STATISTICAL ANALYSIS OF MISSION PROFILE PARAMETERS OF CIVIL TRANSPORT AIRPLANES

By Otto Buxbaum
Laboratorium für Betriebsfestigkeit
Darmstadt-Eberstadt, Germany

SUMMARY

To evaluate fatigue life, manufacturers must define and use typical mission profiles. The probability with which a mission profile (or one of its parameters) occurs can be used to quantitatively describe the term "typical." The airplane weight at any point in the mission is, of course, a very important parameter; the present paper presents some weight data and analyses from several types of airplanes. Several long-, medium-, and short-range airplanes, flown either in passenger or in cargo service of Lufthansa German Airlines, were observed between January and April 1969.

The statistical analysis of flight times as well as airplane gross weights and fuel weights of jet-powered civil transport airplanes has shown that the distributions of their frequency of occurrence per flight can be presented approximately in general form. Before, however, these results may be used during the project stage of an airplane for defining a typical mission profile (the parameters of which are assumed to occur, for example, with a probability of 50 percent), the following points have to be taken into account.

Because the individual airplanes were rotated during service, the scatter between the distributions of mission profile parameters for airplanes of the same type, which were flown with similar payload, has proven to be very small. Significant deviations from the generalized distributions may occur if an operator uses one airplane preferably on one or two specific routes.

Another reason for larger deviations could be that the maintenance services of the operators of the observed airplanes are not representative of other airlines. Although there are indications that this is unlikely, similar information should be obtained from other operators. Such information would improve the reliability of the data of the present report.

16

INTRODUCTION

The airworthiness standards for transport category airplanes require that the fatigue strength evaluation include the typical loading spectrum expected in service. (See ref. 1.) The loading spectrum, however, depends on the mission profile, which has been chosen in agreement with the requirements of the customers. Since the operational conditions will vary from flight to flight and probably different customers may operate the same type of airplane differently, several mission profiles will always be discussed for an airplane that is in the project stage. (See ref. 2.) The manufacturer then has to combine the various mission profiles into one or two so-called representative or typical ones on which to base the fatigue-life evaluation.

A quantitative description of the term "typical" may be obtained by defining the probability with which a mission profile or one of its parameters will occur. This definition can be achieved possibly for parameters like flight altitude and airspeed by means of results from measurements which have been carried out on airplanes of similar design features, for example, from VGH recordings. There is, however, still a lack of information insofar as parameters such as flight-time airplane weight and weight distribution are concerned.

In order to investigate the variation of mission-profile parameters and to gather information which could be used for the design of similar airplanes, the following analysis has been performed.

The author is indebted to the German Government, Ministry of Defense, for financial support and to the departments of structural engineering and performance and operation engineering of Lufthansa for their assistance and collaboration.

AIRPLANE TYPES, ANALYZED PARAMETERS, AND PERIODS OF OBSERVATION

Several long-, medium-, and short-range airplanes flown either in passenger or in cargo service of Lufthansa German Airlines have been observed during a period lasting from January to April 1969. As far as it was possible, the following parameters have been taken for each flight from flight and fuel logs as well as from the so-called "load sheets:" airborne time, take-off gross weight, landing gross weight, fuel take-off weight, and fuel landing weight. Information about the individual airplanes and their characteristics is presented in table 1. In addition to the analysis performed for the airplanes and the period of observation as mentioned, results from earlier similar investigations have been included for information.

PRESENTATION AND DISCUSSION OF RESULTS

The results are presented for each of the mission-profile parameters in form of cumulative frequency distributions, from which the number of occurrences per flight and the respective magnitude can be read, and in form of cross plots for any two parameters, which have occurred during the same flight. In order to achieve the intended generalization, the airplane and fuel weights have been related to the maximum allowable weights as specified in table 1.

Airborne Time

The cumulative frequency distributions of airborne times for the different types of airplanes are presented in figure 1. The longest flight time has been observed for a 707C airplane in cargo service; its flight time was 9.75 hours. Also a difference in flight times between cargo and passenger airplanes of the same type can be noted.

If the cumulative frequency distributions of airborne times are plotted on Gaussian probability paper with a logarithmic grid for the variate, then the distributions for the individual airplanes may be approximated by one or by a combination of several straight lines (fig. 2); that is, they correspond to logarithmic normal distributions, as it was demonstrated in reference 2. Only those data have been included in figure 2, which were obtained during the same period of observation. The following conclusions can be drawn:

(a) The scatter between airplanes of the same type which were flown with similar payload is very low.

(b) The distributions can be separated into three groups which actually correspond to short-range, medium-range, and long-range airplanes.

(c) The difference between passenger and cargo airplanes increases with the range.

(d) All long-range airplanes show the same asymptotic behaviour, which has been observed in a previous investigation. That behaviour could be caused either by the specific station-to-station distances as flown in service by the operator concerned, or by the limitation of fuel capacity, or – and that seems to be very likely – by a combination of the two reasons.

If it is assumed that other airlines operate similarly and the scatter for very short flights (which occur with probabilities above 99.5 percent) is neglected, then the following generalized information may be derived for the airborne times of jet-powered civil transport airplanes. The logarithmic mean value of the airborne time amounts for short-range airplanes to 37 minutes and for medium-range airplanes to 60 minutes. (See fig. 3.) The corresponding standard deviations, by which the slope in the probability paper is defined, are 0.155 and 0.215. The two logarithmic normal distributions intersect at a flight time of 11 minutes and are assumed to occur with a probability of 99.5 percent. At the same point also, the distributions for the long-range airplanes are assumed to have their origin. As has been mentioned before, the long-range airplanes show an asymptotic behaviour, which may be expressed by a mean value of 440 minutes and a standard deviation of 0.040; they do not, however, follow this distribution completely but only to a certain percentage, which is about 25 for the passenger and 70 for the cargo airplanes. As the distribution for the long-range passenger airplanes leaves the asymptote already at a probability of 25 percent, its mean value is about 245 minutes instead of 440 minutes for the cargo version.

