INTERNATIONAL COMMITTEE ON AIRCRAFT FATIGUE

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SUMMARY

An assessment is made of recent repeated loads data from short-haul jet transports and several general aviation airplanes. The jet transport data indicate that except for check flight maneuvers the load histories are essentially independent of operator and airplane type. General aviation data show a large amount of scatter in the repeated load history. The use and geographical location of operations may be the primary means of specifying the repeated loads environment.

INTRODUCTION

About the time engineers interested in repeated loads feel that they can provide the fatigue specialist with stable and valid information, someone either develops a new aircraft or a new use for aircraft. On this basis the demand is always present for additional collections of information or refinements in past results. The current changes are the introduction of small jet transports into short-haul operations and the increasing diversity and utilization of general aviation aircraft. In both cases potential problems are created by applications of aircraft not fully anticipated in the past.

At the fourth ICAF symposium in 1965, Mr. Coleman presented an excellent summary on repeated loads on transport airplanes (ref. 1). Since that time data have become available to augment this summary in regard to the load expectancy of the small jet transports and to permit some assessment of the effect of the operator and geographical environment. In regard to repeated loads on transports, then, the present paper will up-date the information reported in reference 1.

There has been little information available on general aviation aircraft, but NASA and FAA in a cooperative effort have been collecting data for this category for some 3 years. The slow progress in obtaining information in this area is due primarily to the diverse nature of general aviation. At this time, available information will be presented as a preliminary guide to the uses, to the load experience of representative operations, and will include an assessment of the data collection process for such operations.

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SYMBOLS

a_n	incremental acceleration, g units
$a_{n_{max}}$	maximum incremental acceleration, g units
$a_{n_{LLF}}$	incremental acceleration corresponding to limit load factor, g units
M_{MO}	Mach number corresponding to maximum operating limit speed
n_g	limit gust load factor
n_m	limit maneuver load factor
S	wing area, sq ft
V_A	design maneuvering speed, kts
V_C	design cruising speed, kts
V_D	design diving speed, kts
V_{NO}	maximum structural cruising speed, kts
V_{NE}	never-exceed speed, kts
M_{MO}	Mach number corresponding to the maximum operating limit speed
U_{de}	derived gust velocity, ft/sec
W	airplane weight, lb

GENERAL CONSIDERATIONS

Transport Aircraft

The continuing sampling of airline operations is to ensure that changes in use of aircraft and type of aircraft have not introduced serious discrepancies in the load histories. There is also a need for continuing study to evaluate the influence of airline practices on load histories. An example of changes that may affect the fatigue life is illustrated when the jet transport is used in short-haul operations, where it will be spending more time in a turbulent environment than would be inferred by results obtained from the intercontinental jet operations.

In regard to airline practices, for example, landing impact loads have varied more widely between operators than aircraft. Questions of this type require examination if, in the long run, we are to make rational decisions as to design for fatigue. While many efforts have been made to resolve these and similar questions, at present our only recourse is to do additional work since answers have not been found.

Another consideration that requires examination is the fact that, for example, United States aircraft are designed and built for the American environment and according to the United States philosophy, yet are used in other environments and operated by nationals with other philosophies. One does not expect the Northern European Operations to be in the same environment as operations in the Tropics. By the same token, examination of airworthiness discussions between nations indicates philosophical differences, although the objective (a safe airplane) is the same.

General Aviation Aircraft

At this stage in data collection, the questions to be answered are many. Certainly a major question is how to classify operations. While the transport operations represent an organized effort and well-defined operations, general aviation represents many individual operations of almost all types and sizes of aircraft. It appears that classification by type of airplane may not be satisfactory since as performance has improved a given type may be used as an executive transport, trainer, or air taxi.

Another distinguishing feature of general aviation may be the classification of flight regimes. The aircraft used as a trainer may not permit the classical climb, cruise, descent segregation of the transport. It is probable that many general aviation operations will require an approach similar to the military concept of mission and nonmission operations. Such an approach may be required for multiuse aircraft and perhaps for survey aircraft.

A factor for consideration is the wide variety of pilot experience and pilot training involved. The airline pilot satisfies specific requirements as to training and currency. The general aviation pilot ranges from the Sunday afternoon once-a-month experience to the professional pilot on a busman's holiday. In some way representative pilot images will have to be established if any generalized load spectra are to have meaning.

A serious problem, at least in the United States, is the question of sample size and bias which may apply in other countries as well. An optimistic estimate is that the current effort represents less than 0.1 percent of general aviation and one cannot be sure that all classes of operations are covered. On the matter of bias, it should be obvious that volunteer participation means a more mature and better than average pilot. The data collected then should show less severe load experience than if some of the less responsible individuals were participating.

INSTRUMENTATION AND DATA EVALUATION

Since members of the symposium may not have convenient access to reference 1, the material used by Mr. Coleman to describe the NASA activities has been reproduced verbatim. It is applicable to both the transport and general aviation operations as all data are collected and evaluated the same way.

Instrumentation

The data to be discussed were obtained primarily with NASA VGH and V-G recorders, which are described in detail in references 2 and 3, respectively. Consequently, only a brief description of the recorders and the type record obtained is given below.

VGH recorder.- A picture of the VGH recorder is shown in figure 1. The recorder consists of three major components: the recorder base, the attached film recording drum, and the acceleration transmitter. The transmitter is installed near (usually within 5 feet) the center of gravity of the airplane, whereas the recorder base may be mounted at any convenient location within the airplane. The installed weight of the VGH recorder is 20 to 25 pounds.

An illustrative VGH record is shown in figure 2. It is a time-history record of indicated airspeed, pressure altitude, and normal acceleration. From this record, it is possible to make detailed counts of the normal acceleration peaks caused by various sources such as gusts, maneuvers, and ground operations, and to determine the associated airspeeds and altitudes.

V-G recorder.- A picture of the V-G recorder is shown in figure 3. It weighs less than 5 pounds installed and is usually mounted within 5 feet of the center of gravity of the airplane.

An illustrative V-G record is shown in figure 4. It is an envelope of the maximum positive and negative accelerations experienced throughout the airspeed range during the period (usually approximately 200 flight hours for commercial airplanes and 60 hours for general aviation airplanes) covered by the record.

Record Evaluation

Detailed methods used for evaluating the VGH and V-G records are given in references 4 and 5. Consequently, only a brief explanation of the methods of evaluating the records is given in the following sections.

VGH records.- The sketch in the left of figure 5 illustrates the method of evaluating the VGH records. The steady flight position of the acceleration trace is used as a reference from which to read the incremental acceleration peaks which equal or exceed a selected threshold value. Only the maximum value of the acceleration is read for each crossing of the reference. The selected threshold values range from ±0.05g to ±0.40g, depending upon the airplane type and the source of the accelerations being evaluated. For each acceleration peak evaluated, the corresponding values of airspeed and altitude are also evaluated. In addition, the airspeed and altitude at 1-minute intervals are read to provide data on the airspeed operating practices and the altitudes flown. The acceleration data are sorted according to source (gusts, maneuvers), flight condition (climb, cruise, and descent), and by altitude.

V-G records.- The sketch in the right of figure 5 illustrates the manner of evaluating the V-G records. As indicated, only one maximum positive and one negative acceleration increment from the reference are evaluated from each record. Generally, it is not possible to determine the source (i.e., gusts or maneuvers) of the maximum accelerations on a V-G record. Consequently, the V-G acceleration data are not generally sorted according to the source, but rather are given as combined data representing in-flight accelerations.

NOTE: For many of the early transport airplanes, the maximum accelerations on the V-G records were ascribed to gusts rather than maneuvers. Because of the relatively high response of these airplanes to gusts, the assumption was considered to be valid. For several types of current transports and for general aviation airplanes, however, detailed data from VGH records indicate that the assumption may not be valid since maneuver accelerations may be as high as gust accelerations.

Method of combining VGH and V-G data.- Because VGH data samples are generally small (approximately 1000 flight hours), they do not provide reliable estimates of the frequency of the large accelerations. They do, however, provide detailed information on the smaller accelerations and the sources of these accelerations. Conversely, the larger samples of V-G data do not provide detailed information on the sources of the accelerations, but do give reliable estimates of the frequency of the large accelerations. The two types of data are complementary and may be combined to obtain an estimate of the total in-flight acceleration experience.

The method of combining the VGH and V-G data is illustrated in figure 6. The figure shows the cumulative frequency distributions per mile of flight of gust and maneuver accelerations as determined from the VGH data sample, the maximum accelerations from the V-G data, and the total in-flight acceleration distribution obtained by summing the ordinate values of the maneuver, gust, and V-G acceleration distributions.

SCOPE

Scheduled Jet Transports

Table I lists the general characteristics of the jet transports for which data have been analyzed. Airplanes I to VII are the large transcontinental and intercontinental transports while VIII, IX, and XIII are the small short-to-medium-haul aircraft with two or three engines. Almost all the data for the large aircraft have been reported in reference 1 and earlier publications. For the small jet transports the samples have been evaluated recently.

Table II is a summary of operations by airplane and operator. For definition the table includes the average flight duration, altitude, and the percent of time spent in climb, cruise, and descent. It is of interest to note that the average flight time and altitude for the large jets are about 3 hours and 32,000 feet while the corresponding values for the small aircraft are 1 hour and about 25,000 feet. Another significant difference between the large and small aircraft is the fact that large aircraft spend about 75 percent of their flight time in cruise as compared with about 40 percent for the smaller aircraft.

The operations of the large aircraft include operations in almost every part of the free world by both United States and other operators. In the case of the small short-haul jets, three of the five operations are within the continental United States while two operations represent an European and an Australian operation. In connection with the intercontinental operations, the recorded data can include any part of the world while the short-haul jets are restricted by range to more localized geographic areas.

As a matter of convenience, the amount of flight operations spent in check or training flights is included in table II for later reference. The category of check flying also includes flights following overhaul or modification to the airframe. No attempt has been made to sort the information on a more specific basis than noted.

General Aviation

Table III is a listing of the pertinent aircraft included in the sampling program even though results will not be presented for every type of aircraft. The table lists five categories which define in a rough way the primary utilization. Table III also lists the number of V-G and VGH installations and the hours of data currently on hand in each case.

Since the categories such as "single-engine executive" and "personal" are not entirely descriptive, the types of operations included in each category are as follows:

<u>Twin-engine executive</u>:

- Charter flight - cargo and personnel
- Business flight - company and individual
- Instrument check flight - training for instrument card
- Instructional - check-out for multiengine

<u>Single-engine executive</u>:

- Charter flight - cargo and personnel
- Business flight - company and individual
- Instrument check flight - training for instrument card
- Instructional - check-out for heavier airplane

Personal:

Flying Club - airplane flown by from 3 to 21 members. Used for pleasure flying, instruction, or business

Individual - used for pleasure and business

Company owned - airplane rented to individual for business or pleasure flying, also aircraft used as check-out for heavier airplane

Instructional:

Training - all instrumented airplanes owned by flying schools. Used as basic trainers for private license. Also used by student after solo for cross-country

Commercial survey:

Pipe line patrol - patrols flown from 250-300 feet above ground to check for leaks or breaks in the pipe line

Forest patrol - patrols flown 1500 feet above terrain for fire spotting. When fire is spotted, descents are made to 200-300 feet to check condition of terrain around fire

Fish spotter - patrols flown 1500-2000 feet above water. Occasional descents are made to 300 to 500 feet.

Figure 7 is a map showing the distribution of the installations throughout the continental United States. The solid symbols indicate a VGH installation while the plain symbol is a V-G recorder installation. Most geographic sections of the country are represented in the sampling, to the extent that instruments are flying in 37 of the 48 domestic states. As can be seen from figure 7 not all classes of operations are represented in each locality.

Table IV shows the time spent in each flight condition, average flight time, and the altitude and airspeed distributions according to category. In contrast to the jet transports the altitudes are below 20,000 feet for all aircraft, and except for airplane T-2 the average altitude is below 10,000 feet. Comparison of transport airplane I with airplane S-12 (single-engine executive) emphasizes the influence of altitude since airplane I spent about 4.0 percent of the flight time in rough air while the single-engine executive spent some 76 percent of the time in rough air. Similar comparisons for the other categories can also be made.

DISCUSSION

Scheduled Transport Operations

General.- Inspection of all the data at hand indicates that the only flight phases which have not entirely stabilized are the loads in landing impact and check-flight maneuvers. Ground loads, gust accelerations, and operational maneuvers all appear to be independent of operator, geography, and aircraft type within the jet category. There has been some concern that operators could be a significant factor. All attempts to find significant differences have been negative.

In regard to landing impact accelerations, although the scatter is great, only one sample shows a wide discrepancy. At the present time it is not possible to state whether this is due to operating techniques or the airplane characteristics.

The check-flight load histories as noted in reference 1, follow no rational pattern. In broad terms, U.S. operators do some two to three times as much check-flight flying as other nations, but the amount varies widely between airlines. As will be shown later, the severity of the maneuver loads also varies widely for the same equipment but different operators.

Ground loads.- Review of ground loads data, that is, taxi, take-off and landing roll-out loads, indicates that for different equipment and operations, the overall histories are essentially the same (fig. 8). Inspection of other data, for the three separate phases, indicates that the landing run-out imposes higher loads than either the take-off run or taxiing. Since the data of figure 8 are on a per flight basis, a single distribution may be suitable for all aircraft in the jet transport category.

Impact accelerations.- Figure 9 summarizes landing acceleration data for all operations and five airplane types. The basic data sorted according to operator showed little or no scatter, figure 9, except for airplane XIII. Since airplane XIII is fairly new in the inventory, one might expect a more severe environment, but airplanes VIII and IX are also fairly new and show less than average load experience. Until the severe load history for airplane XIII can be explained, it does not appear feasible to suggest a single curve. The severe loading could be due to some airplane characteristic or to the training practices of the airline.

Figure 10 shows that three operators of identical equipment had the same landing acceleration histories. As noted earlier it was thought that geography and national traits might have some significance which was not borne out by the data, since two operators are from countries other than the United States. The airplane IX is a short-haul jet introduced a few years ago that appears to have good handling qualities in the approach.

In contrast to figure 10, figure 11 indicates a significant difference between two operators of large jets flying the same equipment. Subsequent study indicated that it was the general practice of one operator to use a fixed descent rate without flare, while the operator with least severe load history trained the crews to flare on landing. Subsequent efforts by the first operator resulted in a reduction in load experience by changes in landing technique.

Turbulence.- Since rough air is the natural environment of the airplane and has been thoroughly discussed in many papers, the general aspects are well known. Figure 12 shows the amount of rough air flown at different altitudes for the short-haul jet transports. The general distribution and scatter are in keeping with past experience and it would be expected that the results presented in reference 1 are applicable. For comparison with the data from other load sources the gust acceleration distribution will be included in later figures.

Operational maneuvers.- Figure 13 summarizes all maneuver data available and indicates that frequency distribution is essentially the same regardless of airplane. Such an observation might be expected since operational maneuvers are basically specified by terminal area and ATC routings rather than by the crew. Since most changes in direction are on a standard pattern, the load experience should be essentially the same. The deviations for two short-haul operations are for samples less than 1000 flight hours while all other samples with a scatter of about 2 to 1 represent samples varying from 18,000 to 9,000 hours of operation by the large jets. As sample size increases it is expected that the small jet will tend to approach the other curves reducing the overall scatter to about 2 to 1.

The data shown are primarily for U.S. operators, and involve operations in a high density environment. It is probable that for some areas of the world where traffic density is low, the maneuver histories would be somewhat less severe.

Check-flight maneuvers.- Figure 14 shows the mean and the extreme distributions of check-flight maneuver loads from some 16 operations involving both the new and the older jet transports. The results indicate a scatter of from 15 to 20 to 1. For a cumulative frequency of 10^{-5} per mile, the mean check-flight acceleration is 0.9g as compared to 0.6g for operational maneuvers. Also at 10^{-5} per mile the maximum and minimum accelerations are 1.04g and 0.72g, respectively. This type of operation produces many large loads on the airframe and it does not appear feasible to suggest a single distribution.

Inspection of the time spent in check flights, table II, indicates a wide variation between operators from about 8.7 to 0.7 percent of the total flight time. While some of the variation in loads could be ascribed to the variation in time, inspection of individual operations also indicates wide variations in the severity of the maneuvers. Variations for one operator ranged from 6.5 to 3.6 percent of the time while another operation indicated variations from 8.7 to 1.8 percent. Some of these variations reflect the transition from training on new aircraft to routine operations since the percentage is highest for the new airplanes. As a point of interest, the two lowest times are for other than U.S. operators.

Summation of acceleration experience.- Four of the many samples are summarized in figures 15(a), (b), (c), and (d), to show the relative importance of the different load sources. Two samples representing intercontinental operations and two short-haul operations are shown. The results indicate that the check-flight maneuver tends to be the most significant source of repeated loads for three of the four operations. In one case, airplane XIII, the landing impact accelerations tended to predominate. Since each load source can be critical for a different structural component, it is not possible to assess fatigue damage according to source, but it is apparent that all elements must be considered in the repeated loads assessment.

While a limited assessment of the influence of airplane type, operator, and geography has been made, the only significant differences appear to be in the landing impact and check-flight maneuver accelerations. It is probable that the reasons for the single unusual landing load experience will be found through further analysis, but accounting for the check-flight load histories may not be practical. In the case of check flights, the load history seems to depend to a high degree on airline training practices and policy and it is not possible to reduce it to a technical problem for solution.

General Aviation

General.- Inspection of sample V-G envelopes for each category, figure 16, indicates consistent exceedance of the design cruise speed V_c and some increase in positive load factors for the instruction and commercial survey categories as compared to the other three. Except for a few peaks, the records indicate negative accelerations only slightly below zero g. Figure 16(a) shows more peaks at high negative g than the other categories but the character of the record indicates that the largest peak at 160 knots is due to a gust. Records from other aircraft indicate more violent maneuvers than shown on the figure, including one that showed exceedance of V_D and both the positive and negative design limit load factor. Insufficient data are on hand, however, to place such records in the proper statistical perspective. From the crude image that emerges for the operations, a 3.0g positive load factor is to be expected; and the operators do not appear to be concerned with excess speed.

Figure 17 is a composite plot of the cumulative frequency distributions for the basic V-G data. The abscissa is the ratio of the maximum acceleration increment divided by the design limit load factor increment from 1.0g. This ratio, which will be referred to as the acceleration fraction, was selected since limit load factors for general aviation airplanes designed to meet the requirements of reference 6 vary widely. The incremental value measured from 1.0g was used to avoid difficulties with values near zero g. For values of the acceleration fraction less than 0.4, the shape of the distribution curves is not significant since it is highly dependent on the number of records and the number of hours represented by each record.

Figure 17 indicates that the cumulative frequency distributions of the acceleration fraction are symmetrical and essentially the same for all categories. Since the positive design limit load factor is somewhat higher than the negative load factor, the symmetry indicates some tendency for the positive accelerations to be higher as might be expected for maneuvering aircraft. The bias is not very strong since inspection of table III indicates differences between positive and negative limit load factors of about 20 to 30 percent. Since the individual curves of figure 17 are erratic because of data limitations it is not possible at this time to extrapolate the results to the total population of general aviation.

The landing acceleration data shown in figure 18 indicate as might be expected, that the accelerations are most severe for the instructional category. The commercial survey and "twin" executive show the least severe load histories with the "single" executive and personal only slightly higher. For comparison with figure 18, the extremes for the jet transports have been superposed as the dashed lines. At a probability level of 0.01, the best general aviation record is more than 0.2g above the lower limit for the transports while the most severe history (instructional) is about 0.15g above the worst jet transport history. The scatter of 3 to 1 between the lower four curves is considered to be reasonable since records from individual aircraft in a category can vary by factors from 10 to 100.

The several factors that influence the load histories are the pilot, the airplane characteristics, and the landing-gear characteristics. Consideration of airplane and pilot characteristics indicates that for the high performance aircraft the wing loadings are high, about 30 pounds per square foot, and decrease for instructional airplanes to about 10 pounds per square foot. Since the more expensive aircraft such as the "twin" executive probably have commercial or experienced pilots, and the light instructional aircraft have the least experienced pilots, the variations in wing loading and pilot experience would tend to exaggerate the differences in load experience. By the same token, the large aircraft have the more sophisticated landing gear while the instructional will tend to have the more elemental landing gear which could also affect the landing load history. The resolution of these questions will have to await more information and analysis.

Twin-engine executive.- The twin-engine executive aircraft have an average flight time of about 1 hour and the cruise altitude for piston-engine aircraft is about 5500 feet. Examination of one sample from a twin turbopropeller aircraft indicates the same average flight time but the average cruise altitude is about 15,000 feet. For these aircraft the amount of rough air varies from about 45 percent of time for the low cruise altitude to 30 percent for the cruise altitude of 15,000 feet. These figures are at least twice as great as the values for transport operations but will require more definition as the sample size increases. Since general aviation would be expected to be predominantly a daylight operation as compared to scheduled transport, the increased exposure to rough air may be accounted for by operations during the roughest part of the day.

Gust velocities, figure 19(a), appear quite consistent for the two twin-engine executive aircraft. For airplane T-7, the high negative gust velocities up to 48 feet per second appear to be a "rare" event and the tail of the distribution may follow the trend of the data at lower load levels as further data are acquired. Comparison of the distributions in the reliable range (from 8 to 30 fps) indicates a gust experience about 4 feet per second less than for transport aircraft and the curves are almost identical for the sample airplanes. The difference between the transport and executive gust experience could be ascribed to the fact that the transport goes on schedule in most weather conditions whereas the light twin is probably operated mainly in the daytime and under more selective weather conditions, or the difference may be due to sample size.

The maneuver accelerations in figure 19(b) emphasize the unsymmetrical experience for positive and negative loads and the apparent practice of rather gentle maneuvers. Comparison of figures 19(b) and (c) shows that for these operations the gust accelerations are more severe than the maneuvers. At an acceleration fraction of 0.3 the accelerations due to turbulence would be about 10 times more frequent than the maneuver accelerations. For airplane T-2 the ratio is about 2 to 1 due in part to the higher wing loading of the turbine-powered aircraft, table III, and in part because of flight at a higher altitude.

If the values for landing impact of figure 18 are considered, the landing impact appears to be a less severe environment than flight for the airframe, although it could be critical for particular airplane components.

