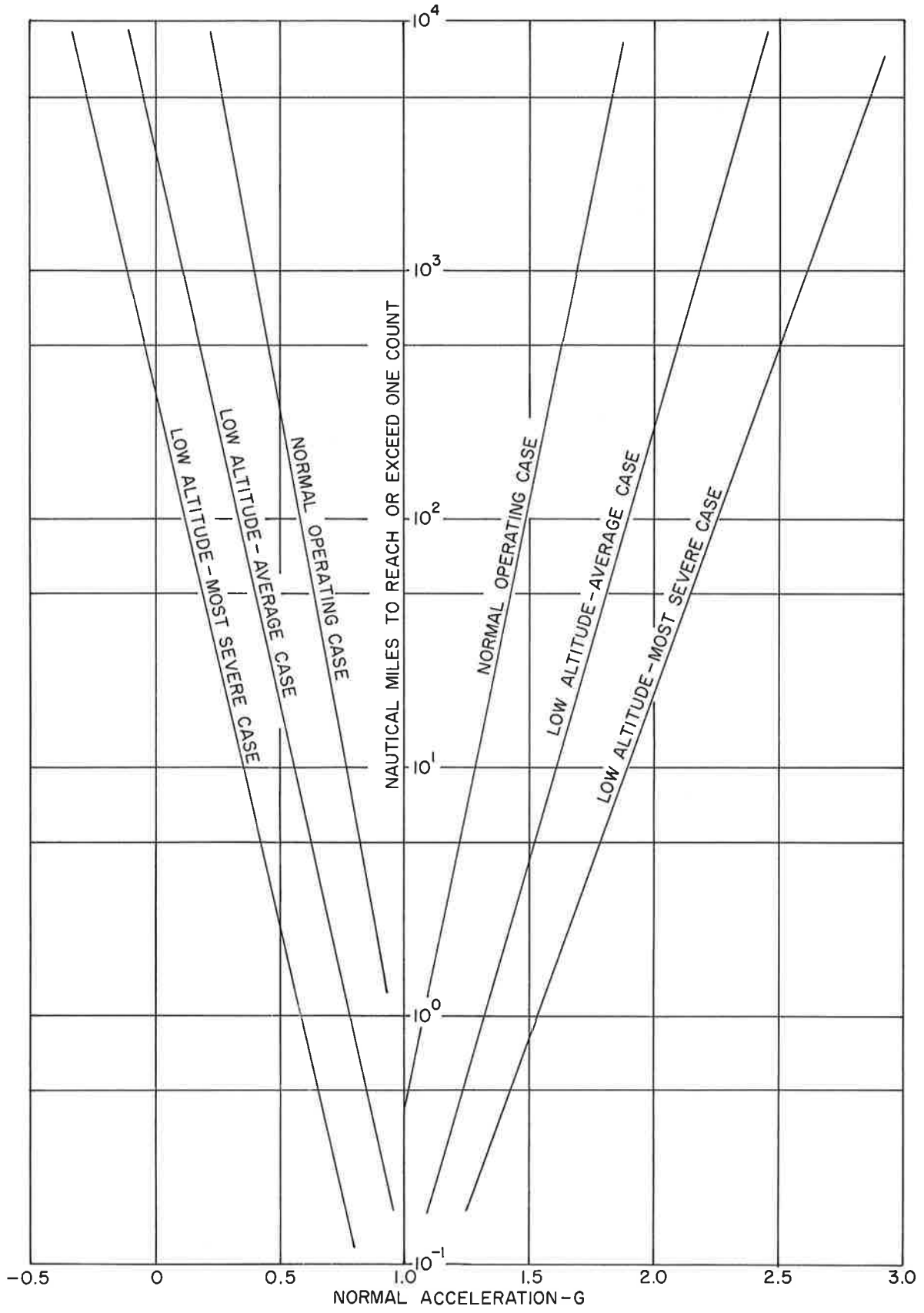


FIG. 8 COMBINED GUST AND MANOEUVRE SPECTRA