Two distributions for short- and medium-range airplanes can be used directly for an estimation of an airborne time belonging to a typical mission profile; in the case of the long-range airplanes a distinction has to be made between cargo and passenger service, and prior to the estimation, an assumption has to be made about the percentage of flights which will follow the asymptote, that is, which actually can be called long-range flights.

Take-Off Weight

A similar analysis has been made for the take-off gross weights. As it has been said before, the results are presented in relation to the corresponding maximum allowable take-off weight. (See the cumulative frequency distributions in fig. 4.) It has to be noted here that for the 737 type airplanes only those take-off weights which have occurred at flights departing from and arriving at Frankfurt airport could be obtained. The data for the other airplanes resulted from succeeding flights in the periods of observation as given in table 1.

The scatter between the cumulative frequency distributions for the individual airplanes of the same type, which flew with the same payload, was very small. (See, as an example, that of passenger and cargo long-range airplanes in fig. 5.) This graph shows also that the cargo airplanes are generally flown with a much higher take-off weight than the passenger airplanes. An indication that this happens not only with the long-range airplanes as investigated for one operator but also with the whole fleet of all airplanes from all operators may be derived from the fact that a certain type of fatigue failure in the wing structure has occurred at a significantly shorter service life for cargo airplanes than for passenger airplanes. A careful fatigue-life evaluation has demonstrated that the reason why cargo airplanes have the shorter life must result from generally higher airplane gross weights. The data as presented in figure 5 confirm that prediction.

In order to obtain the intended generalization, the data as observed during the same period of time for jet-powered short-, medium-, and long-range airplanes have been plotted on probability paper. (See fig. 6.) The distributions for the short- and medium-range airplanes can be approximated by a rather small scatter band of two straight lines with a standard deviation of 0.03. It says that 99.95 percent of all flights were made with a take-off weight exceeding 70 to 75 percent of the maximum allowable one, and that in about 5 percent of all flights, 100 percent of the maximum take-off weight was reached. The variation of the relative take-off weight of long-range airplanes is larger than that of short- and medium-range types. But also the difference between passenger and cargo service is larger for the long-range airplanes, because only 0.5 percent of all flights of passenger airplanes took place with the maximum allowable take-off weight, whereas in the case of cargo airplanes it was almost every second flight.

As supplementary information, a cross plot of the variation of take-off weight with airborne time as observed on three long-range passenger airplanes is shown. (See fig. 7.) This example has been selected because it was the best correlation which has been obtained. For the other types of airplanes, the trend was not as clear. More details about this subject are given in reference 3.

Landing Weight

If the cumulative frequency distributions of relative airplane landing gross weight (fig. 8) are compared with those of the take-off weight as shown in figure 4, it is evident that the curves for the landing weight of the individual types of airplanes are much more consistent and conformable. When plotting these distributions on logarithmic probability paper and approximating them by straight lines (fig. 9), it becomes apparent that for all types of airplanes, between 2 and 15 percent of all landings occurred with the maximum allowable landing weight. The distributions have almost the same slope with one exception, which is again the long-range cargo-type airplane. It has to be mentioned further that the scatter between the distributions for the individual airplanes of the same type was similar to that of the take-off weight and was very small. Unfortunately, for the short-range airplanes, only the landing weights for flights from and to Frankfurt airport could be obtained because of matters of organisation. This fact seems, however, to be of secondary importance with regard to the result.

In order to investigate the relation between airborne time and the respective landing weight, cross plots have been made which showed that the landing weight is more or less independent of the flight time. An example of this type of plotting is shown for three long-range passenger airplanes in figure 10.

Take-Off Fuel Weight

The definition of a mission profile to be used for fatigue analysis has to include not only the airplane gross weight but also the appropriate weight distribution. Since the weight of the fuel, which the airplane is carrying, allows information to be derived about the weight distribution, an analysis similar to that for the airplane weights has been performed also for the fuel weights.

Figure 11 shows the cumulative frequency distributions of take-off fuel weights for the different types of airplanes in relation to the respective maximum fuel weights. This form of presentation is not very suitable for deducing a general trend, because the individual curves intersect at several points. Therefore an attempt was made to plot the ratio between take-off fuel weights and the respective allowable airplane take-off weights on logarithmic probability paper. (See fig. 12.) The distributions appear as a family of curves with increasing standard deviation for increasing airplane size. They are clipped at the respective value of the ratio of maximum fuel to maximum allowable airplane take-off weight. Only the distributions for the long-range cargo airplanes behave as exceptions because they consist of two parts, each of which can be described by a logarithmic normal distribution. It has been demonstrated that almost every second flight of long-range cargo airplanes is made with the maximum allowable take-off weight. (See fig. 6.) If the maximum allowable payload was reached, the fuel weight had to be restricted in order not to exceed the maximum allowable airplane gross weight. That may have led to this combination of two logarithmic normal distributions. Furthermore, it can be seen in figure 12 that the variation between the cumulative frequency distributions as observed for airplanes of the same type which flew with similar payload is very small.

A generalized presentation and a good approximation to the results is obtained when the scatter as occurring in the range of probabilities between 90 and 99.5 percent is ignored and is replaced by a fictitious point at 95 percent, where all distributions are assumed to intersect at a weight ratio of 13 percent. (See fig. 13.)