Single-engine executive.- These aircraft show an average flight time of about 1 hour, with average operating altitude of about 6000 feet and about 76 percent of the flight time in rough air. The high percentage of time in rough air may also be explainable in terms of flight during the most turbulent hours of the day. The largest sample represents operations in mountainous sections of the United States and contains a fair amount of "bush" operations.

Comparison of figure 19(a) with figure 20(a) indicates that the gust experience is about 2 feet per second less than for the twin executive. Inspection of a smaller sample from operations in the plains states shows that for such operations the tendency is for a somewhat less severe gust history. Other things being equal, the reduced severity of the gust velocity distributions suggests more fair weather flying than for the twin-engine executive aircraft.

The maneuver load distributions, figure 20(b), are more severe than for the twin-engine executive and indicate perhaps two operations since the curves are concave downward at the high end. Comparison with figure 19(b) shows the activity is about 10 times that for the twin. Another notable feature of figure 20(b) is the high incidence of negative maneuvers. In contrast, another sample of single-engine executive operations produced only one negative acceleration in 138 flight hours, and positive maneuvers at a frequency of about one-thirtieth that of figure 20(b). Discussions with the operator of the aircraft, whose data are presented in figure 20, indicate that many of the operations involved carrying sportsmen into mountainous areas to landing sites which required "dragging" the strip before touchdown. Brief inspection of commercial survey operations using the same airplane type shows the same probability of the larger maneuver loads but about 20 times as many of the more moderate loads. Referring back to figure 17, which indicates the large load probability is essentially independent of category, one must conclude that little or no relation will exist between the extreme values and the frequency of repeated loads.

Comparison of the gust and maneuver acceleration fractions indicates that at moderate load levels, about 0.3, the two load sources will be of equal importance for the single-engine executive category. The scatter between samples previously discussed raises the question of whether the category is homogeneous and whether any refinement in load spectra may require a more detailed breakdown of the operations.

Personal aircraft.- Operations by airplane P-14 indicate about 52 percent of the time in rough air with an average operating altitude of about 2500 feet. The flight duration of some 35 minutes is the shortest for all categories. With an average flight speed of about 100 miles per hour this would imply that most flights take place within about 60 miles of the home airport. The amount of rough air experienced is at about the right level in comparison with the other categories for the operating altitude.

Figure 21(a) shows that, for the limited sample of gust velocities, the experience is somewhat more severe than the single-engine executive operations. The maximum gust velocity experience of 28 feet per second would imply gust accelerations corresponding to an acceleration fraction of about 0.55 whereas figure 21(c) indicates a maximum acceleration fraction of about 0.35. On this basis it would appear that the more severe gusts were encountered at low speeds, probably well below the structural cruising speed.

Figure 21(b) indicates a rather severe maneuver environment, particularly the negative acceleration distribution. As in the other categories there is bias toward positive maneuver accelerations as might be expected. Comparison with figure 20(b) indicates a more severe maneuver load history than for the single-engine executive operations, and at a probability level of 10^{-3}, about the same acceleration frequency as for the commercial survey.

Figures 21(b) and (c) indicate that for the sample studied, the maneuver loads would produce more repeated loads than the rough air in the range of interest. Since the flight time is only 35 minutes, the landing accelerations could be a significant feature of the repeated load history for the airplane.

Instructional.- The 115-hour sample from airplane I-18 indicates, as might be expected, a large amount of flight time, 75 percent, in rough air since the average operating altitude was only 1500 feet. These operations were of very short flight duration amounting to about 40 minutes.

The gust velocities, figure 22(a), experienced in these operations were quite low with a maximum value of 16 feet per second. If it is assumed that basic training is primarily a fair weather operation, then flights close to the airport would experience a great deal of light to moderate turbulence since operations would be at the lower altitudes.

The maneuver accelerations of figure 22(b) are also quite moderate with the acceleration fraction having maximum values of about 0.4. Comparison with the gust accelerations of figure 22(c) indicates that the maneuvers would be the prime source of repeated flight loads although neither load source appears to provide a severe environment. When the limited sample is viewed in terms of the V-G data of figure 17, it appears that it may not be entirely representative and there is a distinct possibility that, as a category, instructional flying may show more scatter between operations than the other categories.

Commercial survey.- The commercial survey (the sample is for pipeline operations) is characterized by spending 97 percent of the time in turbulence, an average operating altitude of 1200 feet, and flight times of about 3 hours. Since most of the flight operations are at altitudes of 200 to 400 feet, the continuous exposure to turbulence is not surprising. The long average flight time is characteristic of commercial operations that involve spotting ground objects. In the case of the pipeline aircraft (airplane C-19) the average flight speed is 89 knots and the design cruising speed is 104 knots. Such operations are conducted in VFR weather since visibility is a prime requisite of the mission.

The gust velocity distribution, figure 23(a), is the most severe of the general aviation experience due to the almost continuous exposure to rough air. At large gust velocities, the experience matches that of the twin executive but for lower values, 8 to 20 feet per second, the frequency of occurrence is higher than for the twin. At 16 feet per second the commercial survey airplane experiences about 6 times as many gusts as the twin. Comparison of the trends shown in figures 23(a) and 19(a), if continued, would indicate that for larger samples the maximum gust velocities for the twin would exceed those for commercial survey operations. A possible reason for this trend is that the VFR requirements of survey work indicate a minimum exposure to convective cloud activity while the twin executive would be expected to penetrate such cloud activity during transport type operations.

The maneuver accelerations, figure 23(b), indicate a very strong bias toward positive load factor, and a very high frequency of maneuvers. Since survey work involves banking, turning, and circling flight to avoid obstacles to follow the line and to check for leaks, a high incidence of positive maneuvers would be expected. The shape of the distribution curve for positive acceleration fractions would indicate that very large maneuver loads would not be expected and is, of course, borne out by the data of figure 17 based on V-G recordings. At 20 percent of the limit load factor, the maneuver frequency is about 100 times more frequent than for either the twin- or single-engine executive categories.

Comparison of figures 23(b) and (c) indicates that, for the survey type of operation, maneuver loads would be the prime source of repeated loads. Despite the practically continuous operation in rough air the imposed gust loads for airplane C-19 are about one-hundredth of the frequency at an acceleration fraction of 0.4. Since the flights average about 3 hours as compared to 1 hour for the executive operations the frequency of landing impact accelerations will also be less by a factor of about three. Of the categories studied, the commercial survey is potentially the most severe environment from a repeated loads standpoint.

Comparison of Categories

Most general aviation aircraft, because of speed limitations, are probably best categorized by the geography surrounding the home station, and by the usage of the aircraft, than by the categorization selected in the present paper. As further samples are collected it may be feasible to determine more suitable categories, but at the present time data are not available to define the different environments. In operations that are primarily commercial in character, such as the commercial-survey and twin-engine aircraft, it appears that the operations are single purpose and the load distributions should stabilize quite well.

The image that emerges of the general aviation pilot is, in the main, a man with a large investment in equipment who is interested in this investment rather than in taking chances. The apparent lack of concern for speeds beyond V_C creates the impression that the pilot has not been taught the significance of the structural design speeds and is probably not familiar with FAR 23 or 25, references 6 and 7.

While it is still too early to tell a great deal, the gust environment is different from the transports as to the amount of rough air encountered and the gust severity. Except for the twin executives, the impression is that the maximum gust velocities encountered will be less than those for transports, but the amount of rough air and number of encounters with moderate turbulence will be greater. For the twin executive the results lead one to believe that in the long run the gust environment will approach that for transport aircraft except for some increase in the amount of rough air, which would be most significant for repeated loads experience. The least severe gust experience has been with instructional aircraft which apparently is primarily a fair-weather operation.

The more severe maneuver loads environment appears to be generated by the commercial survey and single-engine executive classes. While the large load experience is not outstanding for these categories, the frequency of occurrence of moderate maneuvers is very high.

The landing impact experience appears to be relatively stable and orderly in that instruction in basic flight technique creates the greater number of large loads while the other four categories indicate essentially the same load experience.

Data Collection for General Aviation

The collection of loads data on general aviation is a discouraging experience. As compared to similar collections of transport data, the major problems are the individual operations and their number. The current U.S. program amounts to about 0.1 percent of the general aviation fleet and was planned to sample both the repeated and large load experience. In 3 years of operation the collection rate varies from 100 to 700 hours of data per instrument with personal aircraft being the lowest. Comparison of data hours for the V-G and VGH recorders indicates about twice as many hours per instrument for the V-G recorder. As might be expected, the simpler the instrument the better the collection. The results also indicate that commercial or semi-commercial operators do a much better job than the individual owner.

Current operations involve an effort of about 4 man years per year and a cost per year of about one hundred and twenty thousand dollars. The cost figure amounts to about ten dollars per data hour with about half the cost being in instrument maintenance, calibration, and adjustment. In the 3-year period some 90 days of travel has been involved to visit the locations of figure 7 for soliciting cooperation and improving the collection. In retrospect, if manpower were available the amount of travel would be doubled or tripled to keep the program moving. The current substitute is very extensive use of the telephone for liaison and follow-up. The need for extensive promotion arises from the low flying hours per year of many aircraft, the difficulty in maintaining enthusiastic cooperation over long periods of time, and the changes brought about by the sale or trade of aircraft. In many cases an owner will trade or sell the aircraft after only a few hundred hours have been acquired.

The three critical problems in extensive data collection programs have been:

1. The lack of uniformity and capacity of electrical supply systems in general aviation aircraft

2. The installation and weight limitations for the smaller aircraft

3. The nuisance effort required to handle the records and necessary bookkeeping

The first two problems have been solved on an individual basis, but the record collection and bookkeeping is still a serious problem, particularly for VGH installations, and no simple solution has been found. Record handling and collection are the limiting factors in maintaining the cooperation of the operator.

For the data collected to date, the evaluation of the VGH records taxes our manpower and facilities even though it is semi-automatic. If, as in the case of transport aircraft, a 1- or 2-percent sample were required, the data evaluation and analysis with current methods would swamp the investigator. In the long run the larger sample will be required and automatic evaluation will be a must, or extremely simple instrumentation such as the V-G recorder, or counting accelerometers, will have to be accepted with the attendant reduction in the amount of detailed information obtained.

CONCLUDING REMARKS

The information on the jet transport category indicates a remarkable consistency in landing, gust and maneuver loads, but that check flying still shows a large degree of scatter. Results to date indicate that in contrast to expectations the histories of repeated loads show a high degree of independence of operator and geographical location.

The picture of repeated load experience on general aviation aircraft indicates wide variations and difficulties can be foreseen in sorting the operations according to homogeneous categories. The categories used in the present study will probably have to be changed on the basis of the evidence presented. While the evidence is inconclusive it appears that geographical location and airplane use will be predominant factors for most categories. The results also indicate little if any relation between the frequency of the extreme and the small repeated loads.

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

3. Taback, Israel: The NACA V-G Recorder. NACA TN 2194, 1950.

4. Walker, W. G., and Copp, Martin R.: Summary of VGH and V-G Data Obtained From Piston-Engine Airplanes From 1947 to 1958. NASA TN D-29, 1959.

5. Staff of Langley Airworthiness Branch: Operational Experience of Turbine Powered Commercial Transport Airplanes. NASA TN D-1392, 1962.

6. Anon.: Airworthiness Standards; Normal Utility and Acrobatic Category Airplanes. Federal Aviation Regulations, Part 23, Feb. 1965.

7. Anon.: Airworthiness Standards; Transport Category Airplanes, Part 25, Feb. 1965.

TABLE I.- TRANSPORT AIRCRAFT CHARACTERISTICS

AIRPLANE TYPE	IA	IC	ID	IIB	IIC	III	VII	VIII	IX	XIII
WING AREA, SQ FT	2433	2892	2892	2771	2771	2000	2250	1579	1650	980
WING SWEEP, DEG	35	35	35	30	30	35	35	20	32	20
MAXIMUM WEIGHT, LB $\times 10^{-3}$	257	312	312	276	315	184	253	110	152	76
W/S, LB/SQ FT	105.6	107.9	107.9	99.6	113.7	92.3	112.4	69.8	92.1	78.1
V_{MO} AT S.L., KNOTS	338	339	339	340	340	373	377	325	380	322
M_{MO}	.884	.887	.852	.88	.88	.84	.86	.775	.88	.785

TABLE II.- DEFINITION OF TRANSPORT OPERATIONS

OPERATOR	E	F	E	F	K	C	E	H	L	I	G	A	S
AIRPLANE TYPE	IA	IA	IC	IC	ID	IIB	IIC	IIC	IIC	III	VIII	IX	XIII
AVERAGE FLIGHT LENGTH, HOURS	3.34	2.18	3.27	3.40	3.82	2.00	2.80	2.56	4.02	1.45	1.08	1.16	0.70
AVERAGE CRUISE ALT., FT $\times 10^{-3}$	31	30	32	34	34	32	31	32	34	32	28	28	21
PERCENT TIME													
CLIMB	14.6	15.6	9.0	8.5	9.1	14.1	9.3	13.2	9.5	17.8	33.1	19.0	22.8
CRUISE	73.6	66.8	78.9	78.3	77.6	64.6	76.4	70.7	78.9	57.3	31.5	47.9	38.9
DESCENT	11.8	17.6	12.1	13.2	13.3	21.3	14.3	16.1	11.6	24.9	35.4	33.1	38.3
CHECK FLIGHTS	6.5	8.7	5.5	1.8	1.1	7.7	3.6	3.1	0.7	7.7	5.6	8.5	5.1
EST AVERAGE OP WT, LB $\times 10^{-3}$	208	208	250	250	249	224	252	252	251	151	92	127	62

TABLE III.- GENERAL AVIATION AIRPLANE CHARACTERISTICS AND SAMPLE SIZE

(a) Twin-engine executive

AIRPLANE TYPE	T-1	T-2	T-3	T-4	T-5	T-6	T-7
VG INSTALLATION	0	0	2	4	1	2	3
VG HOURS	0	0	310	2066	145	831	3895
VGH INSTALLATION	1	1	0	1	0	0	1
VGH HOURS	225	151	0	350	0	0	438
PROPULSION	JET	TURBOP	PISTON →				
MAXIMUM WEIGHT, LB	12 500	9000	8500	4830	4990	5100	4800
WING AREA, FT^2	231.8	279.7	293.9	175	175	175	207
W/S, LB/FT^2	54.5	32.1	28.9	27.6	28.5	29.1	23.2
V_C AT S.L., KNOTS	350	208.5	178	182.3	182.3	182.3	172
V_{NO} AT S.L., KNOTS	358	208.5	208.5	191.5	194.5	198.5	192
V_D AT S.L., KNOTS	400	260.5	260.5	238.8	243	248	240.4
n_m AT V_C	4.4	3.70	3.70	3.8	3.8	3.8	3.8
$-n_m$ AT V_C	-1.78	-1.68	-1.60	-1.52	-1.52	-1.52	-1.52
n_g AT V_C	3.44	3.10	2.97	2.97	2.91	2.84	3.10

TABLE III.- GENERAL AVIATION AIRPLANE CHARACTERISTICS AND SAMPLE SIZE - Continued

(b) Single-engine executive

AIRPLANE TYPE	S-8	S-9	S-10	S-11	S-12	S-13
VG INSTALLATION	0	2	1	2	2	1
VG HOURS	0	997	1050	341	1239	445
VGH INSTALLATION	1	0	0	1	1	0
VGH HOURS	46	0	0	138	262	0
PROPULSION	←		PISTON			→
MAXIMUM WEIGHT, LB	2650	2725	2950	2900	2800	2800
WING AREA, FT^2	177.6	177.6	177.6	178	174	174
W/S, LB/FT^2	14.9	15.3	16.6	16.3	16.1	16.1
V_C AT S.L., KNOTS	138.8	152	160.5	156.1	139	139
V_{NO} AT S.L., KNOTS	173.8	173.8	173.8	175	149	149
V_D AT S.L., KNOTS	217	217	217	218.5	186	186
n_m AT V_C	4.4	4.4	4.4	3.8	3.8	3.8
$-n_m$ AT V_C	-1.76	-1.76	-1.76	-1.52	-1.52	-1.52
n_g AT V_C	3.40	3.40	3.40	3.65	3.30	3.30

TABLE III.- GENERAL AVIATION AIRPLANE CHARACTERISTICS AND SAMPLE SIZE - Continued

(c) Personal and instructional

AIRPLANE TYPE	P-14	P-15	P-16	P-17	I-18	I-19	I-20
VG INSTALLATION	3	1	1	2	4	2	4
VG HOURS	1000	104	469	218	1502	1201	401
VGH INSTALLATION	1	0	0	0	1	1	1
VGH HOURS	276	0	0	0	115	485	144
PROPULSION	←			PISTON			→
MAXIMUM WEIGHT, LB	2400	2200	2200	2575	1650	1600	1500
WING AREA, FT^2	160	174	174	167	147	160	170.2
W/S, LB/FT^2	15.0	12.6	12.6	15.4	11.2	10.0	8.8
V_C AT S.L., KNOTS	128	121.5	121.5	130	95.5	104.2	86.8
V_{NO} AT S.L., KNOTS	142.5	132.2	132.2	146	114.6	125	104.2
V_D AT S.L., KNOTS	178	165	165	182.2	143	156	130
n_m AT V_C	3.8	3.8	3.8	3.8	4.4	4.4	4.65
$-n_m$ AT V_C	-1.52	-1.52	-1.52	-1.52	-1.76	-1.76	-2.18
n_g AT V_C	3.30	3.40	3.40	3.42	3.00	3.46	3.33

TABLE III.- GENERAL AVIATION AIRPLANE CHARACTERISTICS AND SAMPLE SIZE - Concluded

(d) Commercial survey

AIRPLANE TYPE	C-12	C-13	C-19	C-21
VG INSTALLATION	2	2	6	0
VG HOURS	400	170	6806	0
VGH INSTALLATION	0	1	1	1
VGH HOURS	0	197	472	895
PROPULSION	← PISTON	PISTON	PISTON	PISTON →
MAXIMUM WEIGHT, LB	2800	2800	1600	1500
WING AREA, FT^2	174	174	160	178.5
W/S, LB/FT^2	16.1	16.1	10.0	8.4
V_C AT S.L., KNOTS	139	139	104.2	95.5
V_{NO} AT S.L., KNOTS	149	149	125	114.6
V_D AT S.L., KNOTS	186	186	156	163
n_m AT V_C	3.8	3.8	4.4	4.4
$-n_m$ AT V_C	-1.52	-1.52	-1.76	-1.76
n_g AT V_C	3.30	3.30	3.46	3.59

TABLE IV.- DEFINITION OF GENERAL AVIATION OPERATIONS

TYPE OPERATION	TWO-ENGINE EXECUTIVE		ONE-ENGINE EXECUTIVE	PERSONAL	INSTRUCTIONAL	COMMERCIAL SURVEY
AIRPLANE TYPE	T-2	T-7	S-12	P-14	I-18	C-19
AVERAGE DURATION, MIN	70.2	55.1	52.2	35.2	37.0	174.0
AVERAGE TRUE AIRSPEED, KNOTS	192	154	130	102	75	89
AVERAGE ALTITUDE, FT	12,398	4737	7383	2444	1551	1214
PERCENT TIME IN ROUGH AIR	27.7	45.3	76.6	52.3	75.2	97.2

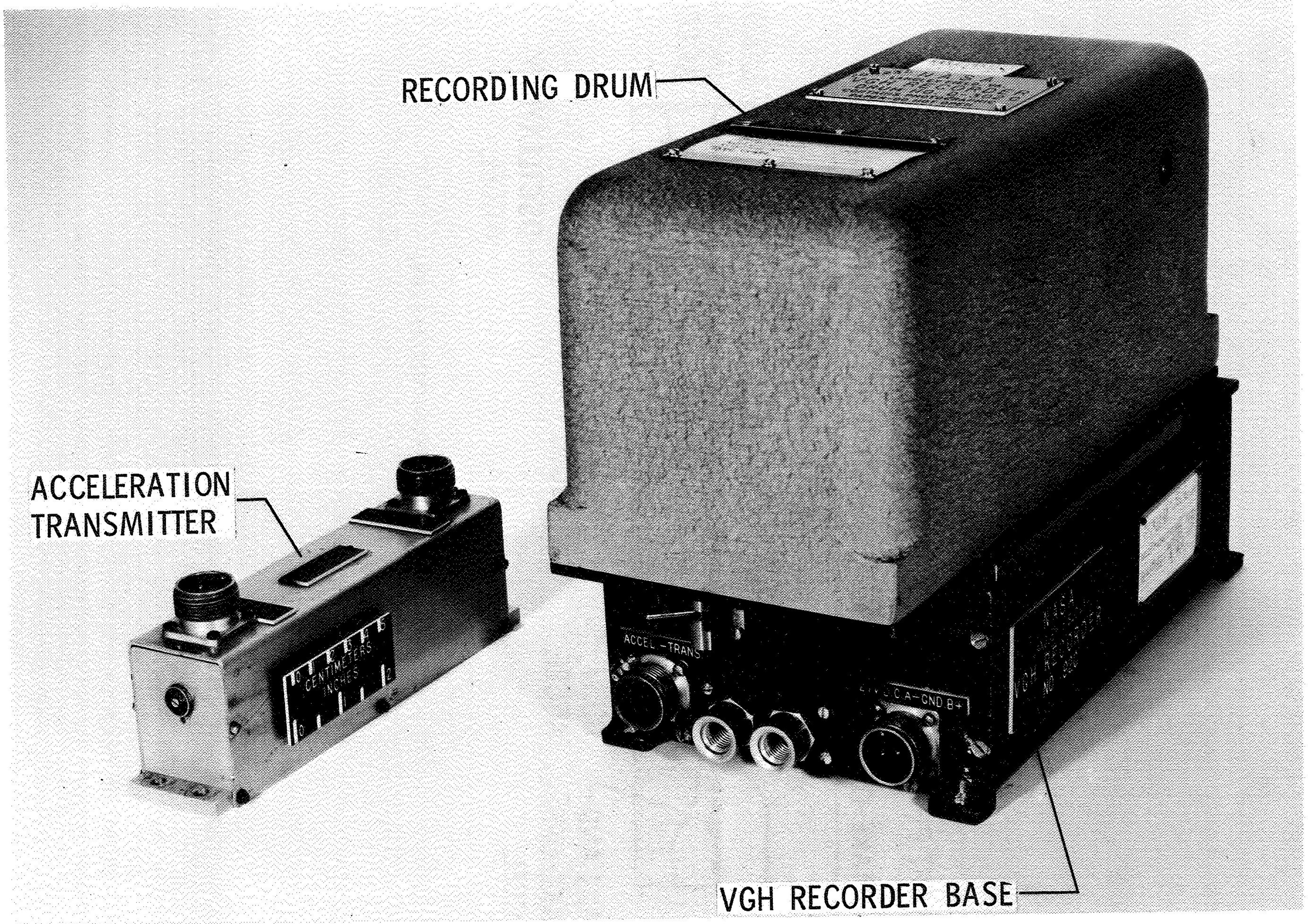


Figure 1.- NACA VGH recorder.