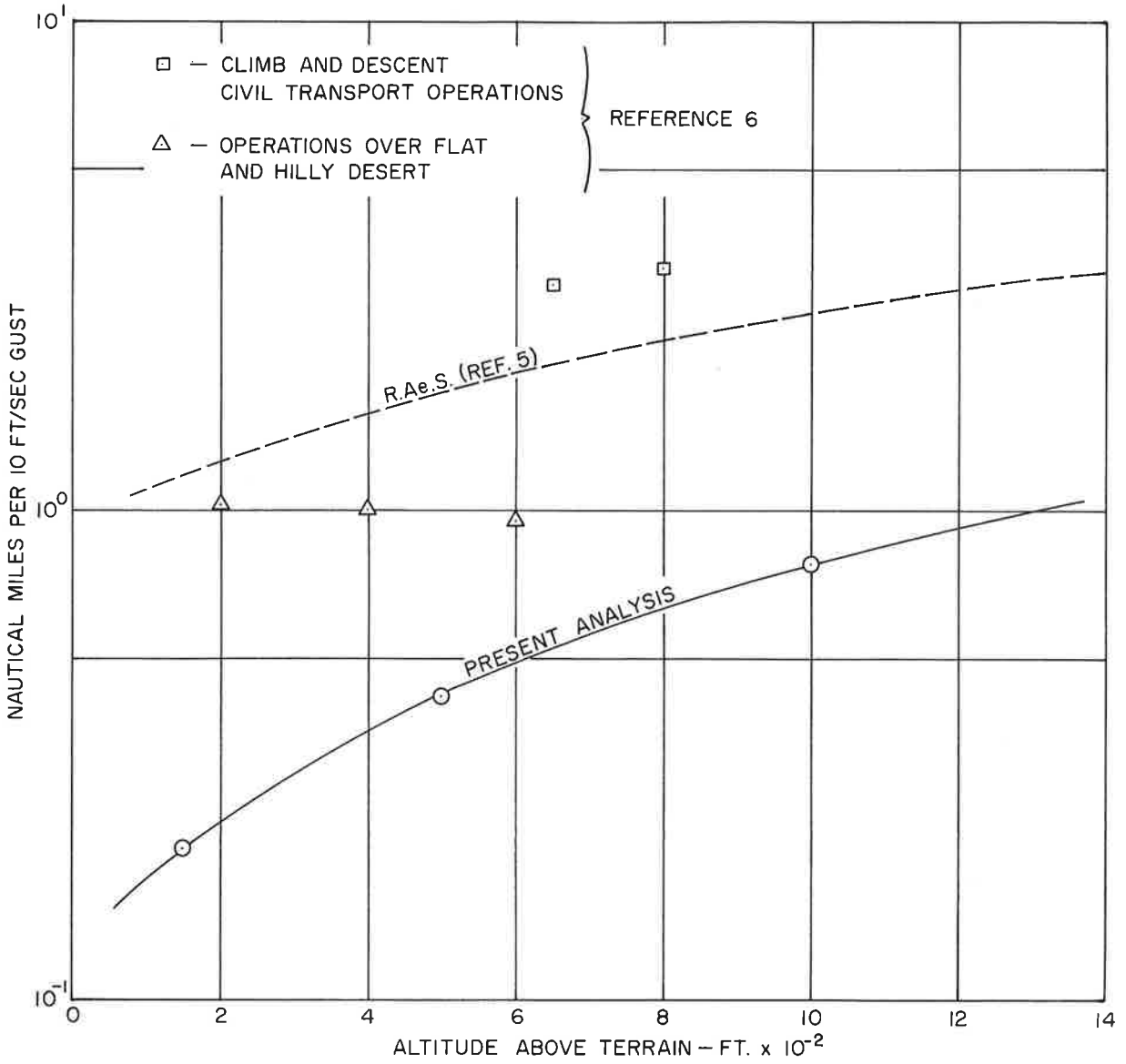


FIG. 9 VARIATION OF 10 FT/SEC GUST FREQUENCY