Landing Fuel Weight

In opposition to the fuel weights as observed during take-off, it is not necessary to relate those occurring during landing to the respective airplane gross weight, it is sufficient for obtaining general information to relate them to the maximum fuel capacity of the airplane type. The results of the analysis are presented again in form of cumulative frequency distributions for the different types of airplanes. (See fig. 14.) From this graph, a further confirmation can be derived for the assumption which was made when explaining the fuel take-off weights of long-range cargo airplanes because it shows that these airplanes have generally the lowest percentage of maximum fuel weight during landing. From the presentation of the distributions in a probability paper (fig. 15), the percentages of maximum fuel weight as occurring during every second landing can be defined as 14.5 for the cargo and 20 for the passenger long-range airplanes. The corresponding figures for medium- and short-range airplanes are 38 and 49 percent, respectively. The latter value seems to be very high; it can, however, be explained by the fact that in short-range service, up to three flights were flown without refueling. It is interesting to note that the distributions for the individual airplane types are almost parallel to each other, a tendency which already has been observed for the airplane landing weights. (See fig. 9.)

CONCLUDING REMARKS

The statistical analysis of flight times as well as airplane gross weights and fuel weights of jet-powered civil transport airplanes has shown that the distributions of their frequency of occurrence per flight can be presented approximatively in general form. Before, however, these results may be used during the project stage of an airplane for defining a typical mission profile (the parameters of which are assumed to occur, for example, with a probability of 50 percent), the following points have to be taken into account.

Because the individual airplanes were rotated during service, the scatter between the distributions of mission profile parameters for airplanes of the same type, which were flown with similar payload, has proven to be very small. Significant deviations from the generalized distributions may occur if an operator uses one airplane preferably on one or two specific routes.

Another reason for larger deviations could be that the maintenance services of the operators of the observed airplanes are not representative of other airlines. Although there are indications that this is unlikely, similar information should be obtained from other operators. Such information would improve the reliability of the data of the present report.

REFERENCES

1. Anon.: Airworthiness Standards: Transport Category Airplanes. Federal Aviation Regulations, Pts. 25 and 25.571, FAA, May 8, 1970.

2. Buxbaum, O.; and Gassner, E.: Häufigkeitsverteilungen als Bestandteil der Lastannahmen für Verkehrsflugzeuge Zeitschr. Luftfahrttechnik-Raumfahrttechnik, Bd. 13, Nr. 4, 1967, pp. 78-84. (Also available as Library Translation No. 1303, Brit. R.A.E., June 1968.)

3. Buxbaum, O.; and Reinhold, P.: Statistische Auswertung der das Einsatzprofil von Transportflugzeugen kennzeichnenden Parameter. Tech. Rep. TB-88, Laboratorium für Betriebsfestigkeit, 1971. (To be distributed as ICAF-Document.)

TABLE 1

AIRPLANE CHARACTERISTICS AND PERIODS OF OBSERVATION

Type of airplane	Payload	Period of observation	Number of airplanes observed	Maximum allowable weights, thousand lb		
				Take-off	Landing	Fuel (a)
Boeing 707 B	Passengers	Jan. 1969 to Apr. 1969	2	150.9	97.5	72.2
Boeing 707 C	Cargo		2	150.9	112.0	72.2
Boeing 727 A	Passengers		2	69.2	61.2	21.7
Boeing 727 C	Cargo		1	72.8	64.6	21.7
Boeing 737 A	Passengers		3	44.2	40.7	10.7
Boeing 737 C	QC (Passenger/Cargo)		1	50.2	46.7	10.7
Boeing 707 B	Passengers	Apr. 1968 to July 1968	1	150.9	97.5	72.2
Boeing 720 B	Passengers	Jan. 1964 to Dec. 1964	1	106.1	79.4	
Bickers Viscount	Passengers	Apr. 1959 to Jan. 1961	1	32.8	29.0	

[a]Assumed fuel density: 0.8 kp/dm^3.