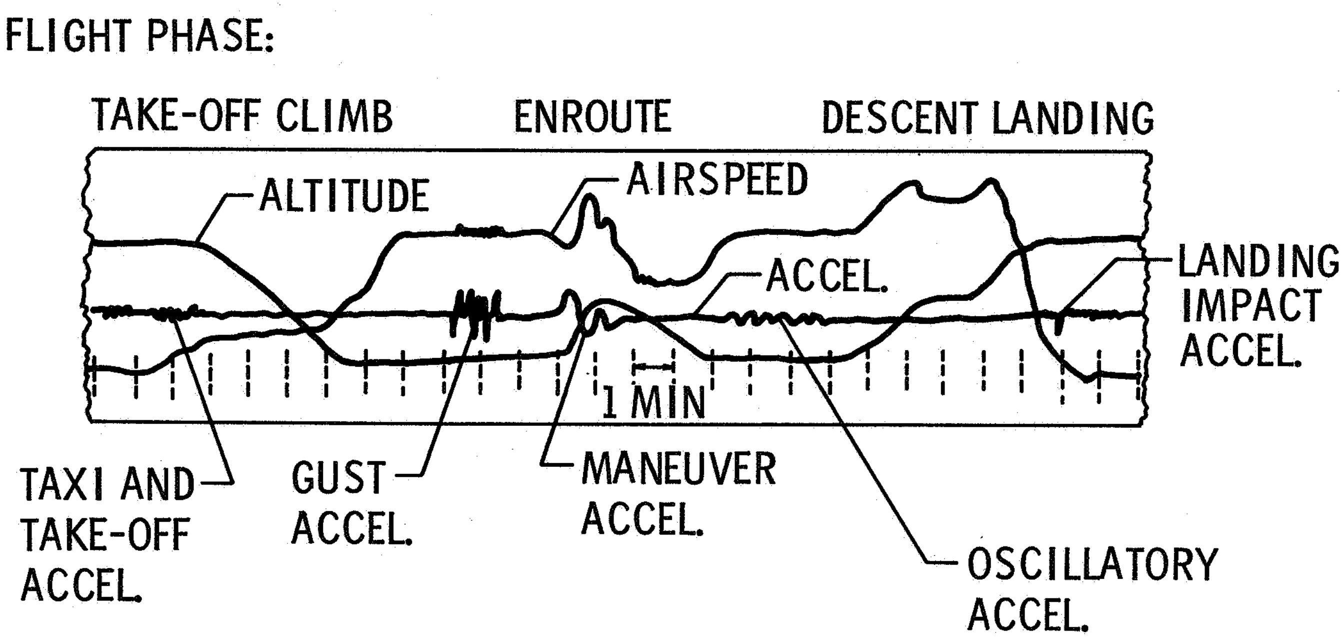


Figure 2.- Illustrative VGH record.

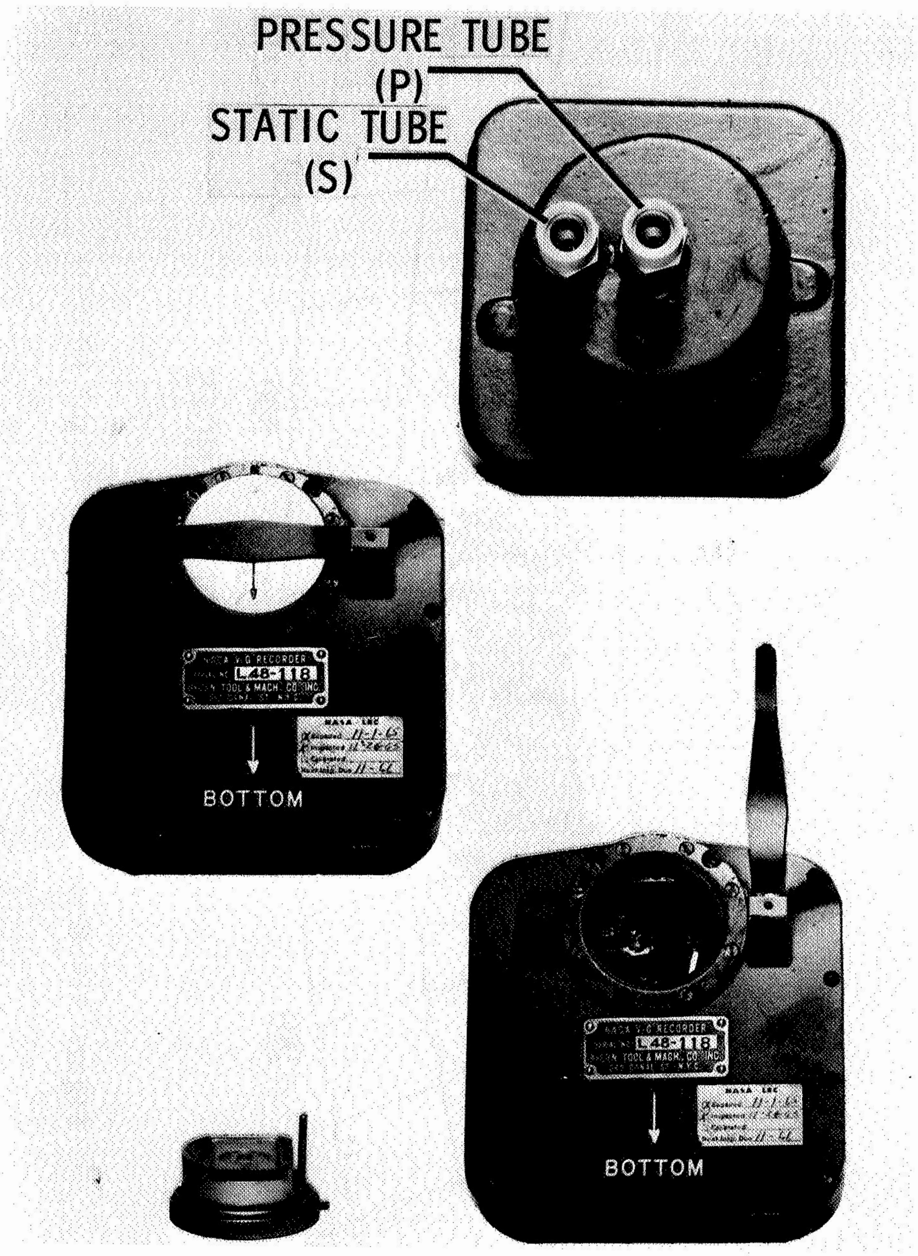


Figure 3.- The NASA oil-damped VG recorder.

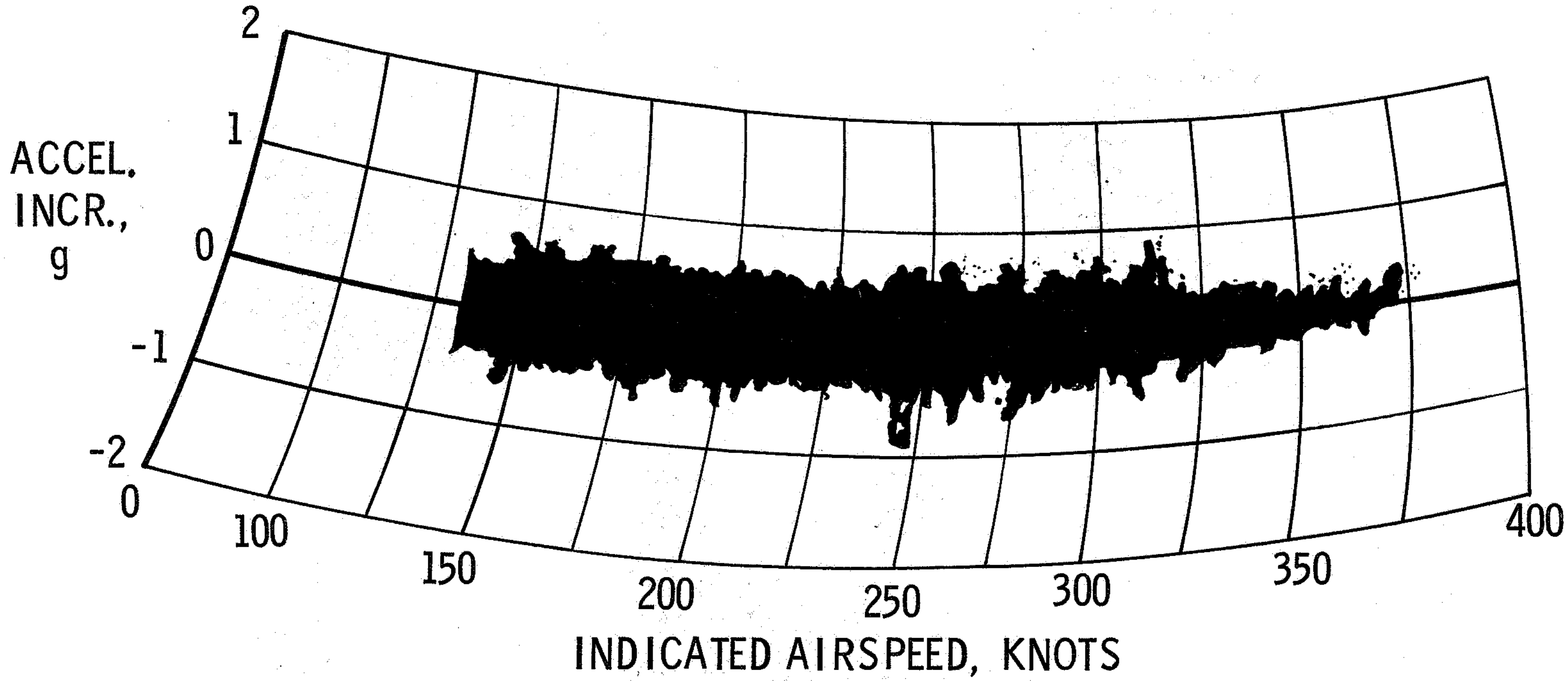


Figure 4.- Example of V-G record (200 flight hours).

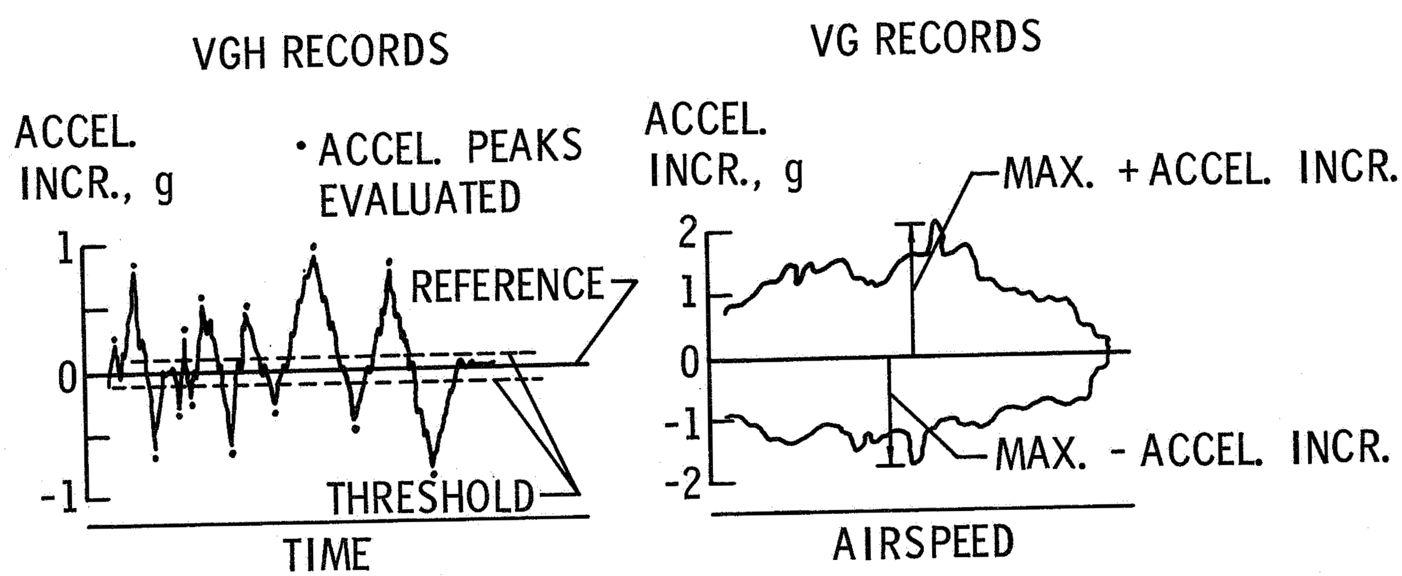


Figure 5.- Method of evaluating accelerations from VGH and V-G records.

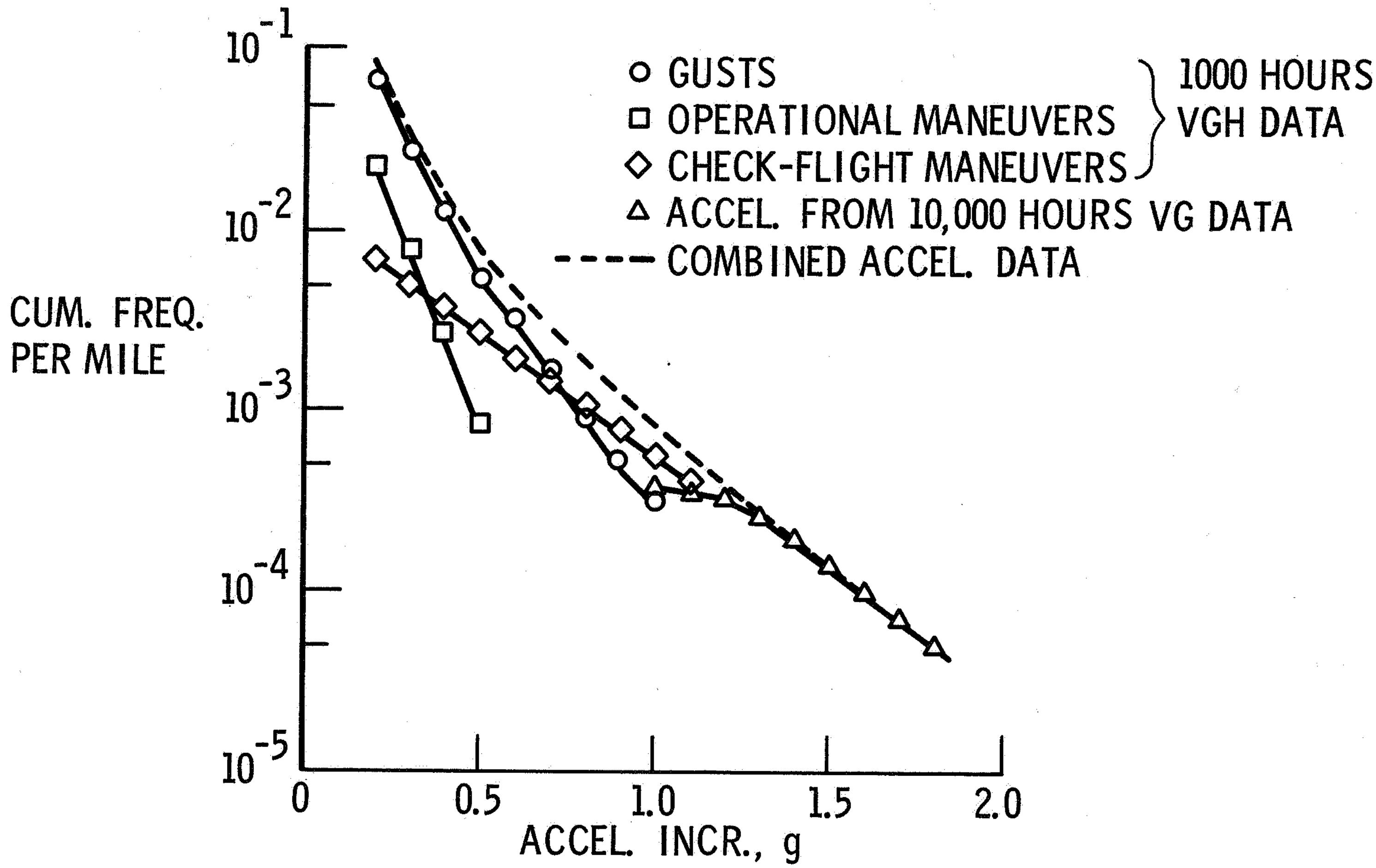


Figure 6.- Method of combining VGH and V-G data.

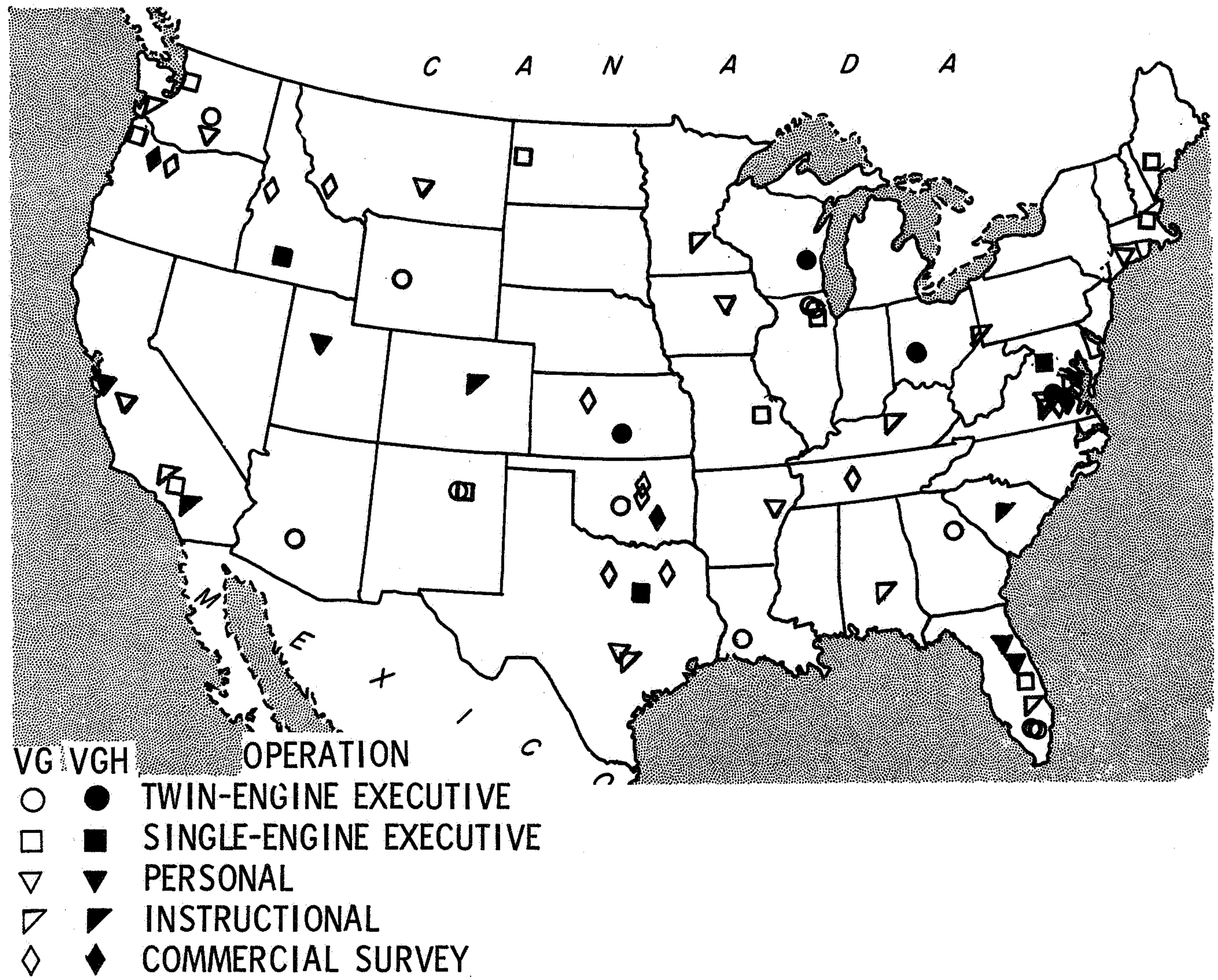


Figure 7.- Location of instrumented airplanes in General Aviation Program.