WITH ALTITUDE
COMPARISON OF PRESENT ANALYSIS WITH OTHER DATA

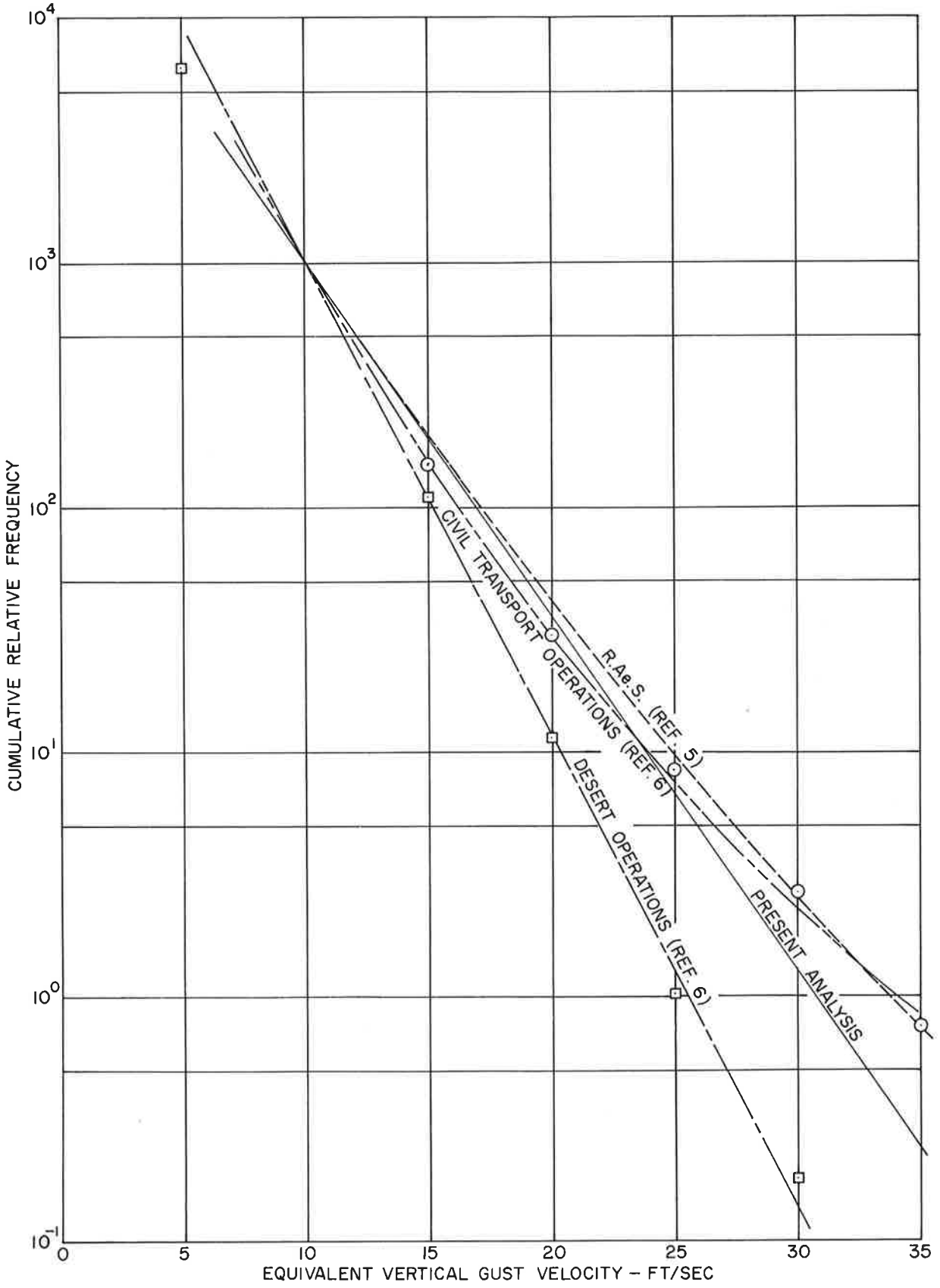