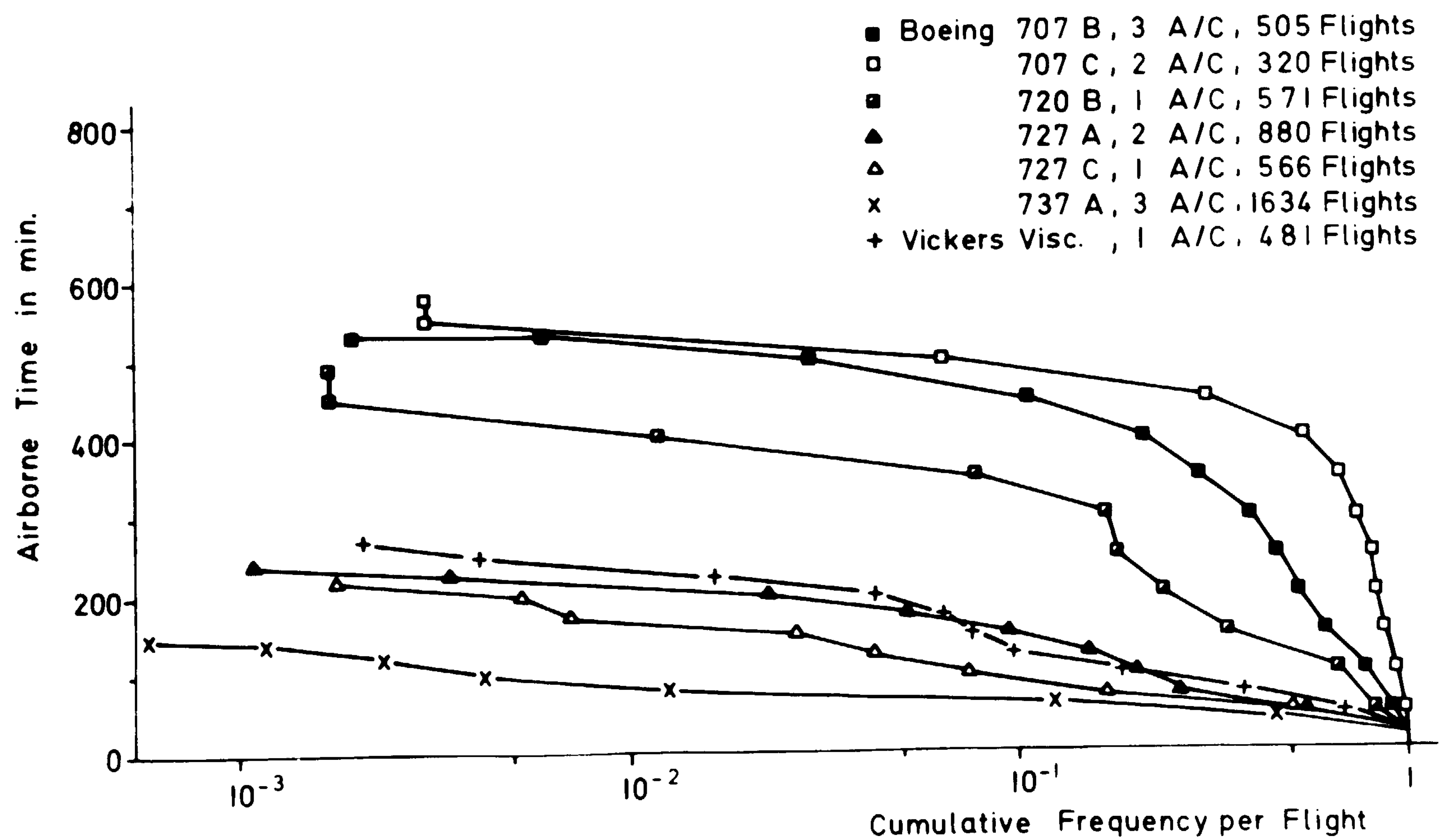

Figure 1.- Cumulative frequency distributions of airborne time for different types of transport airplanes.

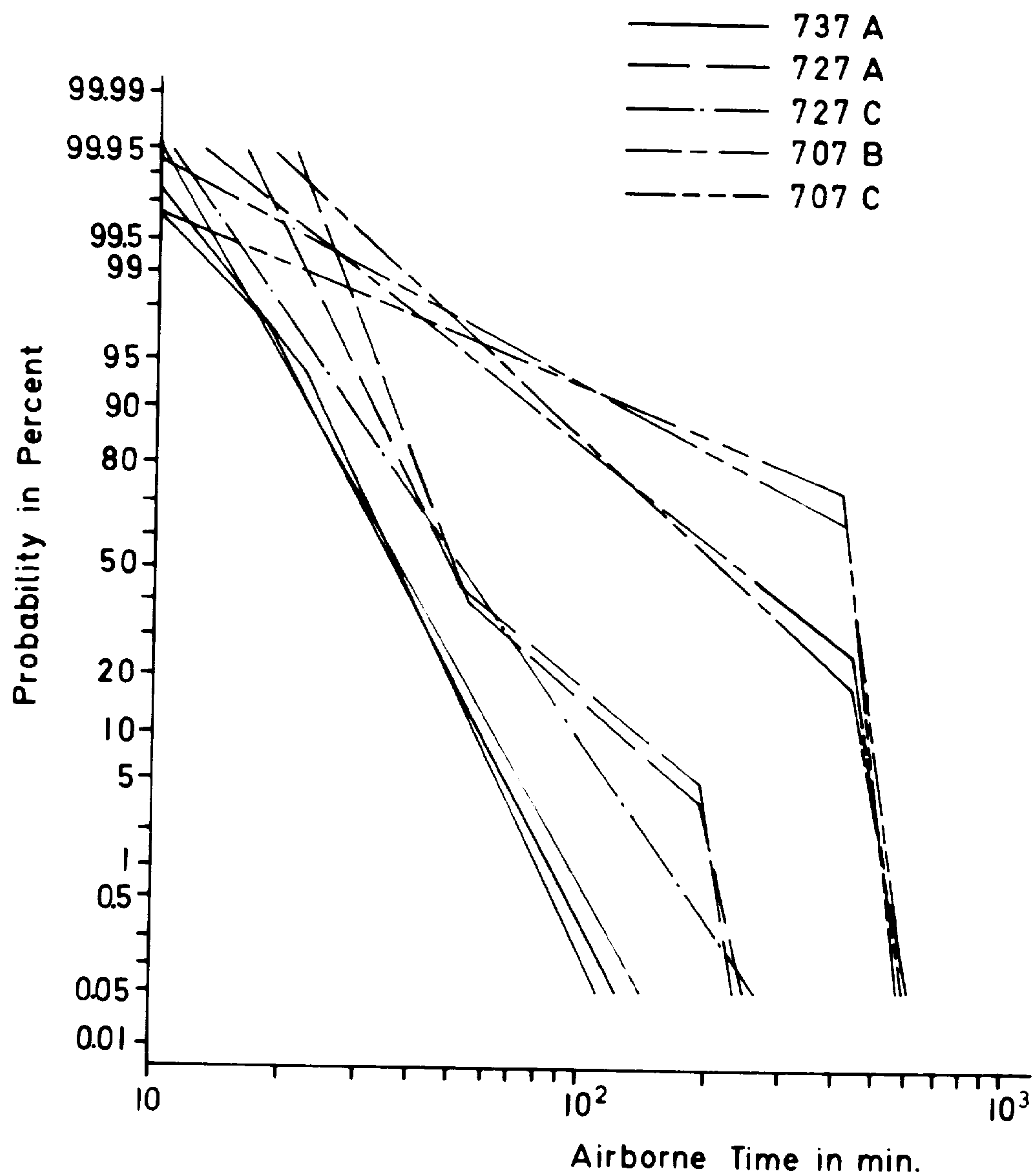

Figure 2.- Cumulative frequency distributions of airborne time for 10 airplanes during the same period of observation.