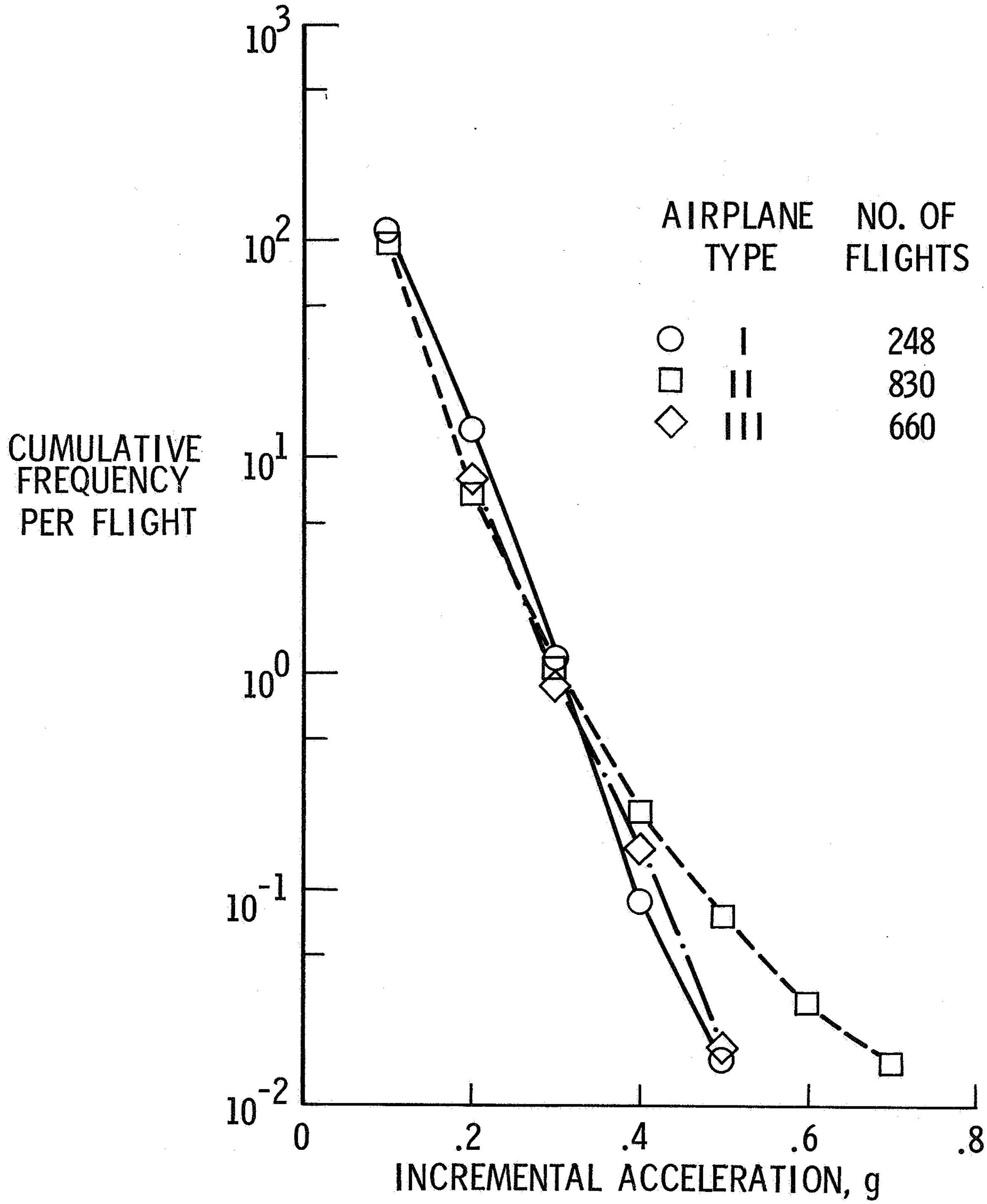


Figure 8.- Comparison of ground-induced accelerations for three operations.

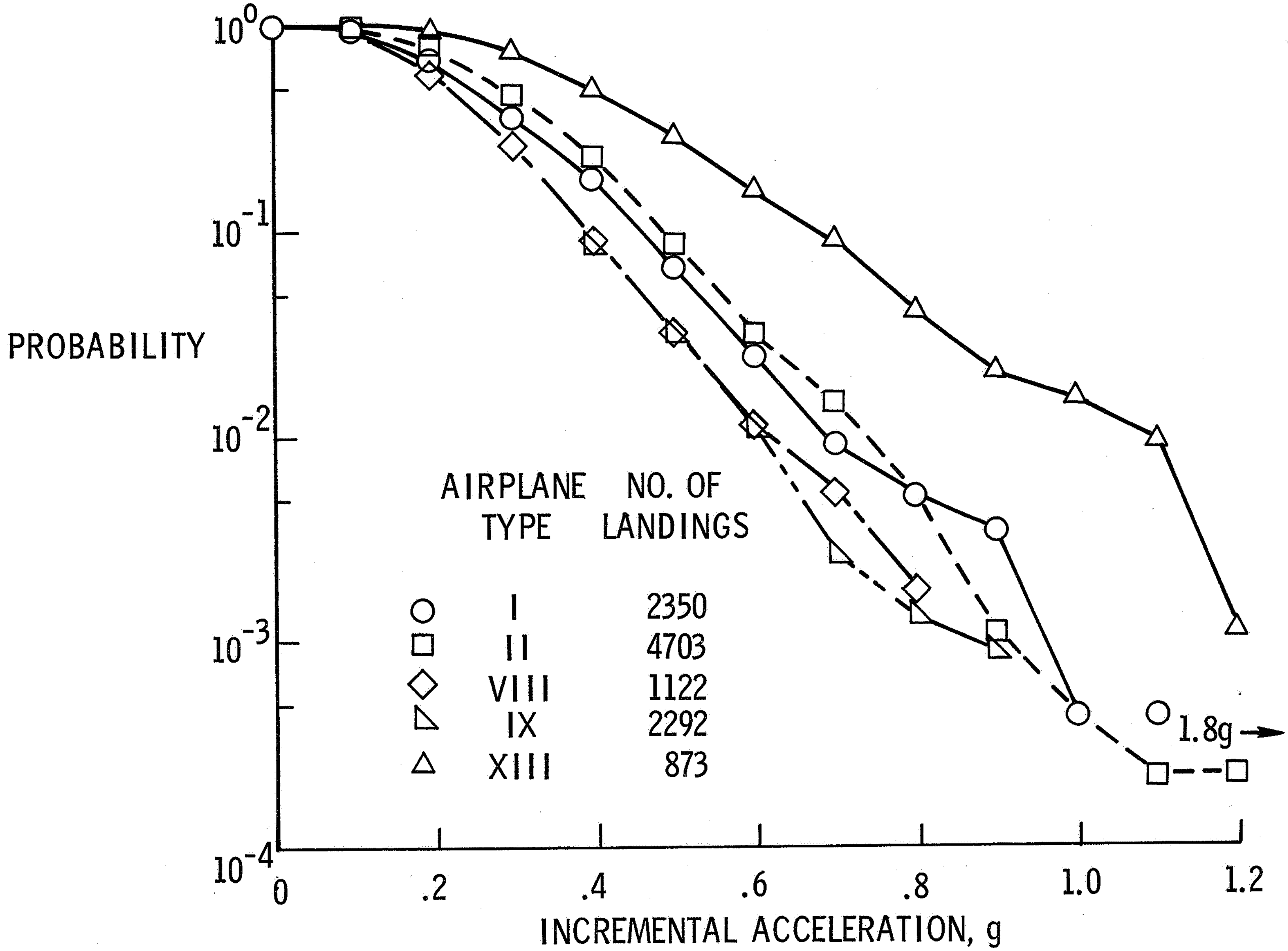


Figure 9.- Landing impact accelerations for five airplane types.

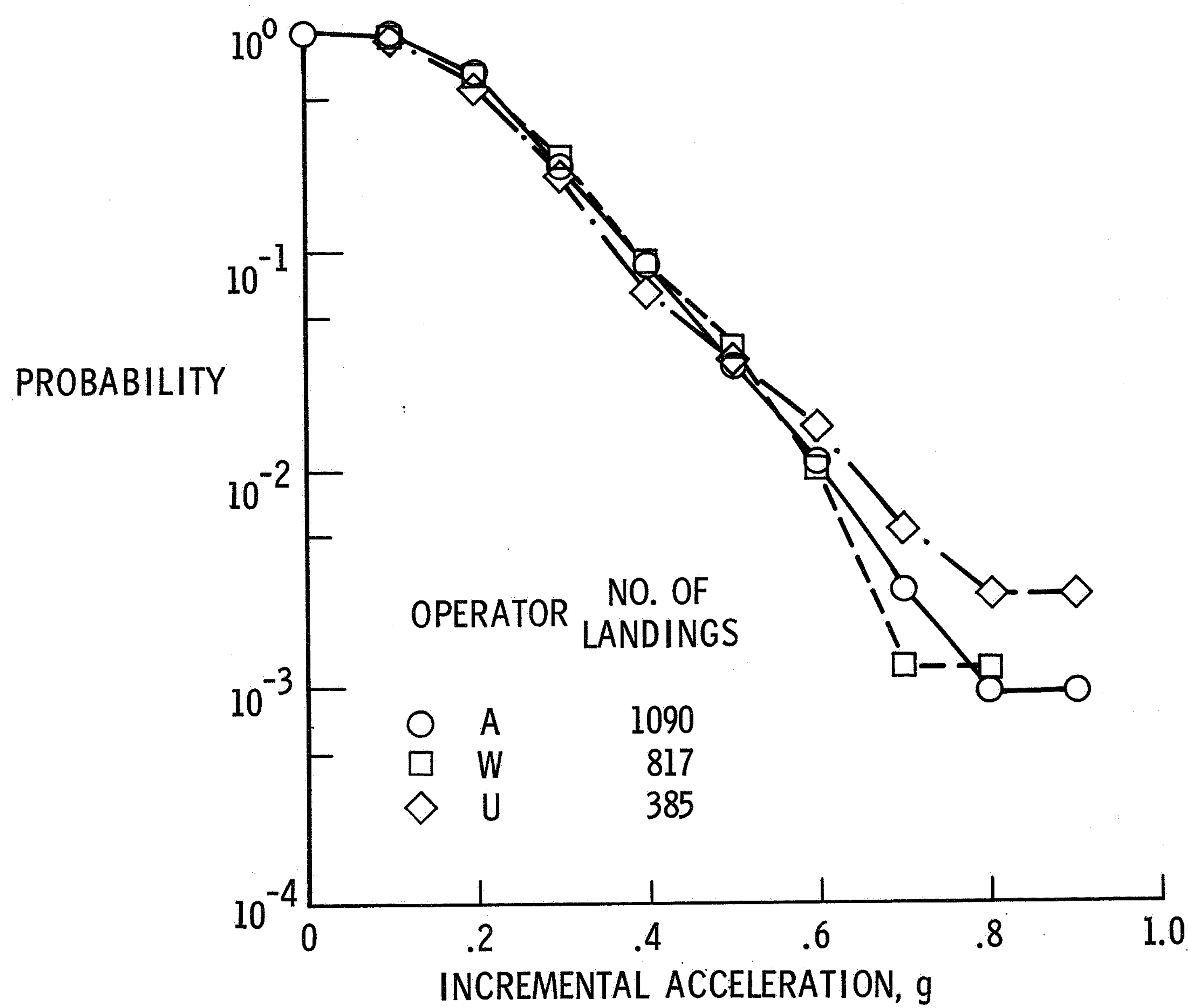


Figure 10.- Effect of operator on landing impact accelerations. Type IX airplane.

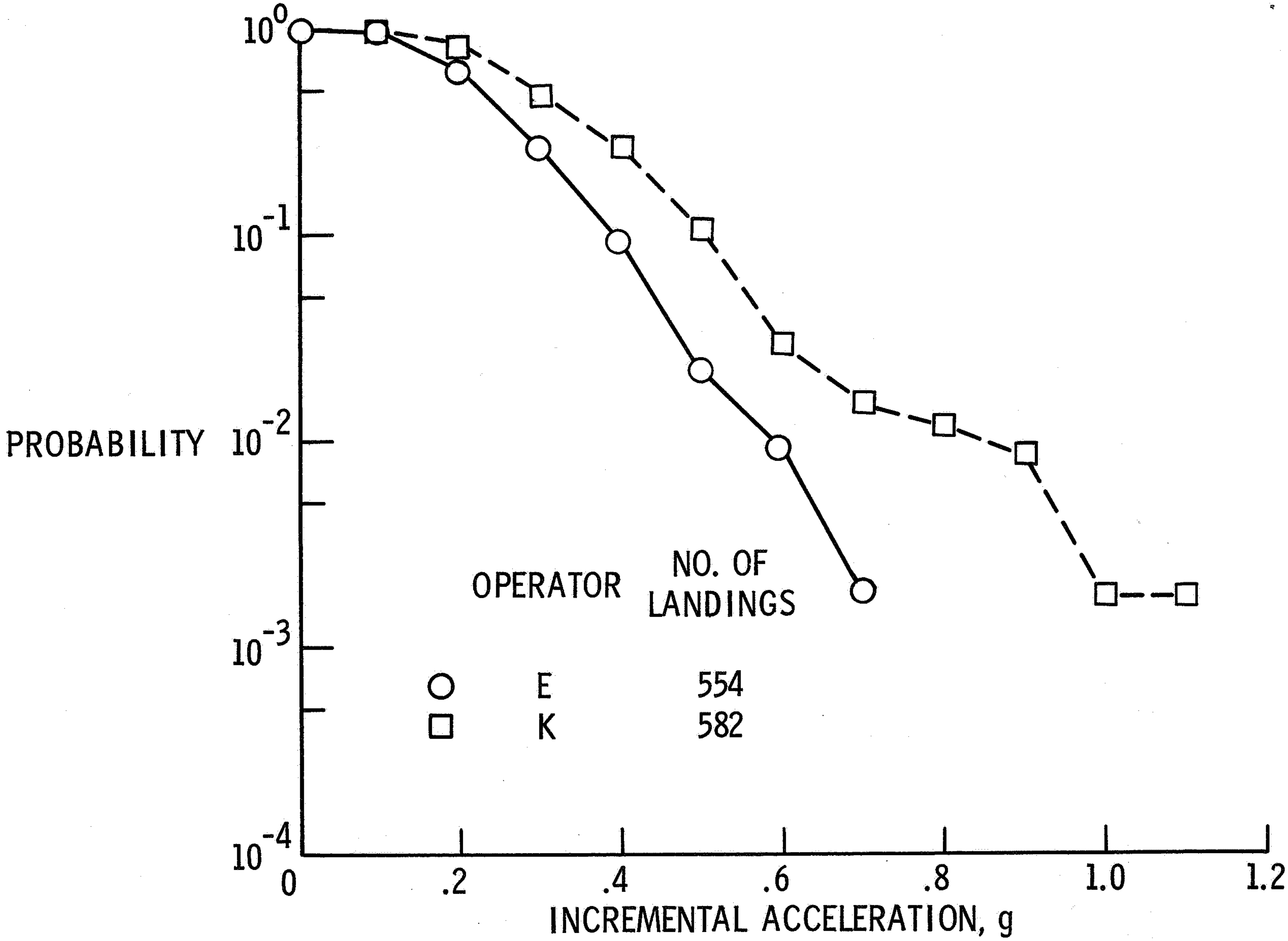


Figure 11.- Effect of landing approach technique on landing impact accelerations. Type I airplane.

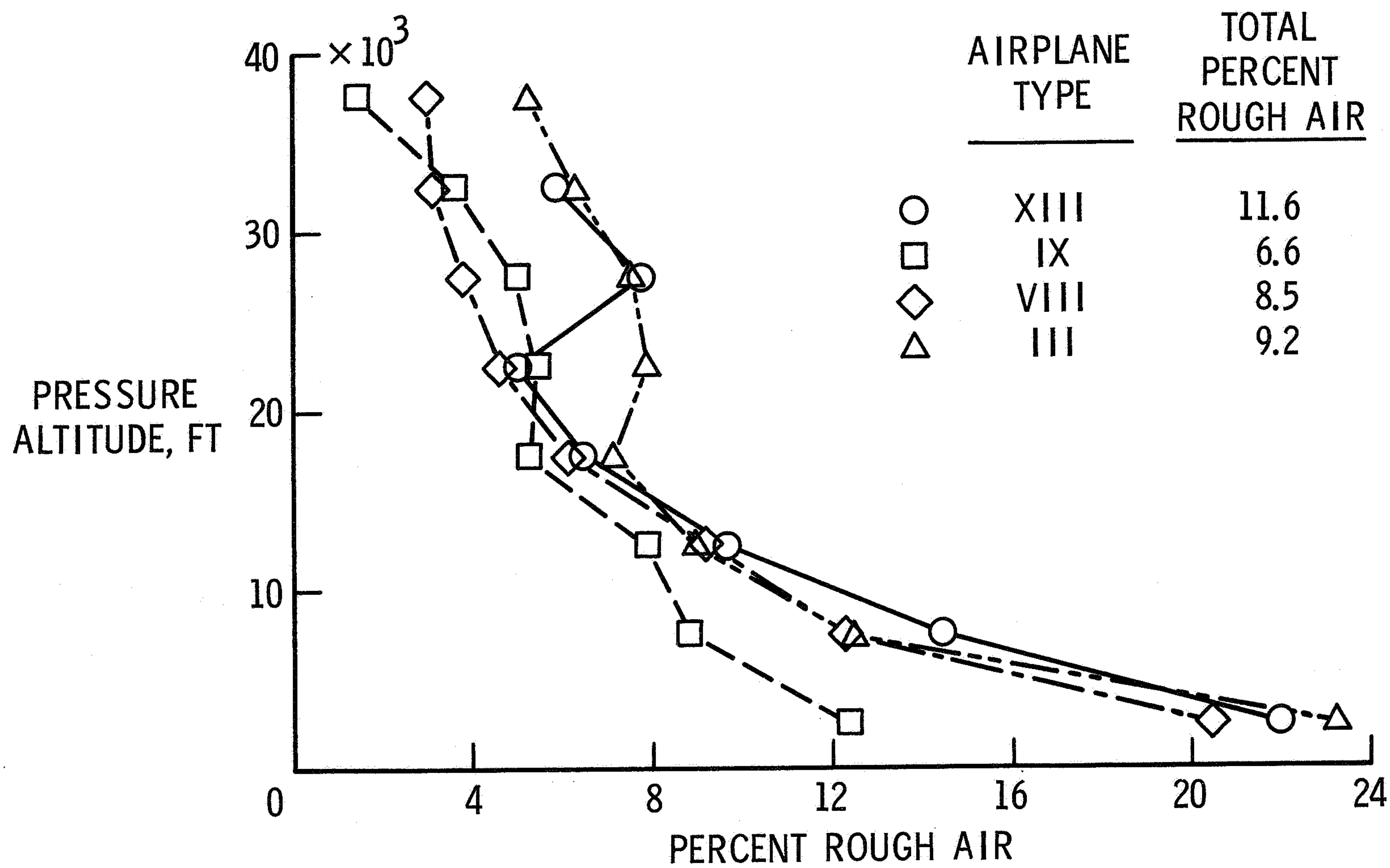


Figure 12.- Amount of rough air as a function of altitude.

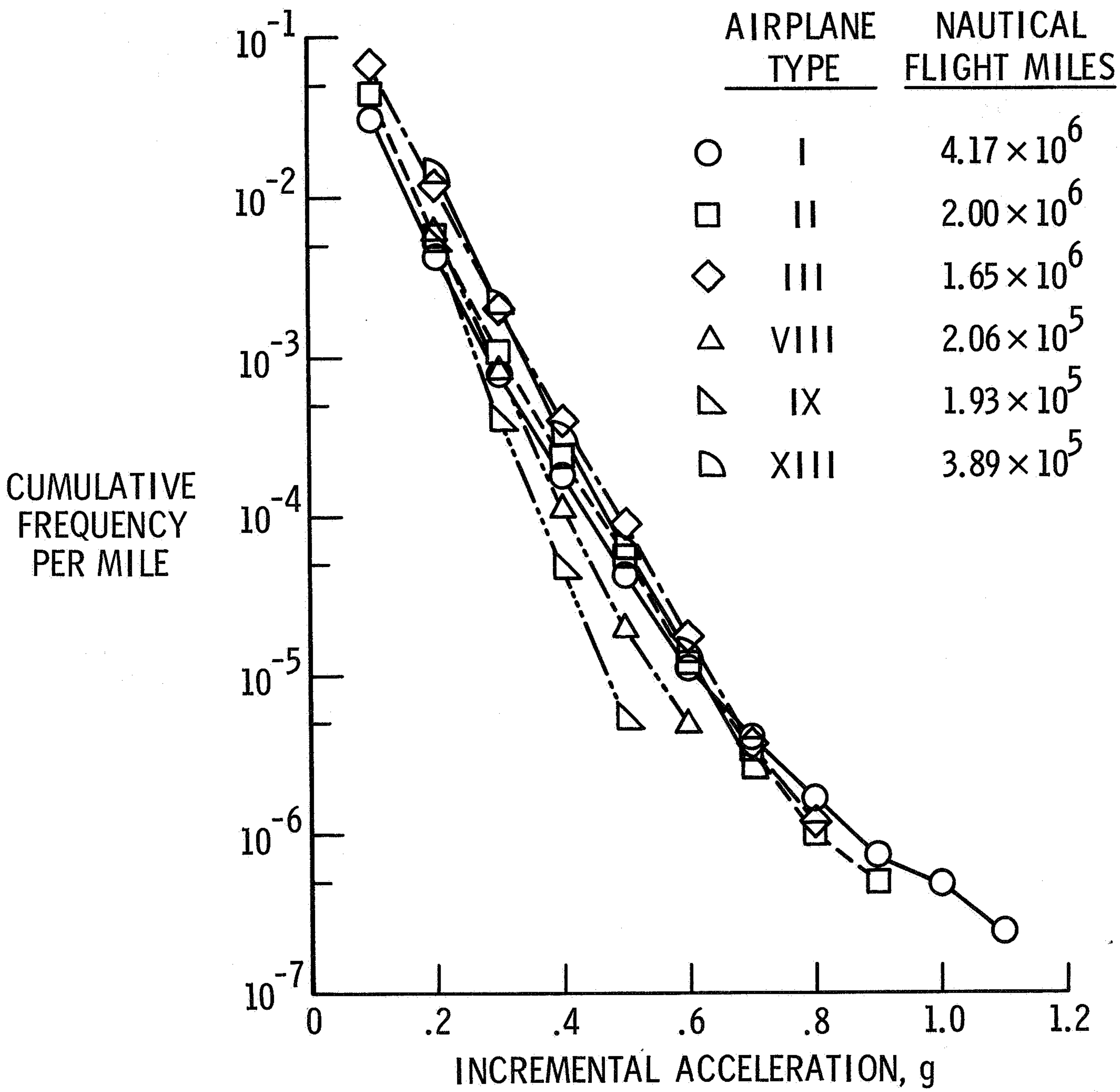


Figure 13.- Summary of accelerations experienced during operational maneuvers.