FIG. 10 CUMULATIVE RELATIVE FREQUENCY GUST DISTRIBUTIONS

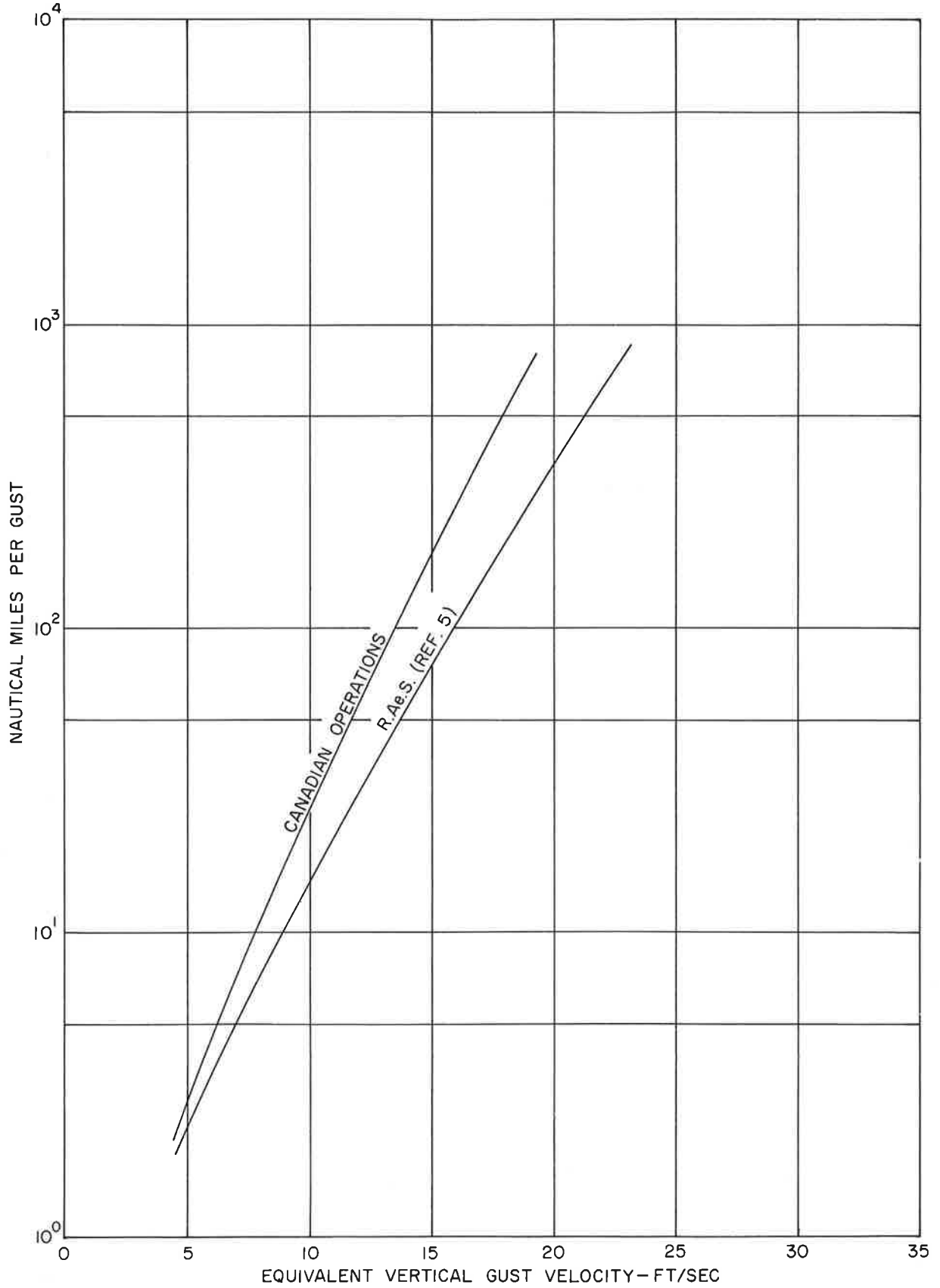


FIG. 11 GUST SPECTRA AT 8000 FEET