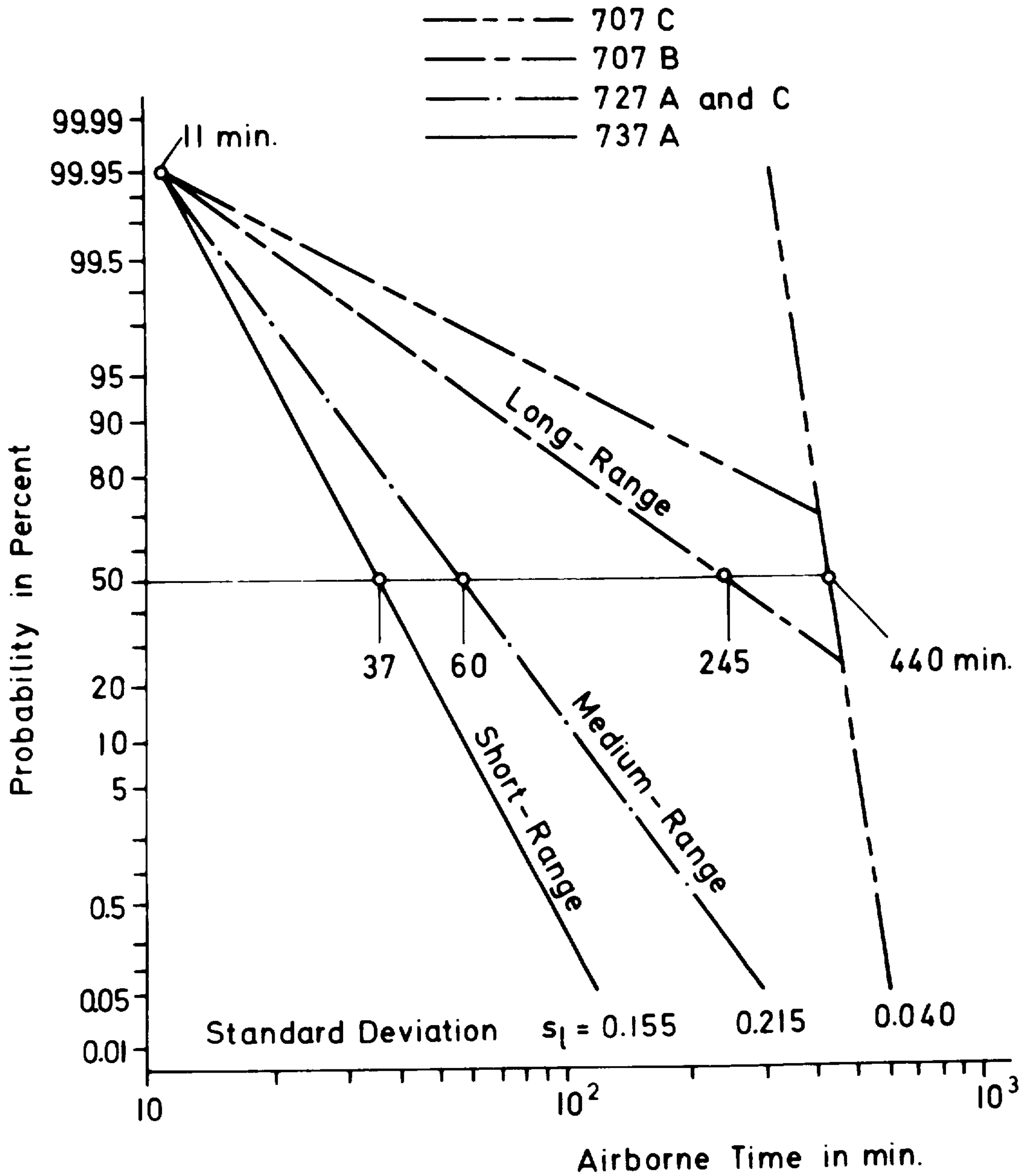

Figure 3.- Flight times of jet-powered short-, medium-, and long-range airplanes.