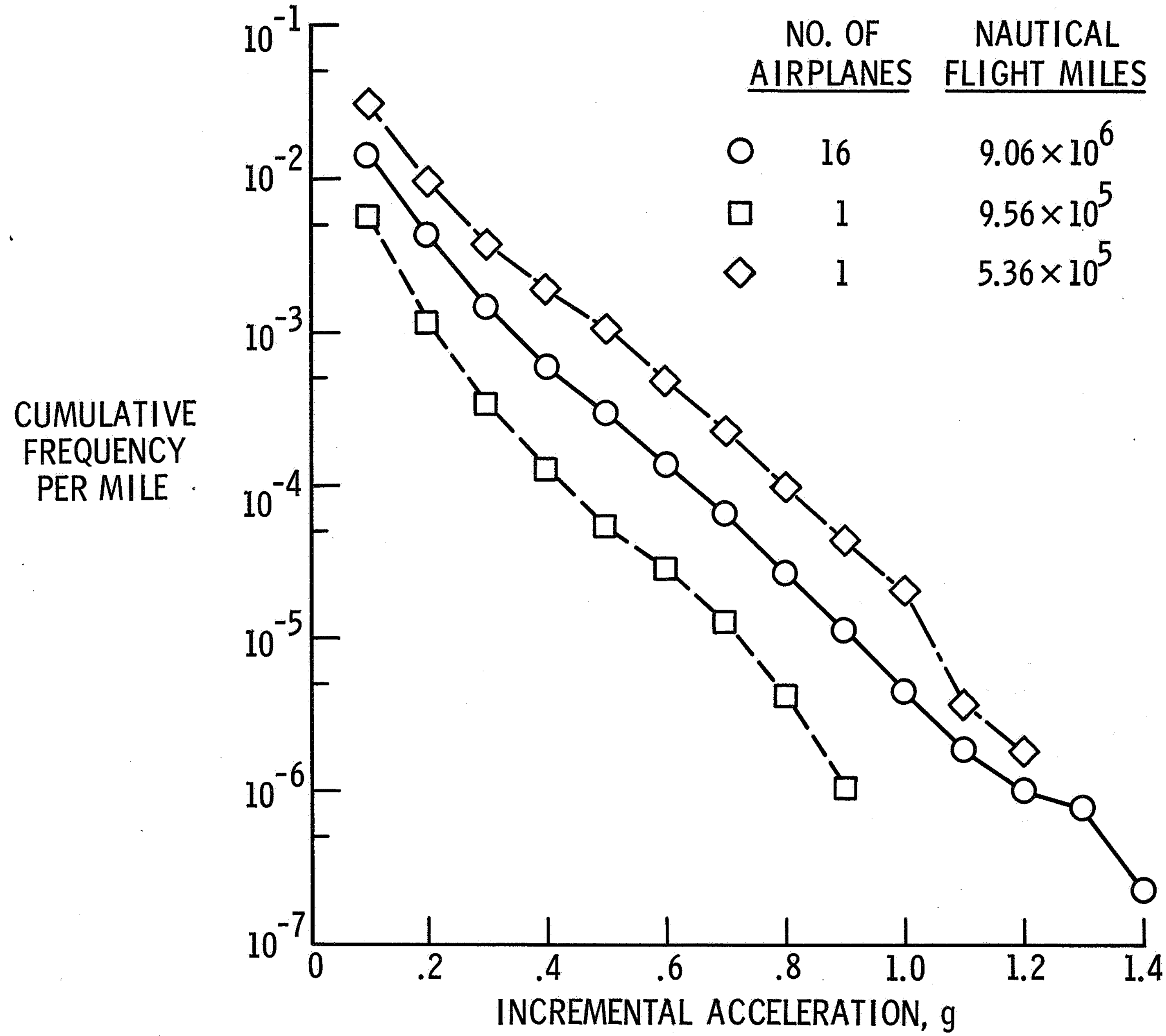
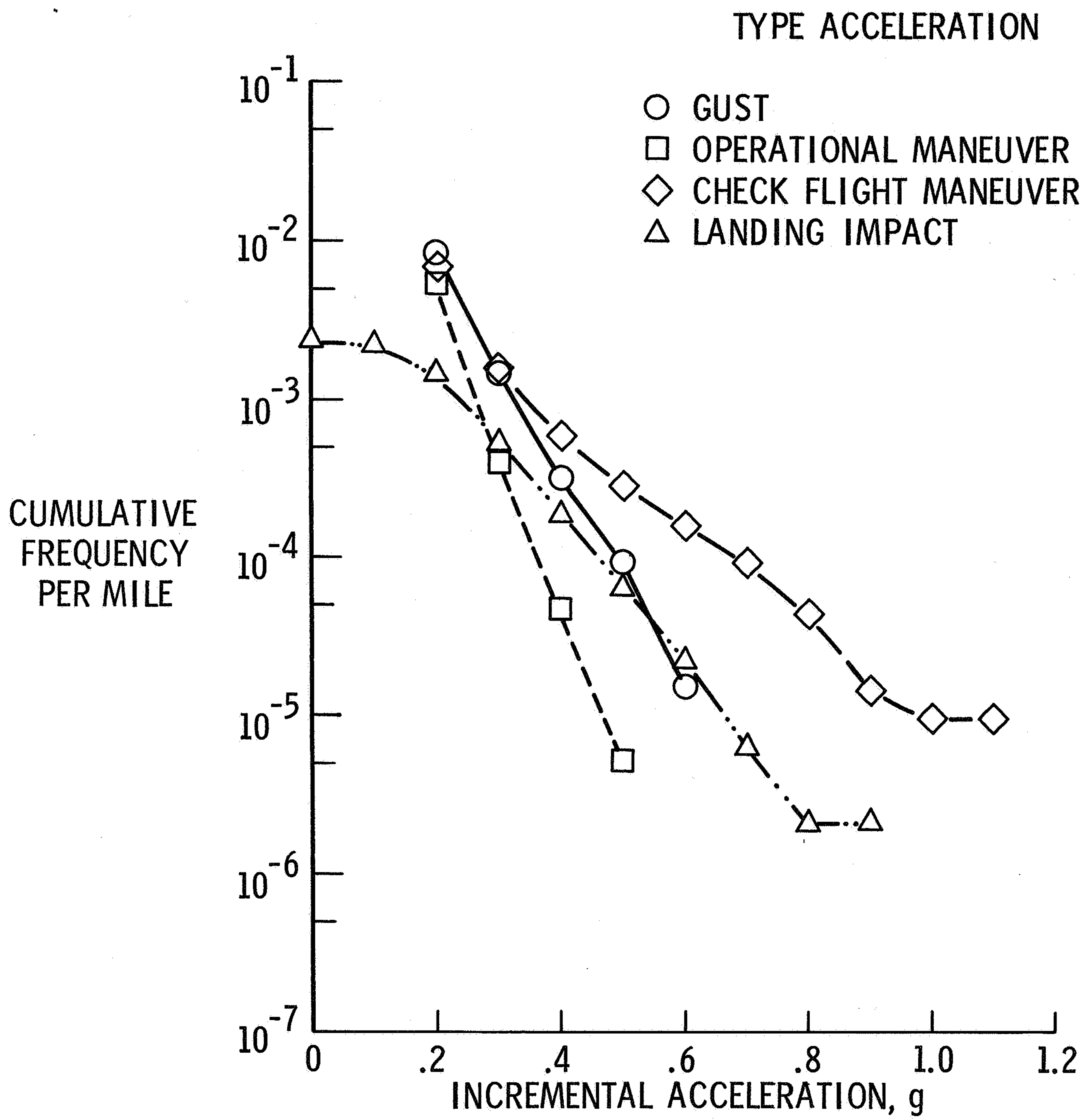
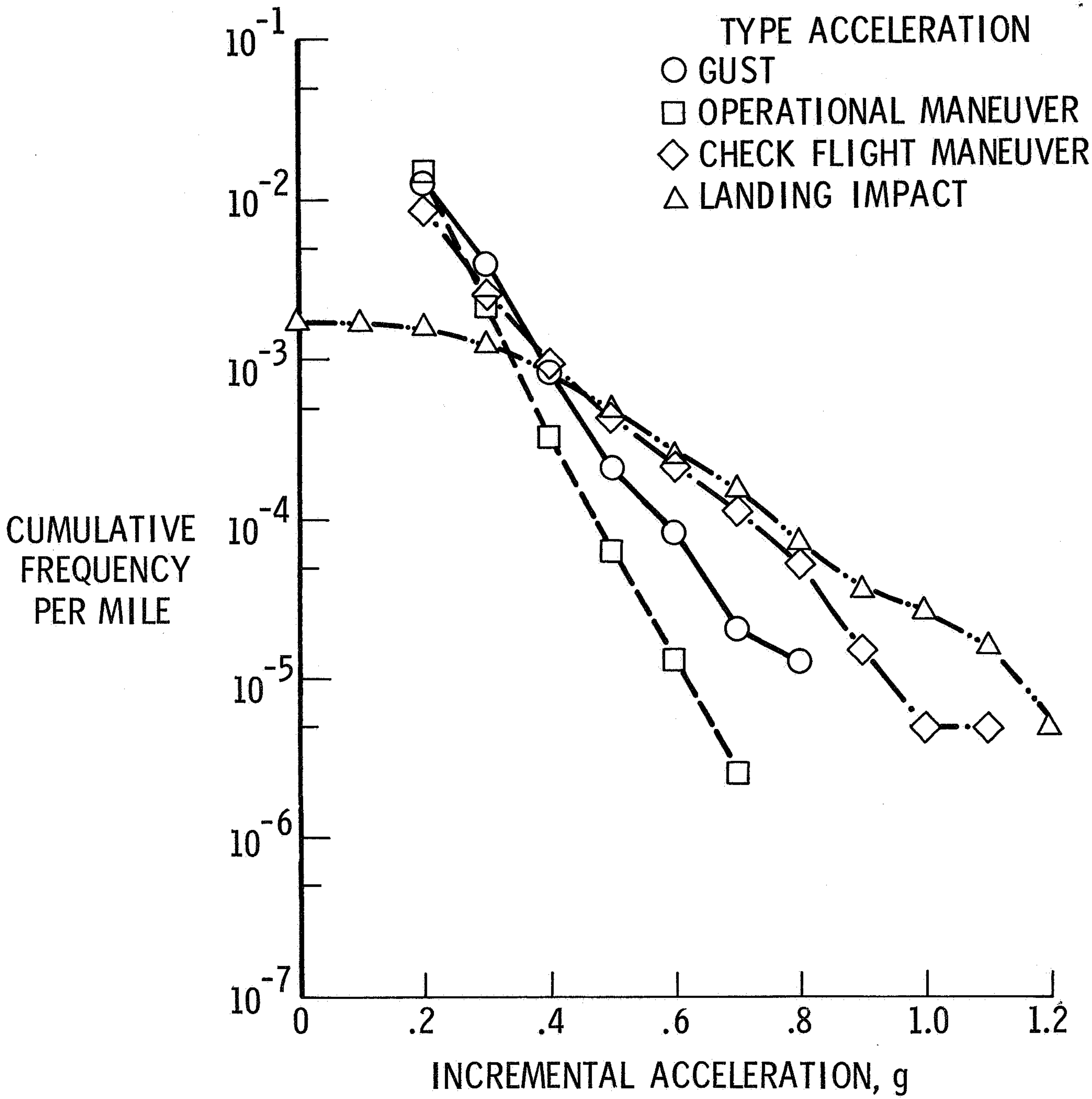


Figure 14.- Summary of accelerations experienced during check flights.



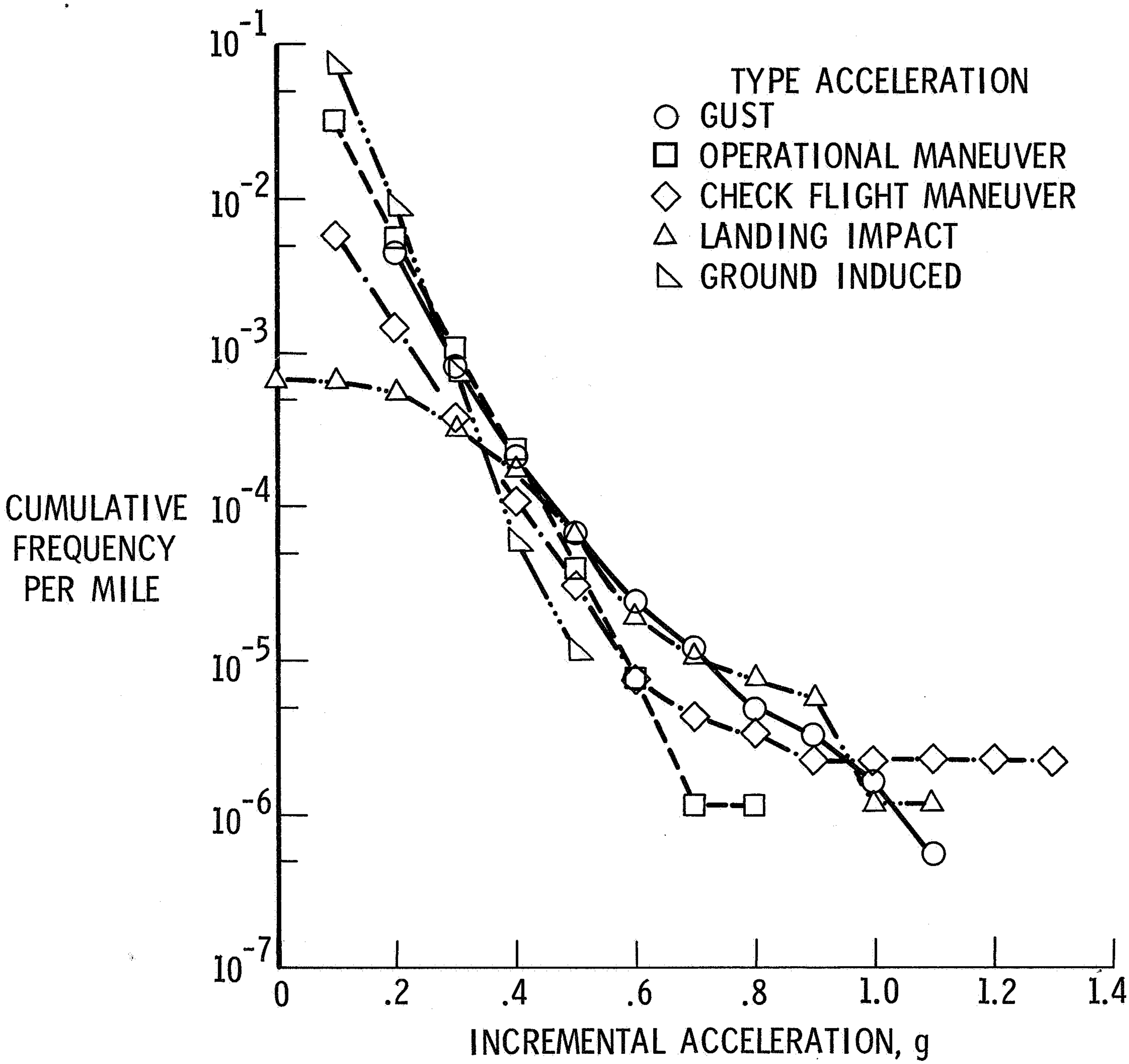
(a) Type IX airplane.

Figure 15.- Summary of total acceleration experience for each of four jet transport operations.



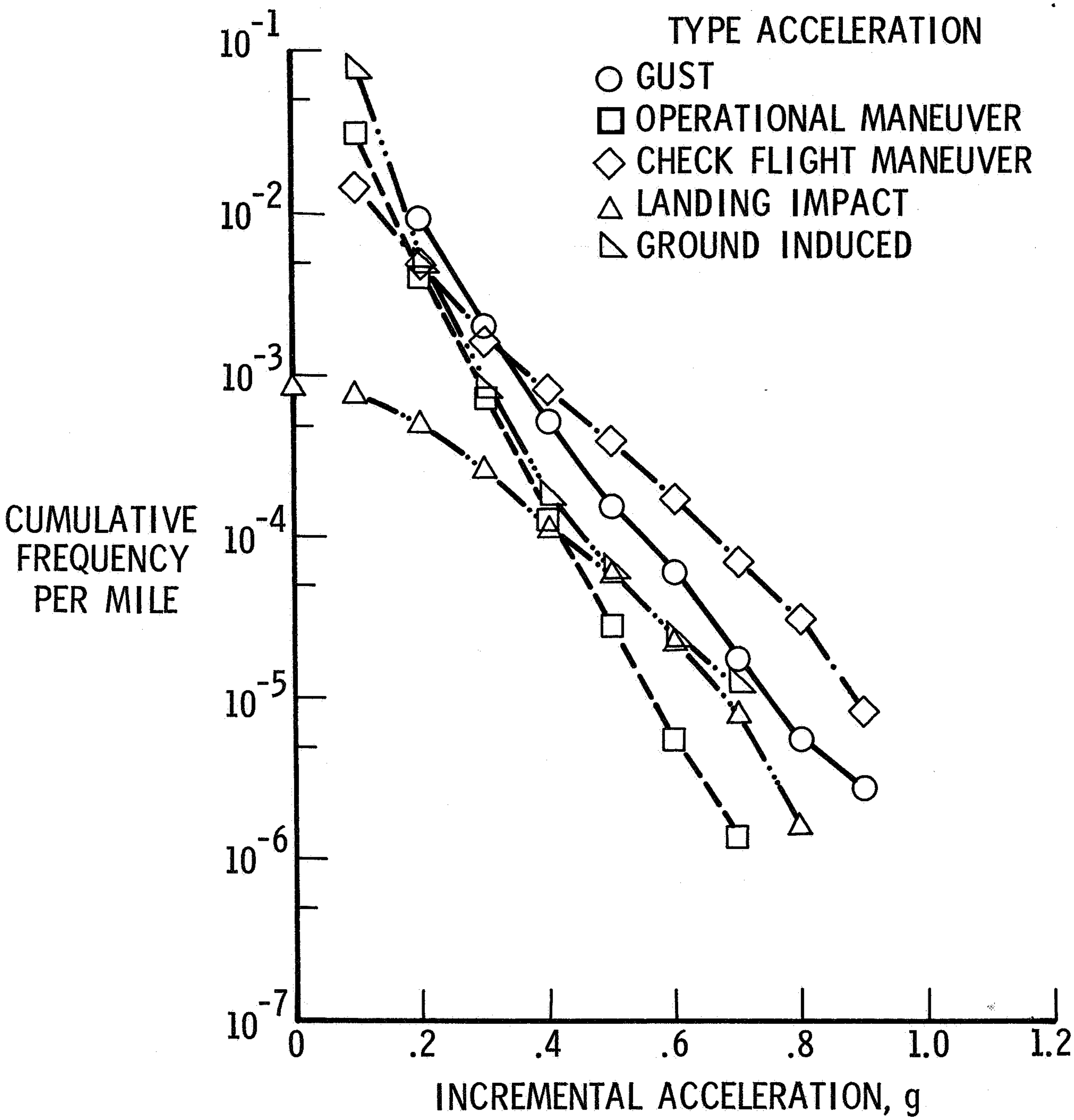
(b) Type XIII airplane.

Figure 15.- Continued.



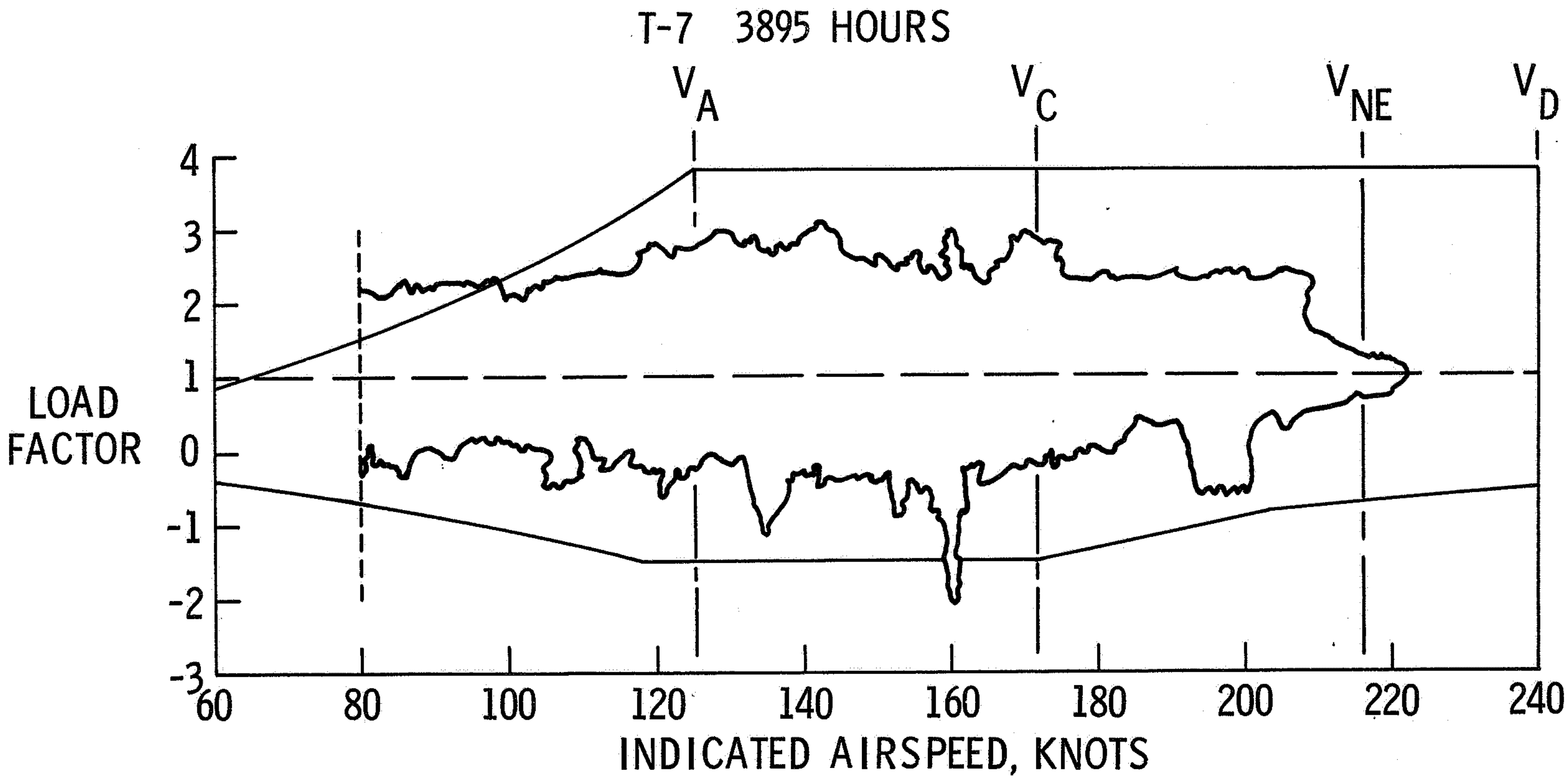
(c) Type ID airplane.