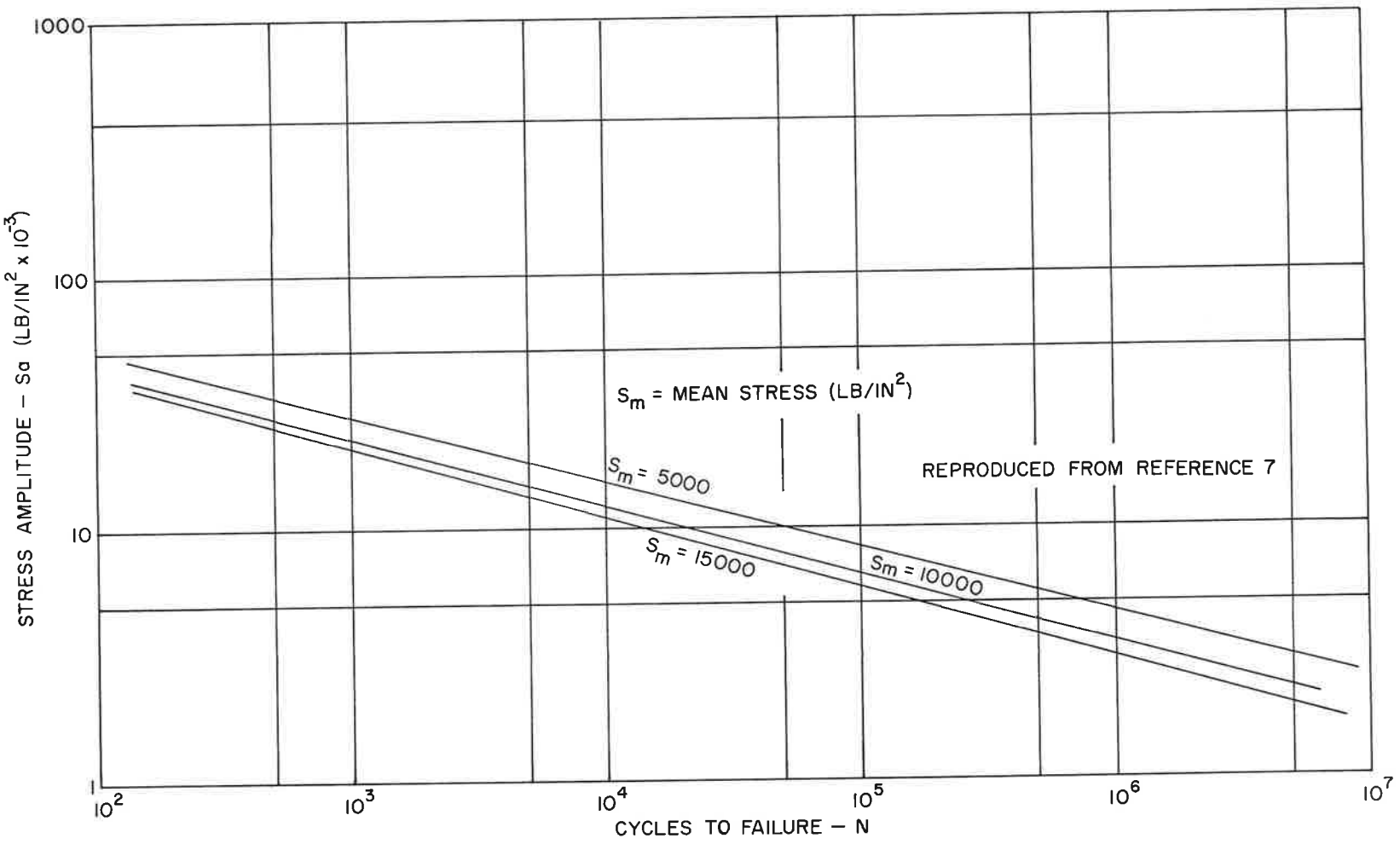


FIG. 12 S – N CURVES FOR ALUMINUM ALLOY WINGS AND TAILPLANES