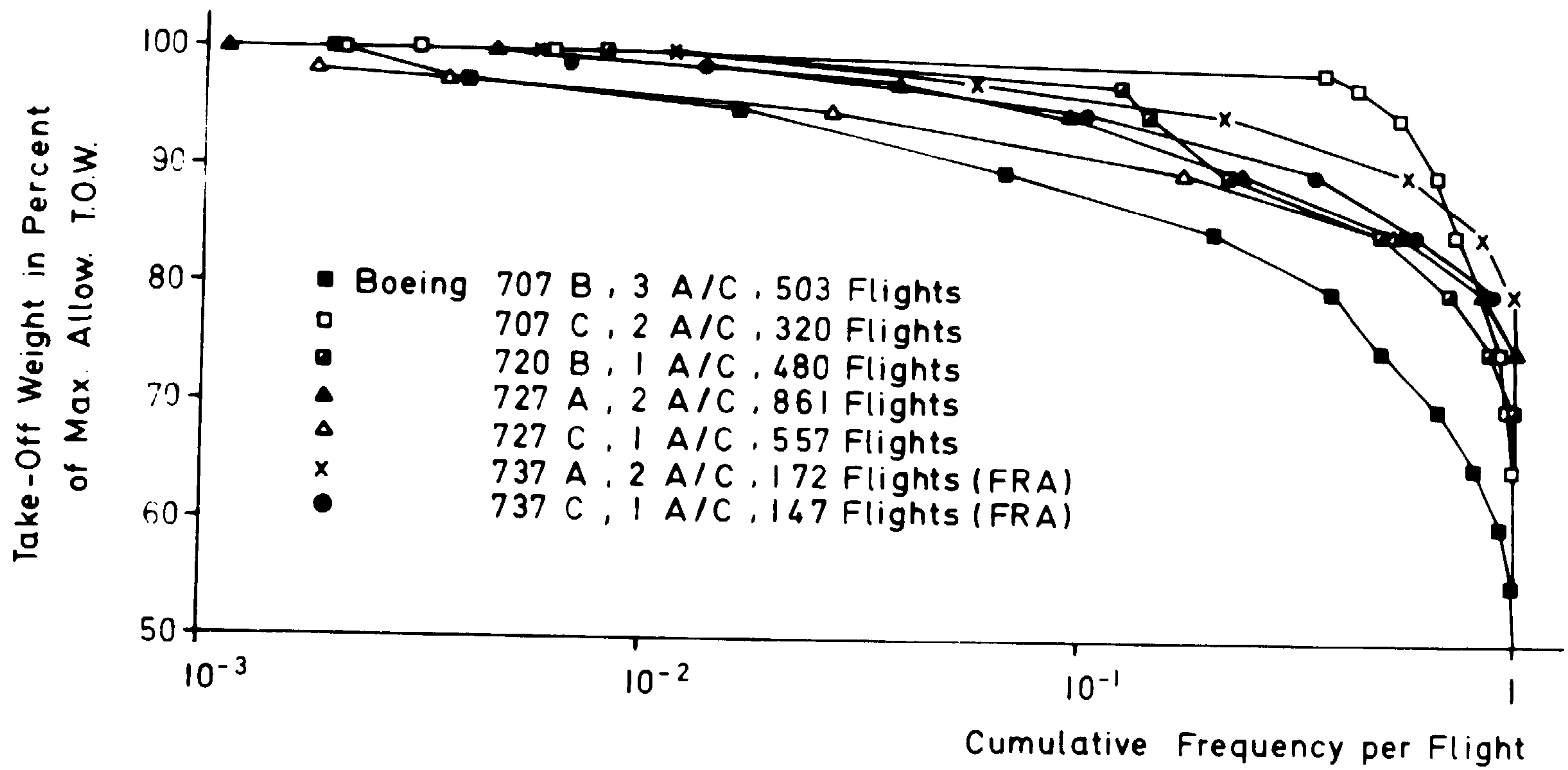

Figure 4.- Take-off gross weights of different types of transport airplanes in percentage of maximum allowable take-off weight.

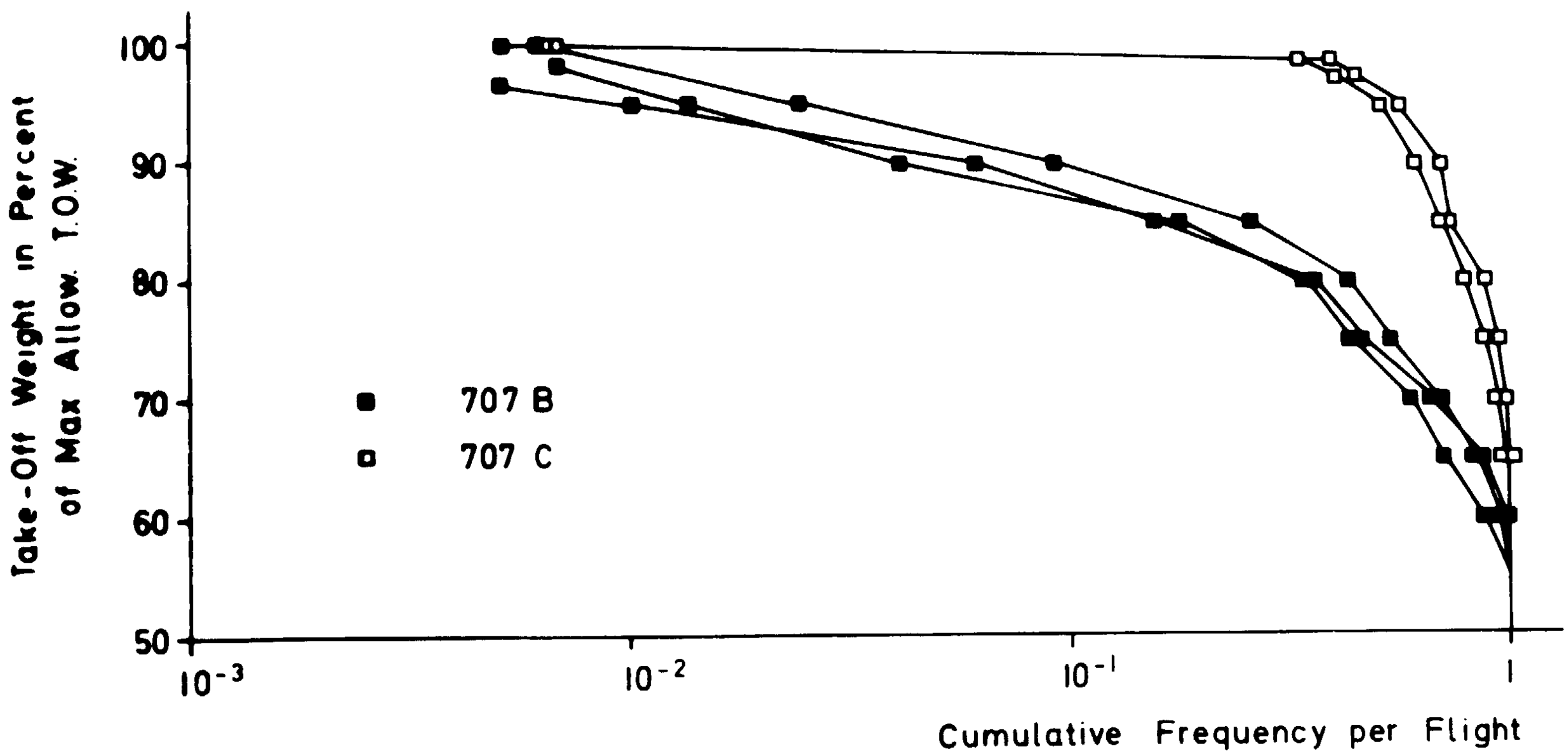

Figure 5.- Variation of cumulative frequency distributions of take-off gross weight for individual long-range airplanes.