Figure 15.- Continued.



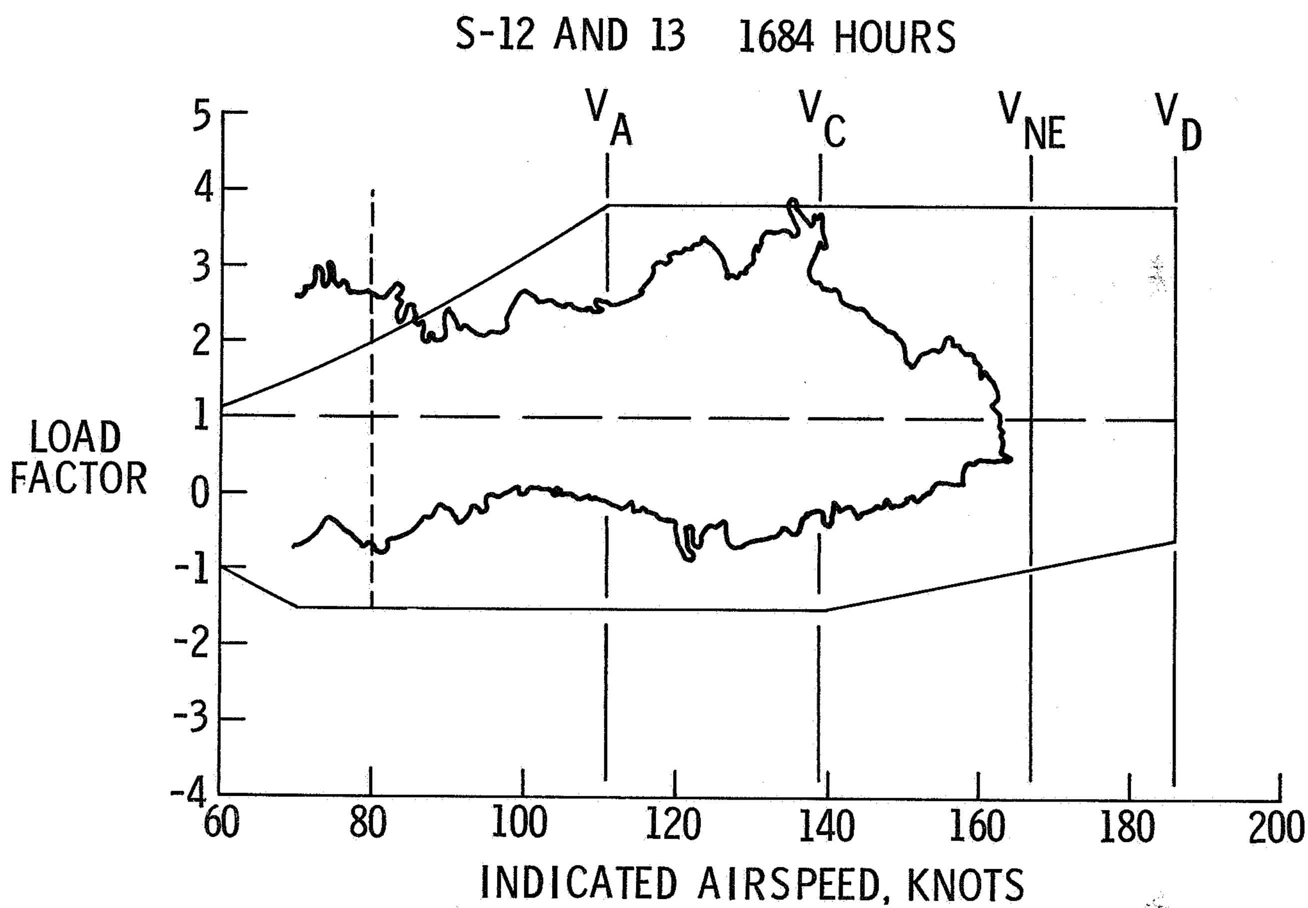
(d) Type II airplane.

Figure 15.- Concluded.



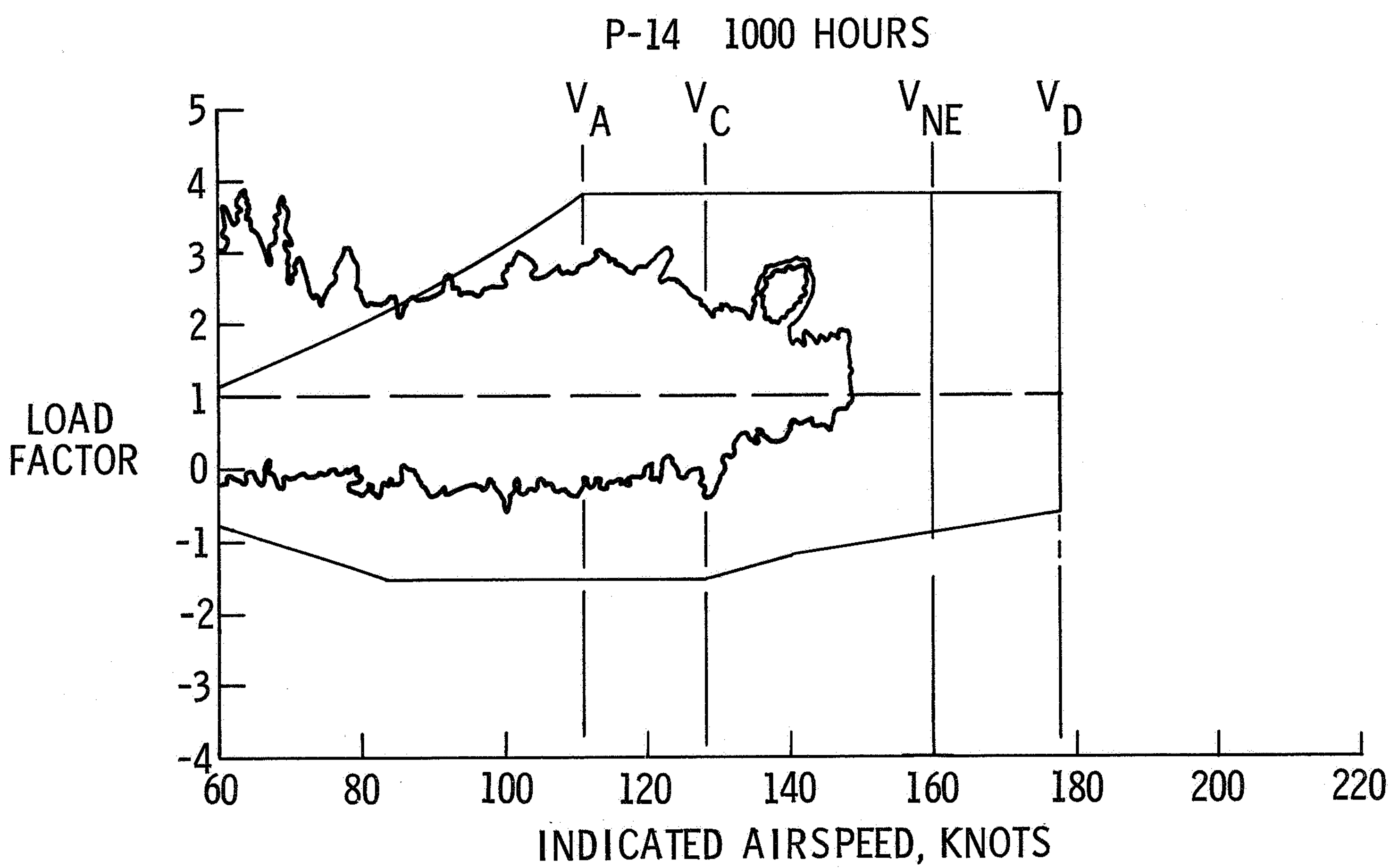
(a) Twin-engine executive.

Figure 16.- Envelopes of airspeed and acceleration experience for General Aviation airplane categories.



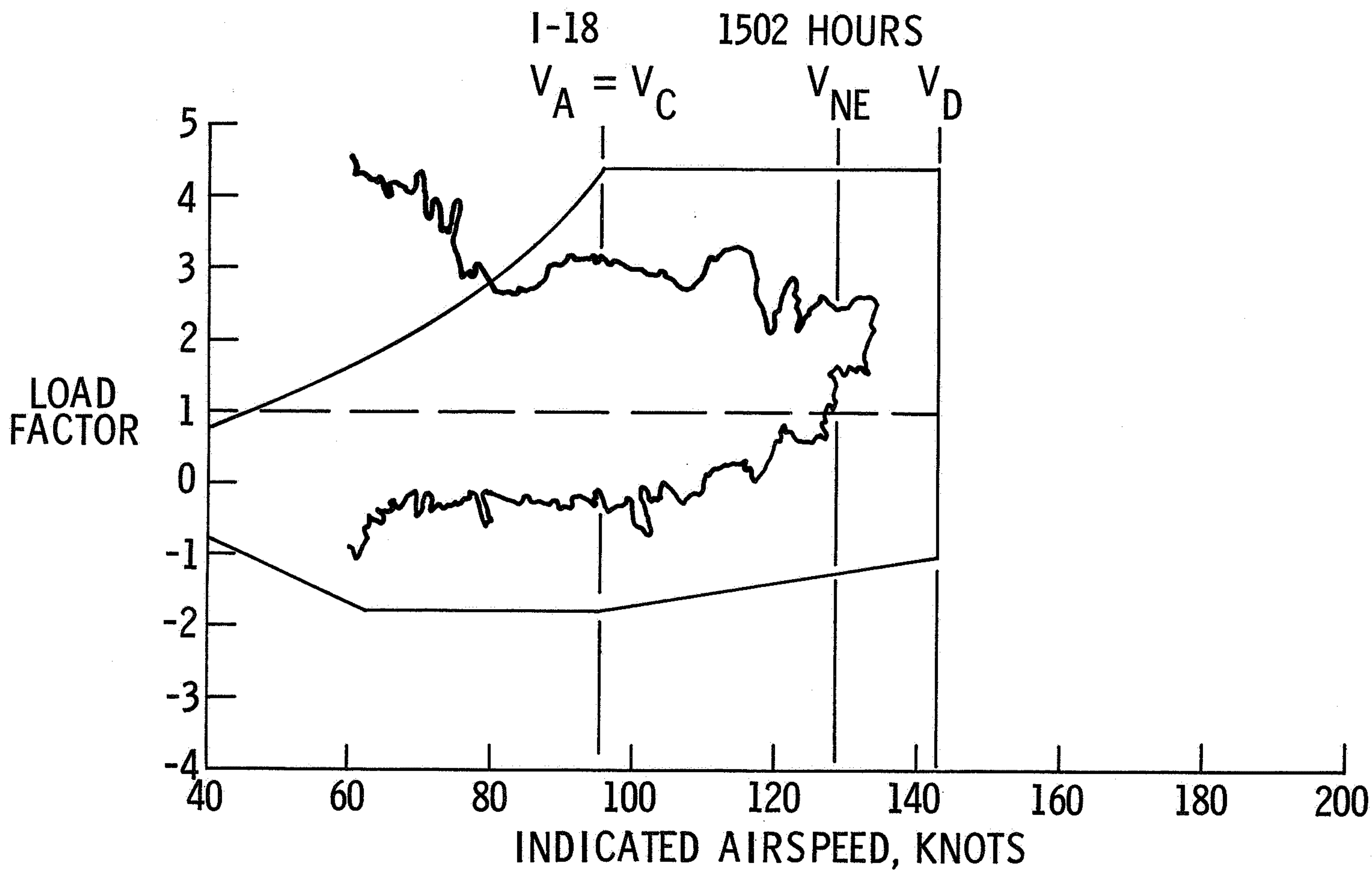
(b) Single-engine executive.

Figure 16.- Continued.



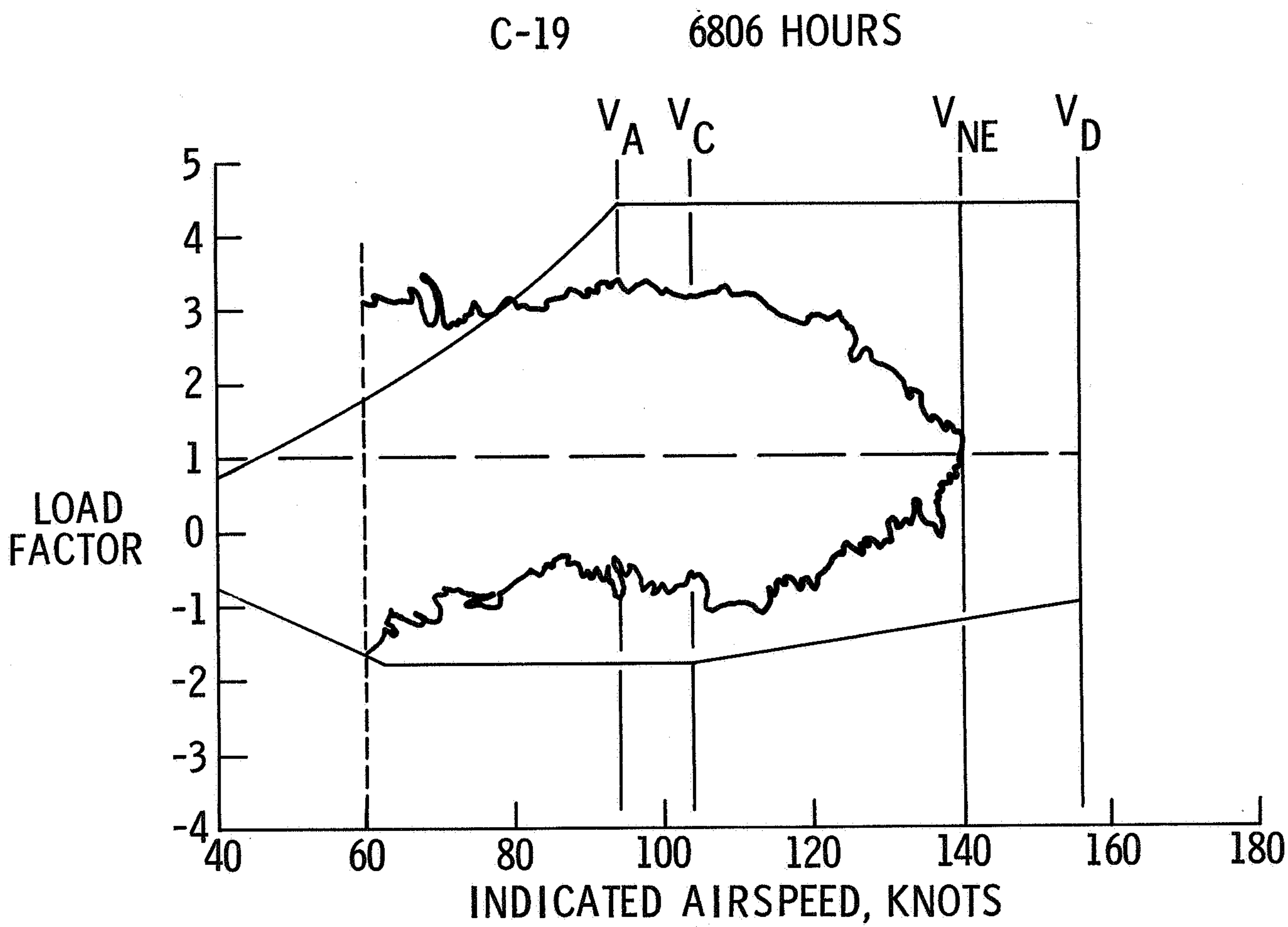
(c) Personal.

Figure 16.- Continued.



(d) Instructional.

Figure 16.- Continued.



(e) Commercial survey.

Figure 16.- Concluded.

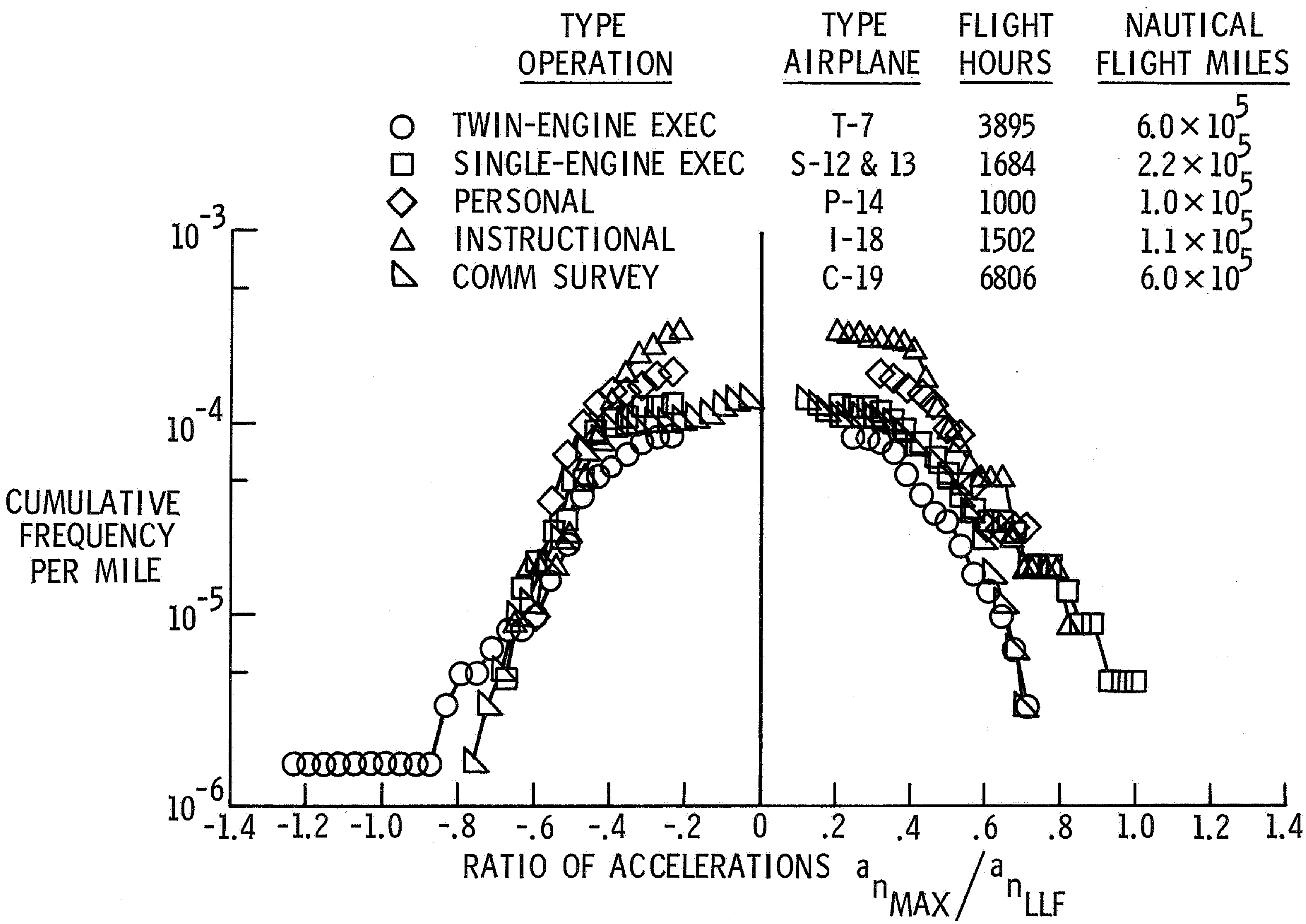


Figure 17.- Comparison of the ratio of maximum in-flight accelerations to the limit maneuver load factor for five types of operations. VG data.