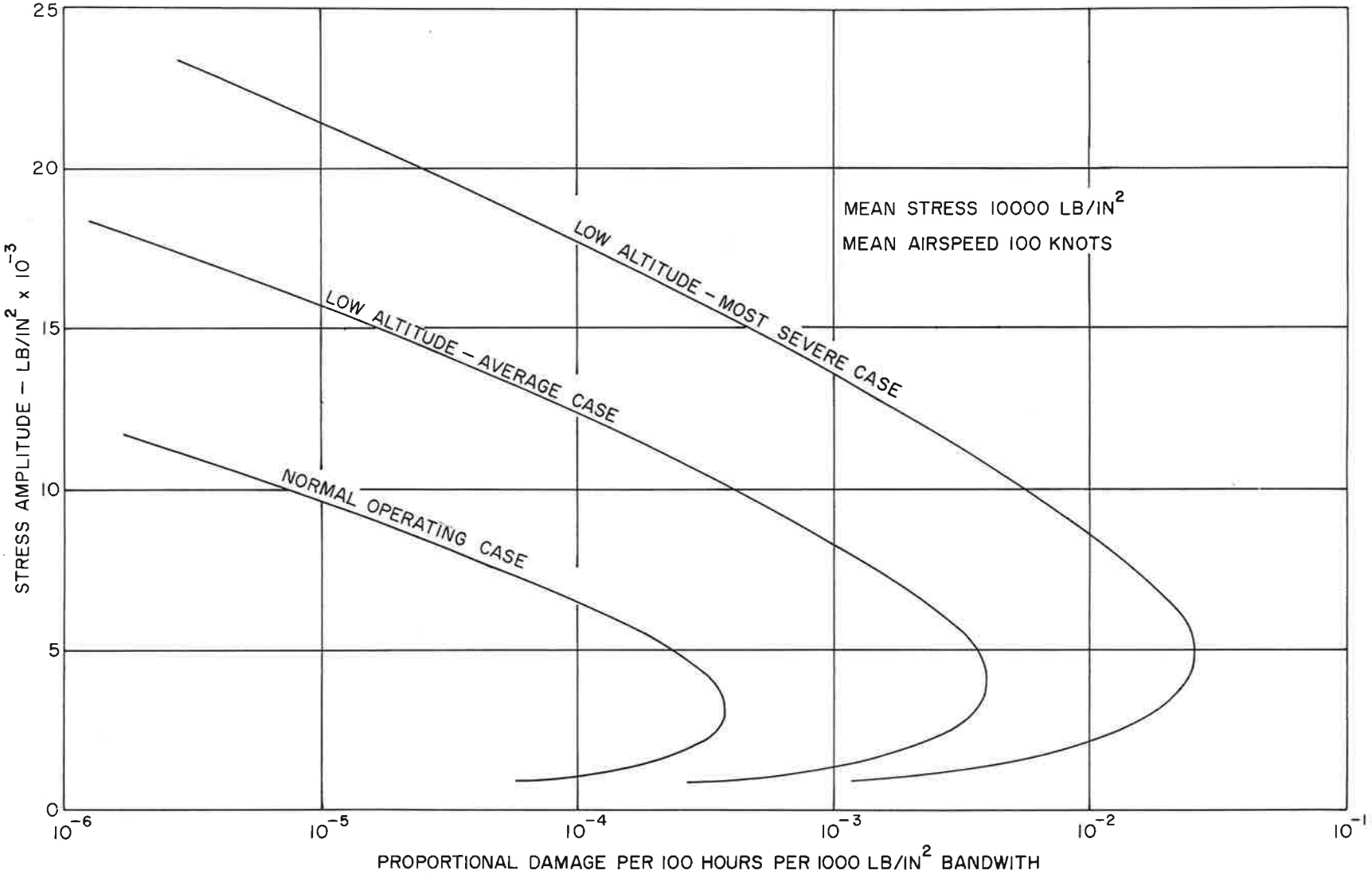
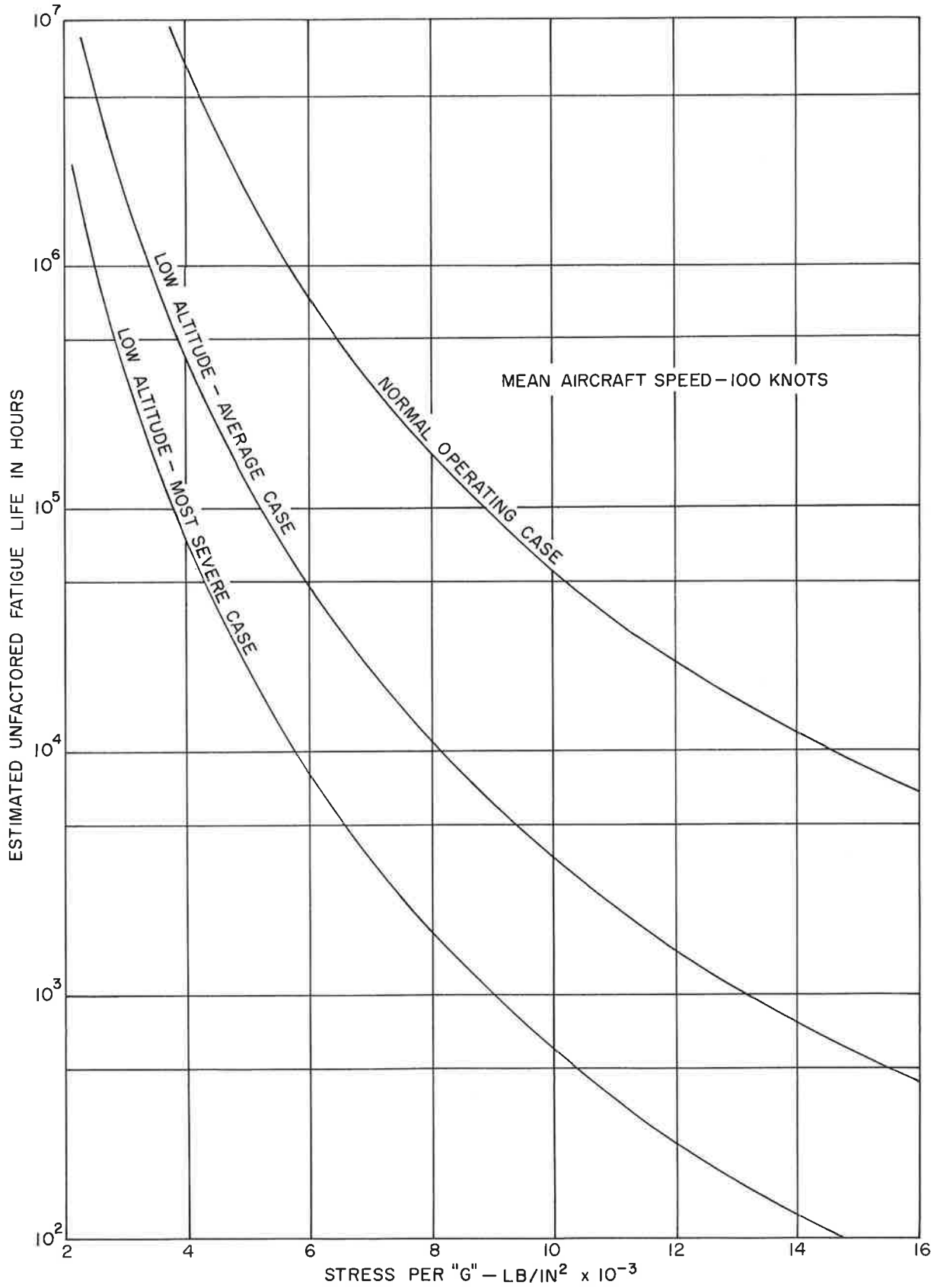