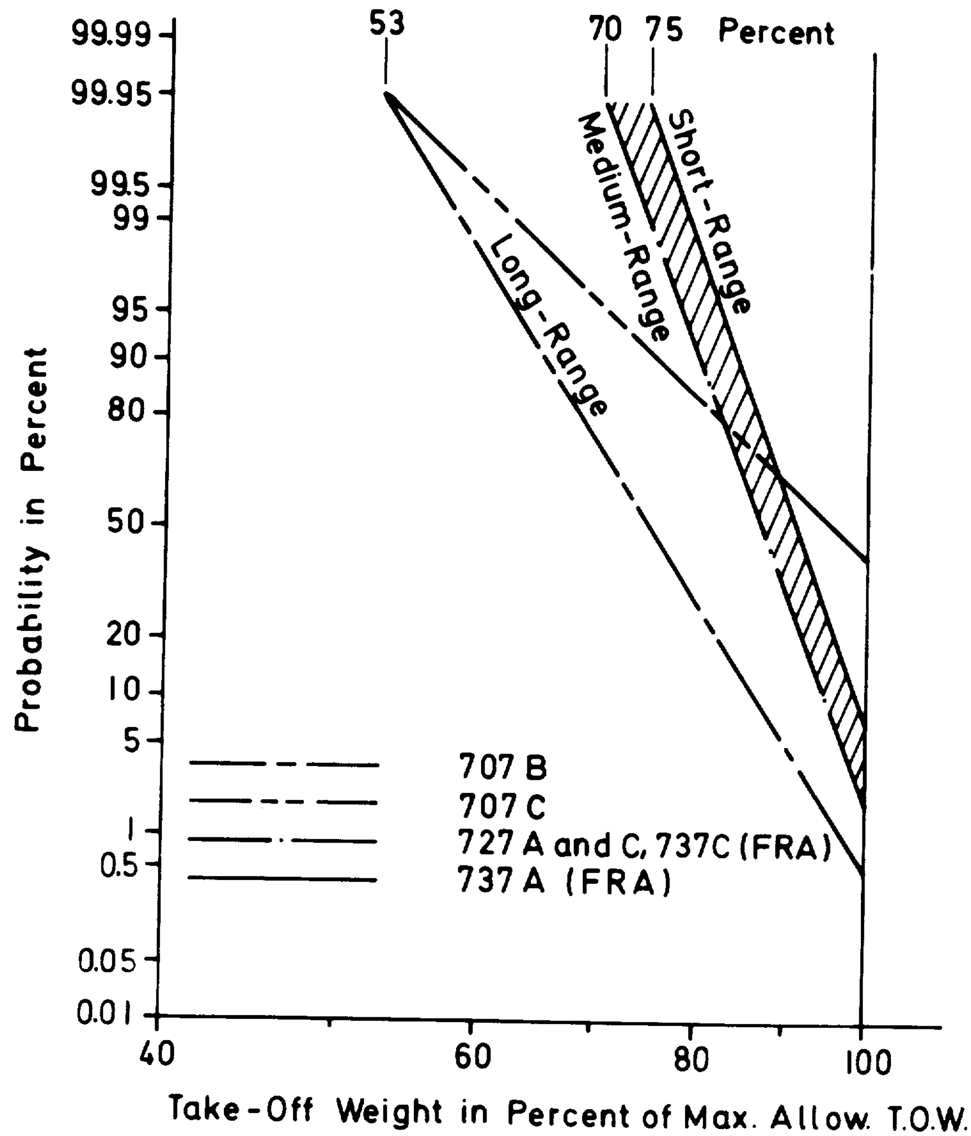

Figure 6.- Take-off weights of jet-powered short-, medium-, and long-range airplanes.