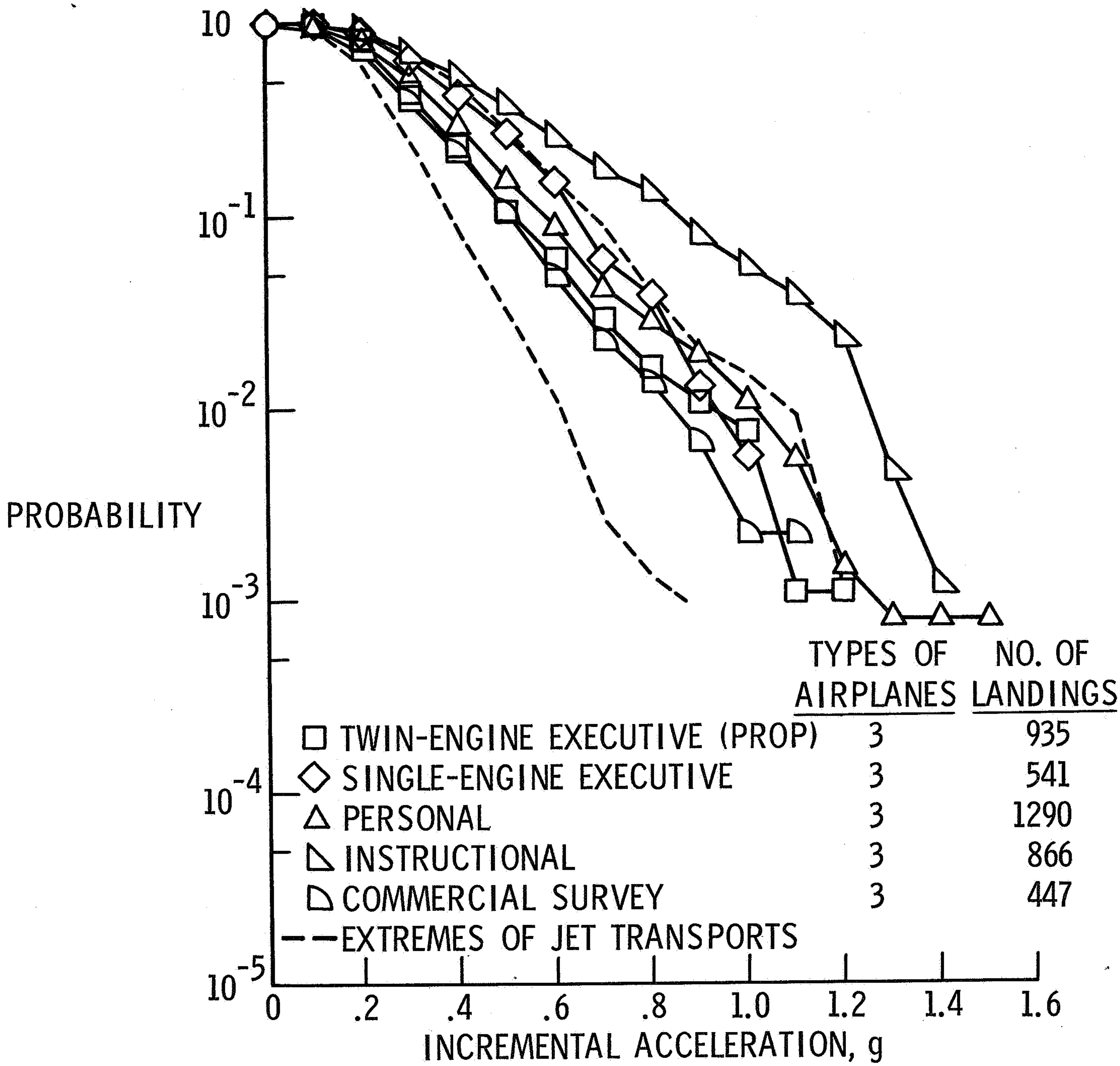
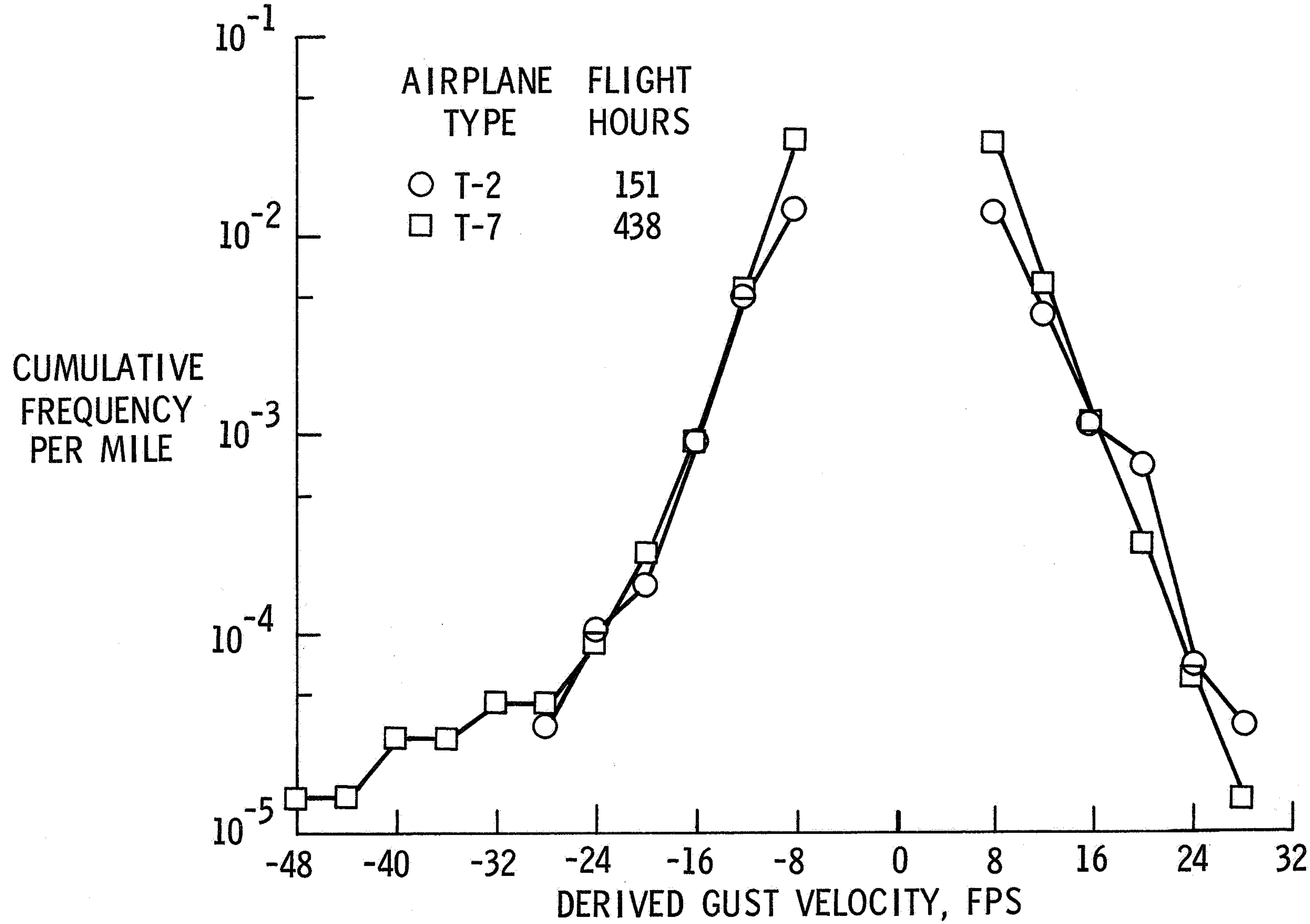
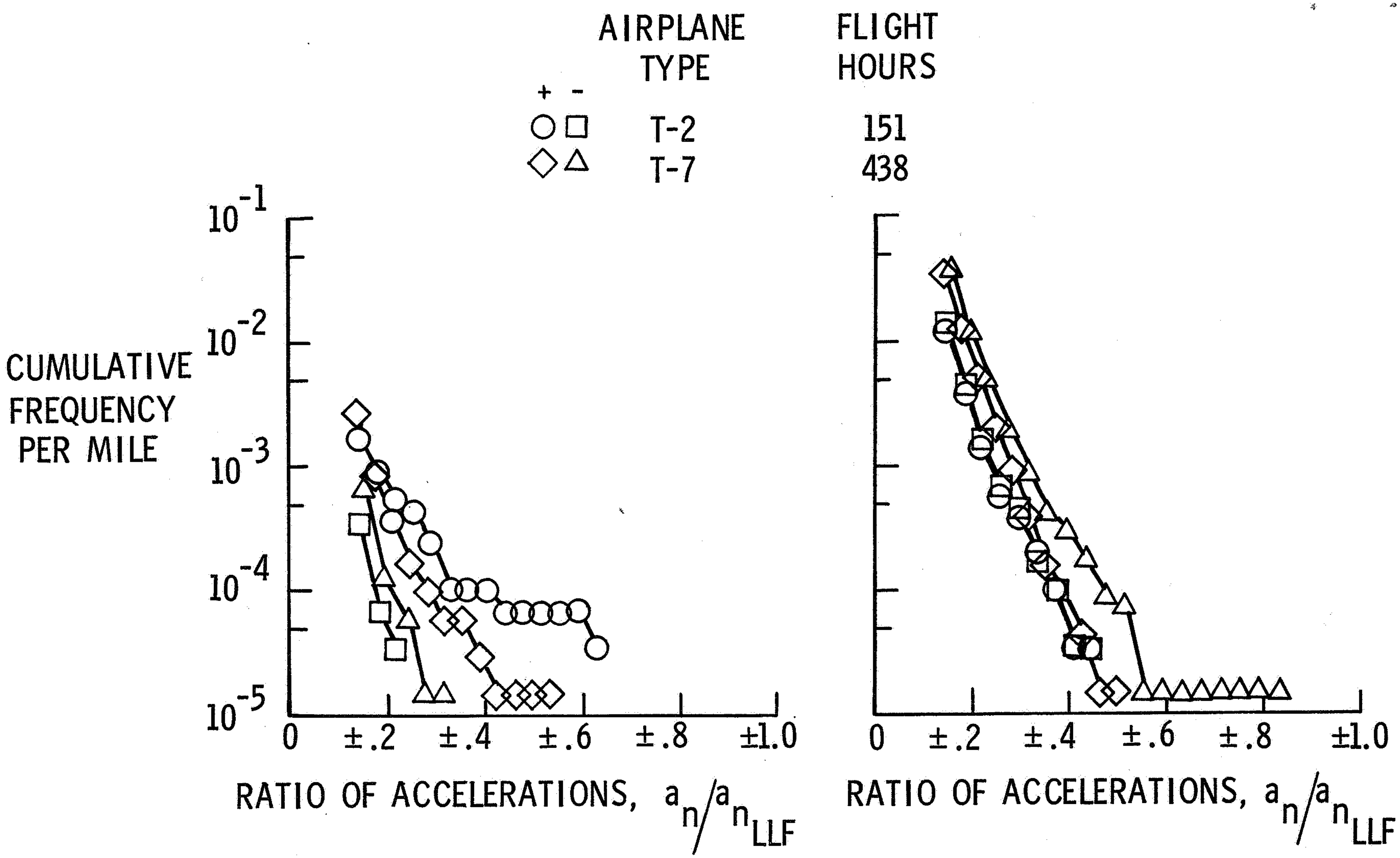


Figure 18. - Landing impact accelerations experienced by General Aviation airplanes.



(a) Gust velocity distribution.

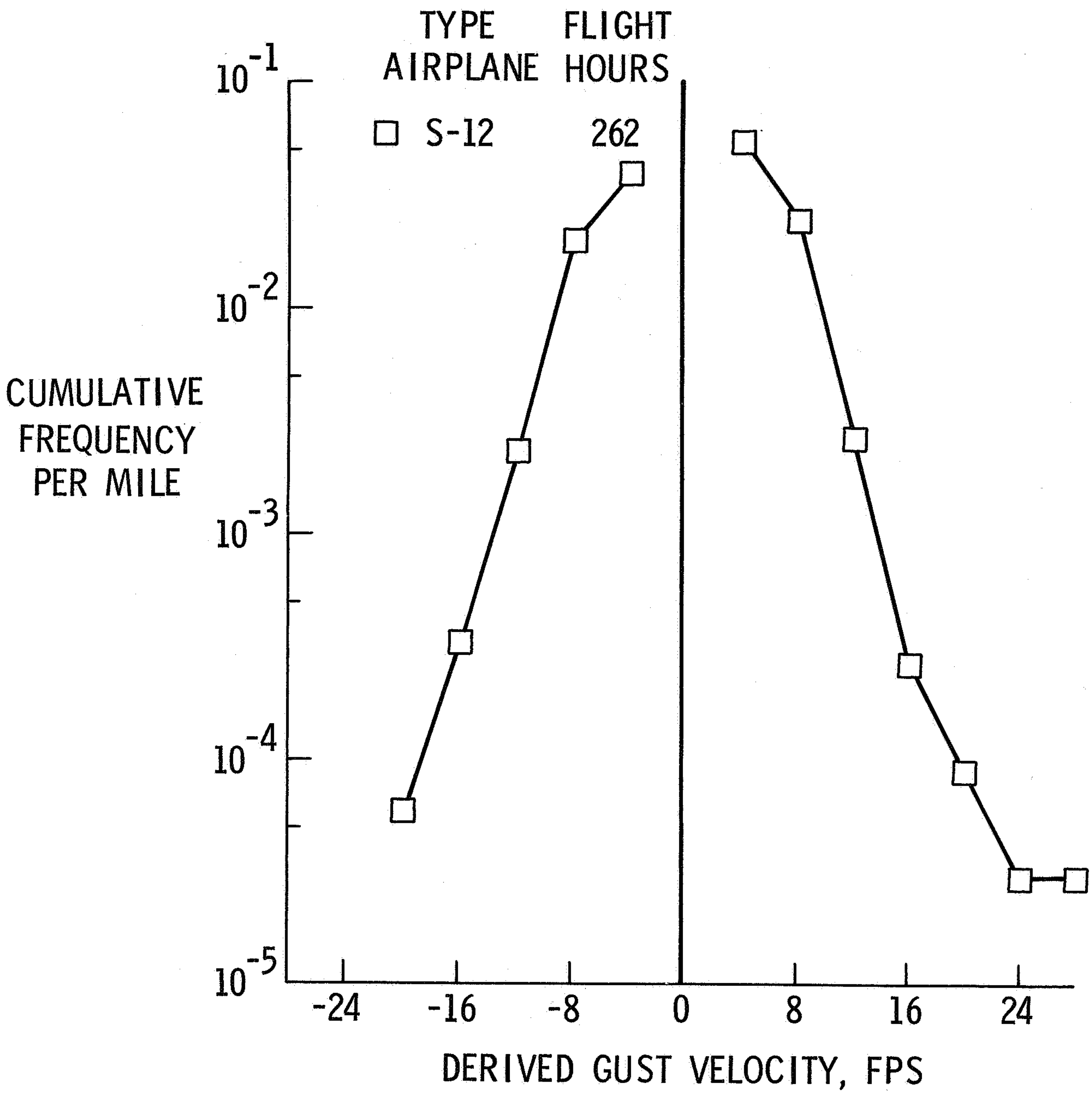
Figure 19.- Gust velocity and in-flight acceleration experience for twin-engine executive operations.



(b) Maneuver acceleration distribution.

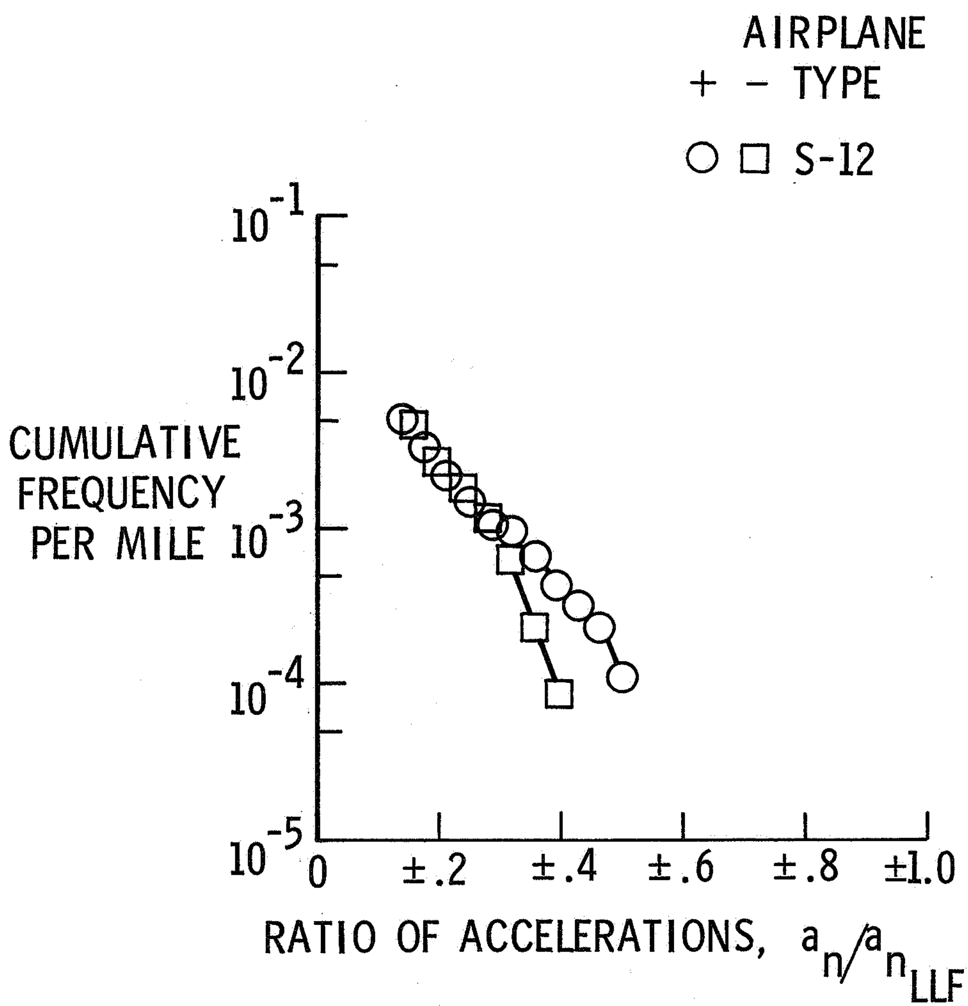
(c) Gust acceleration distribution.

Figure 19.- Concluded.

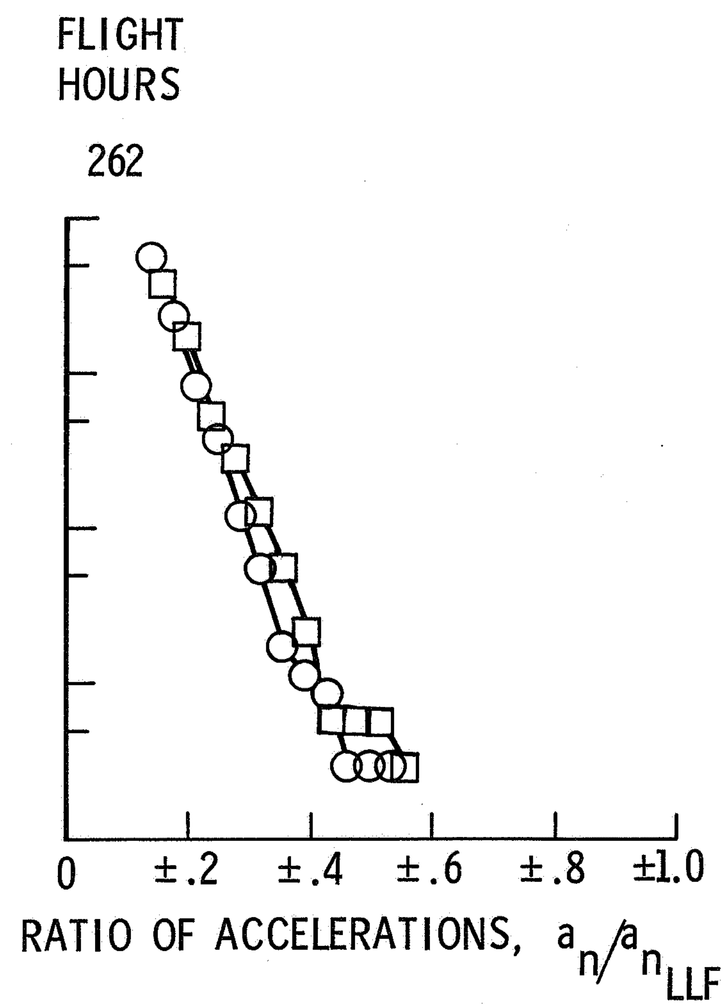


(a) Gust velocity distribution.

Figure 20.- Gust velocity and in-flight acceleration experience for single-engine executive operations.

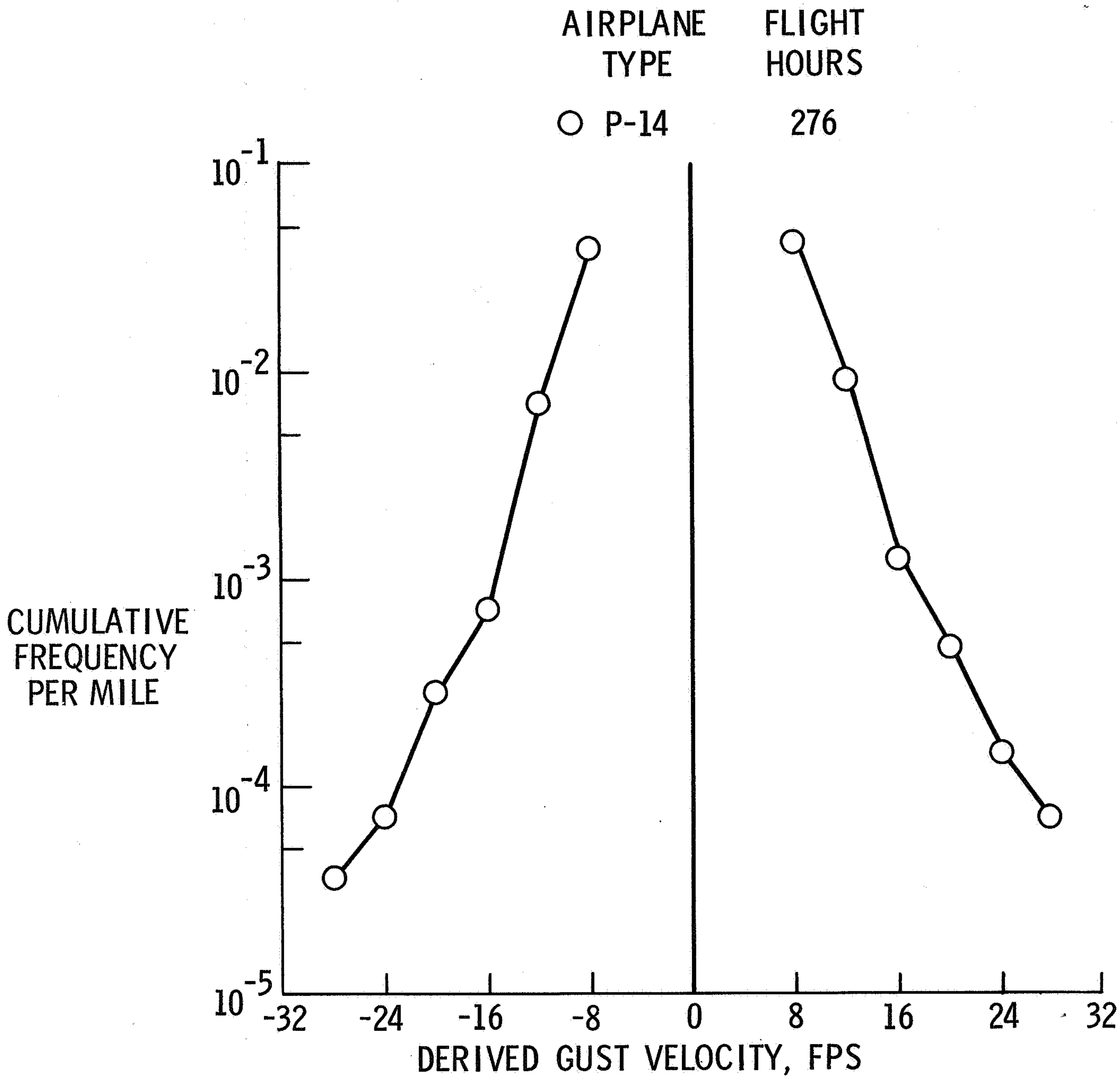


(b) Maneuver acceleration distribution.