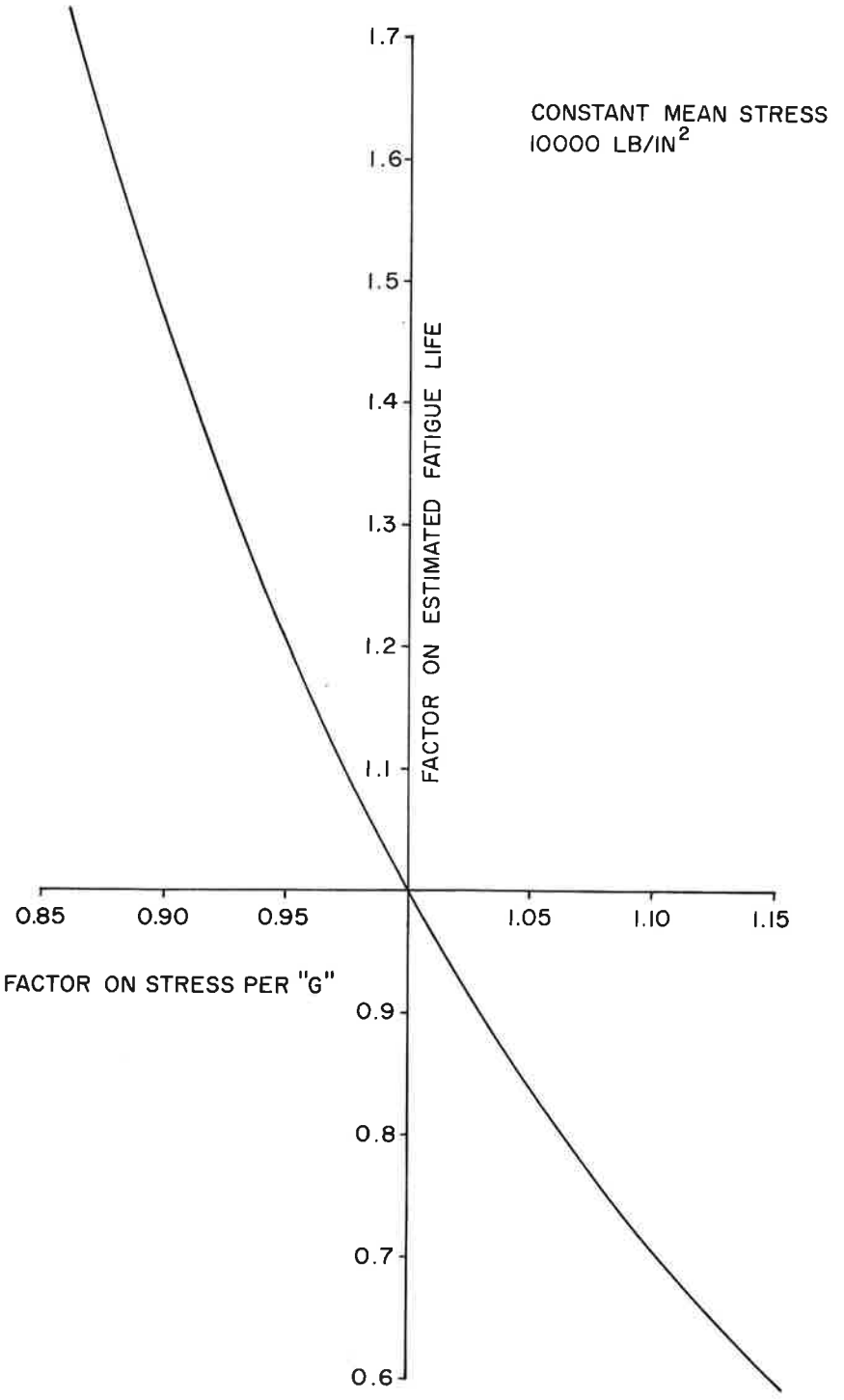
FIG. 13

TYPICAL DAMAGE CURVES



ESTIMATED FATIGUE LIFE AT VARIOUS STRESSES FOR THREE OPERATIONAL CASES

FIG. 14



EFFECT OF VARIATION IN STRESS PER "G" ON ESTIMATED FATIGUE LIFE

FIG. 15