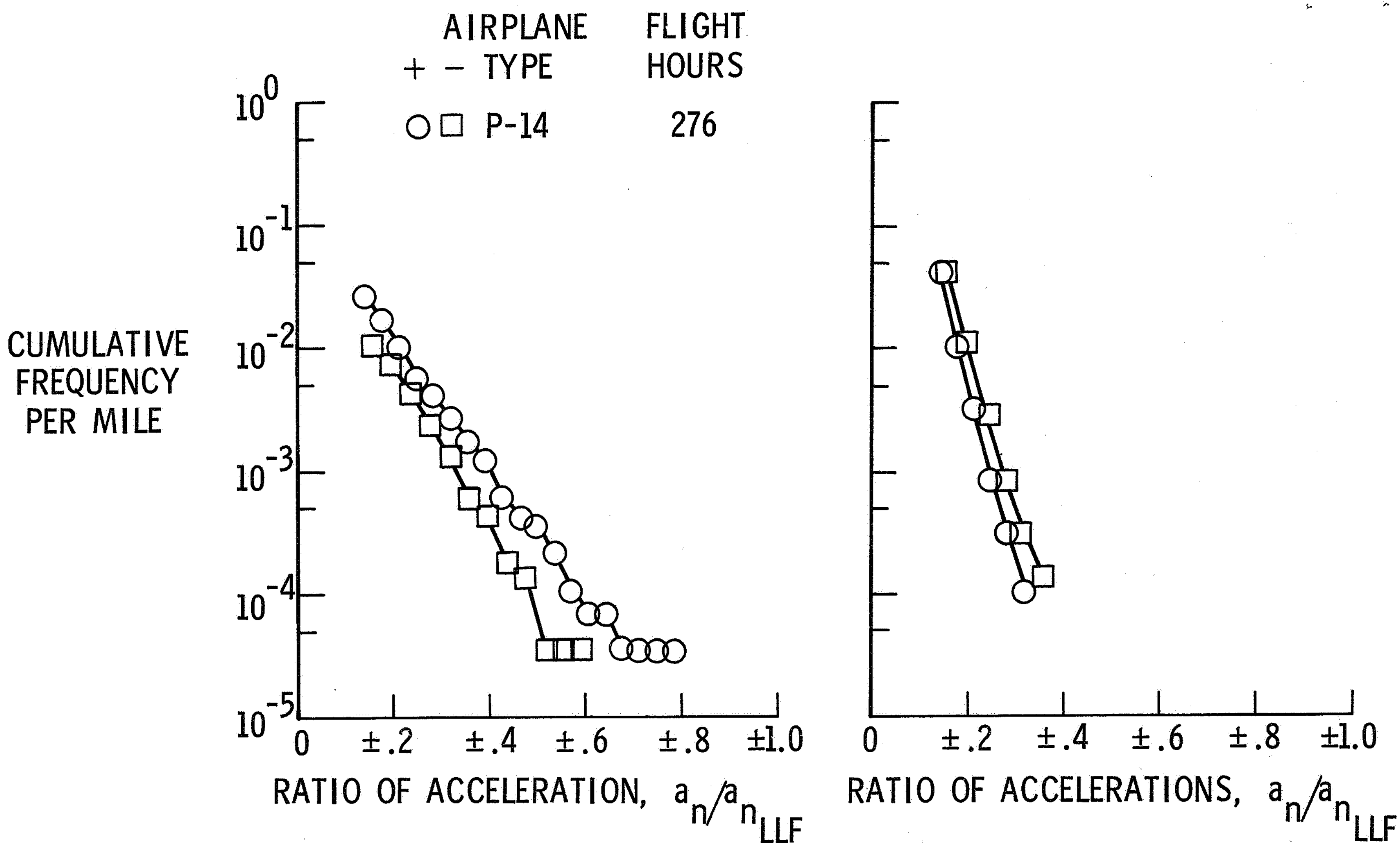
(c) Gust acceleration distribution.

Figure 20.- Concluded.



(a) Gust velocity distribution.

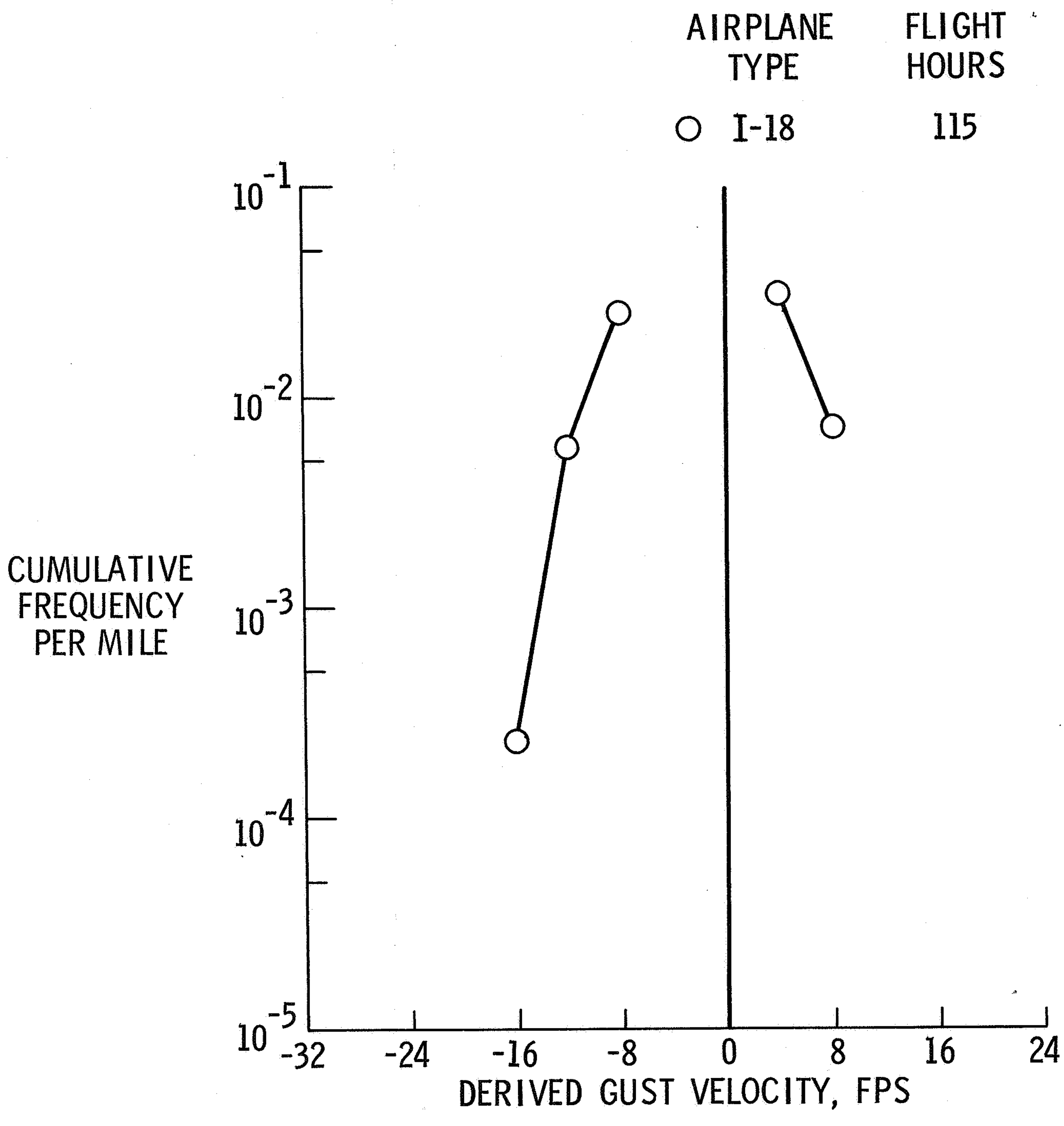
Figure 21.- Gust velocity and in-flight acceleration experience for personal operations.



(b) Maneuver acceleration distribution.

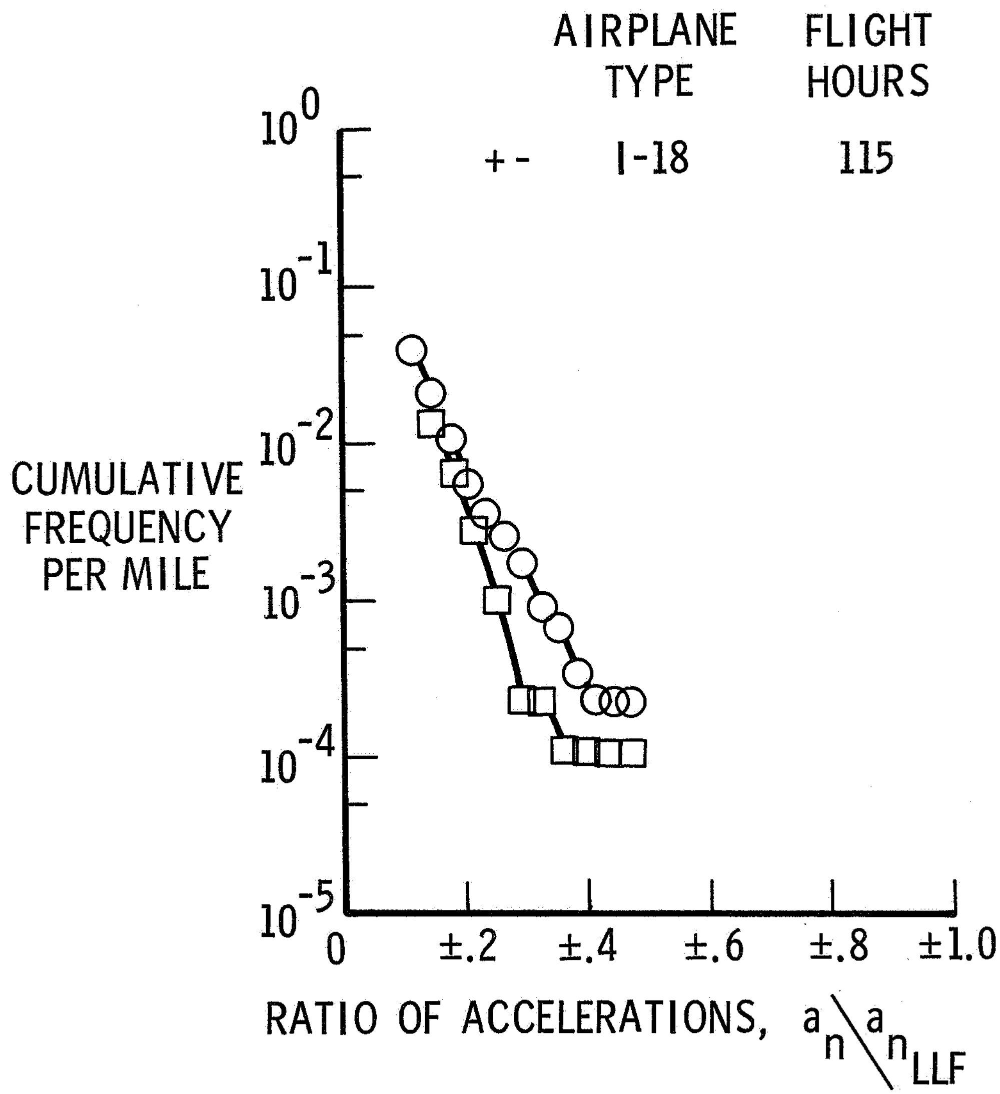
(c) Gust acceleration distribution.

Figure 21.- Concluded.

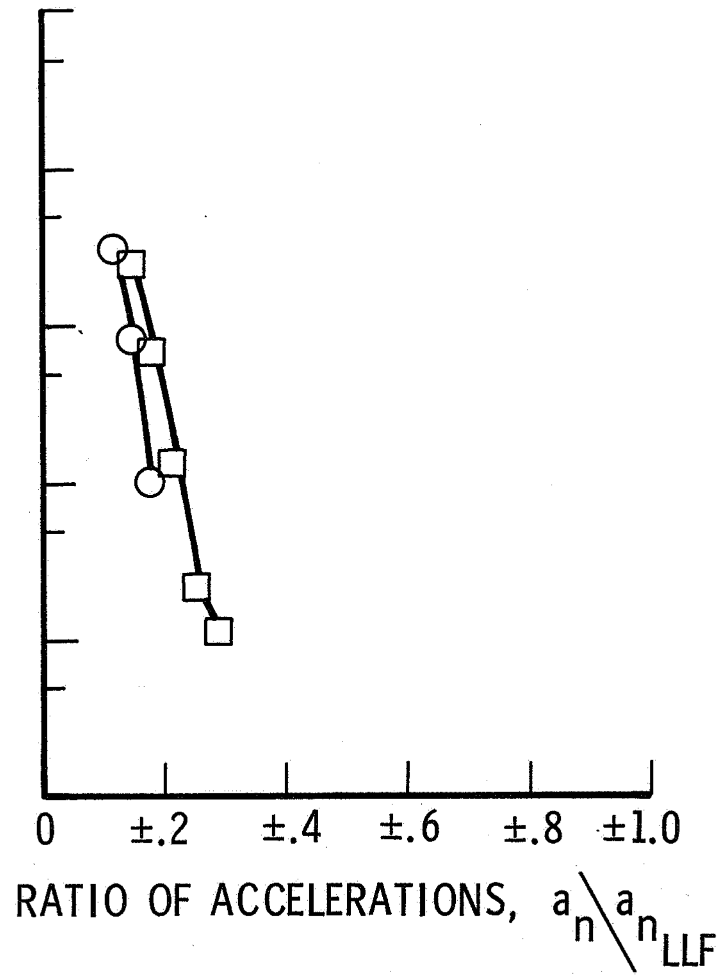


(a) Gust velocity distribution.

Figure 22.- Gust velocity and in-flight acceleration experience for instructional operations.

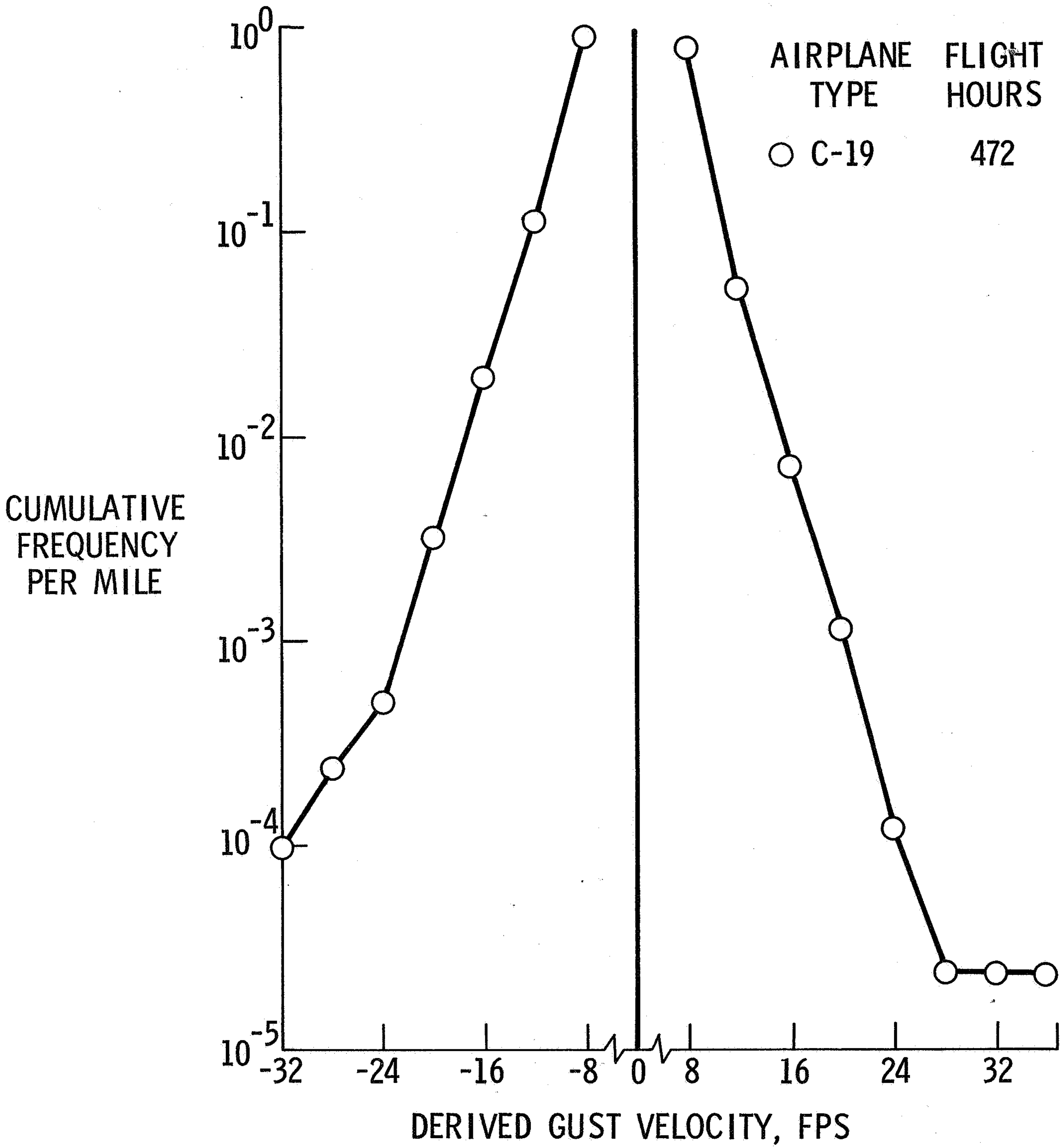


(b) Maneuver acceleration distribution.



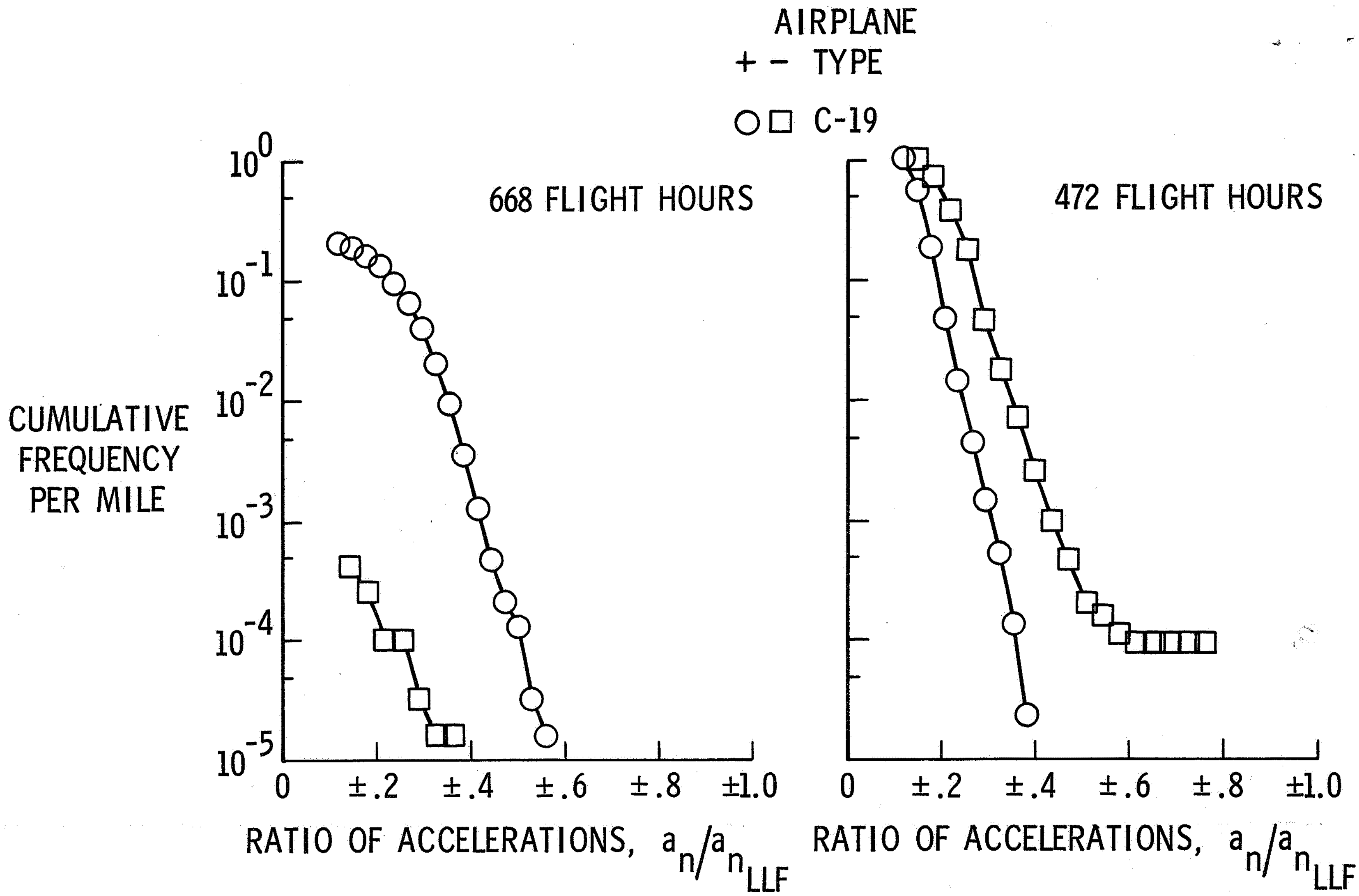
(c) Gust acceleration distribution.

Figure 22.- Concluded.



(a) Gust velocity distribution.

Figure 23.- Gust velocity and in-flight acceleration experience for commercial survey operations.



(b) Maneuver acceleration distribution.

(c) Gust acceleration distribution.

Figure 23.- Concluded.

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