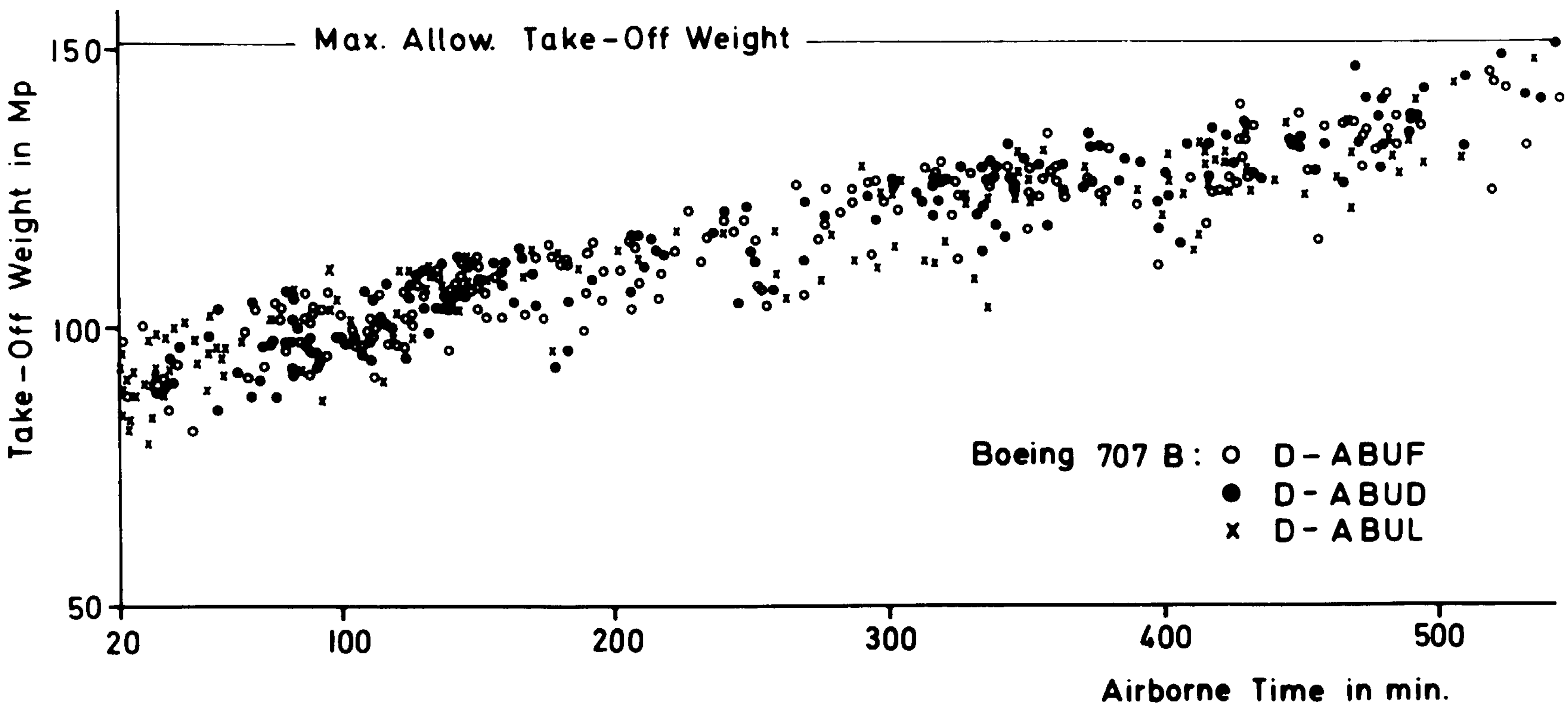

Figure 7.- Relation between take-off weight in megaponds and flight time as observed for three long-range airplanes in passenger service.

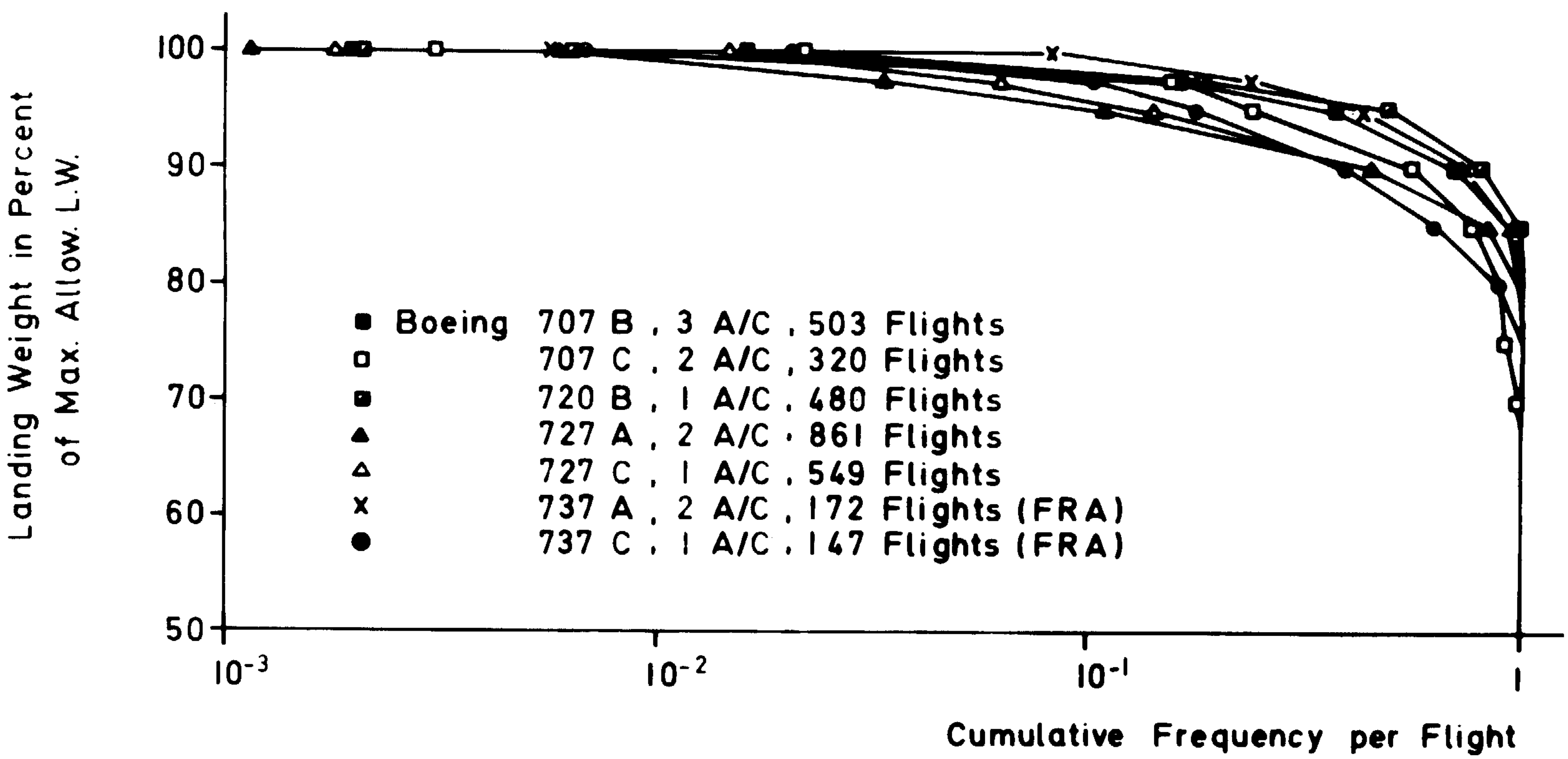

Figure 8.- Cumulative frequency distributions of landing weight in percent of maximum allowable landing weight for different types of transport airplanes.

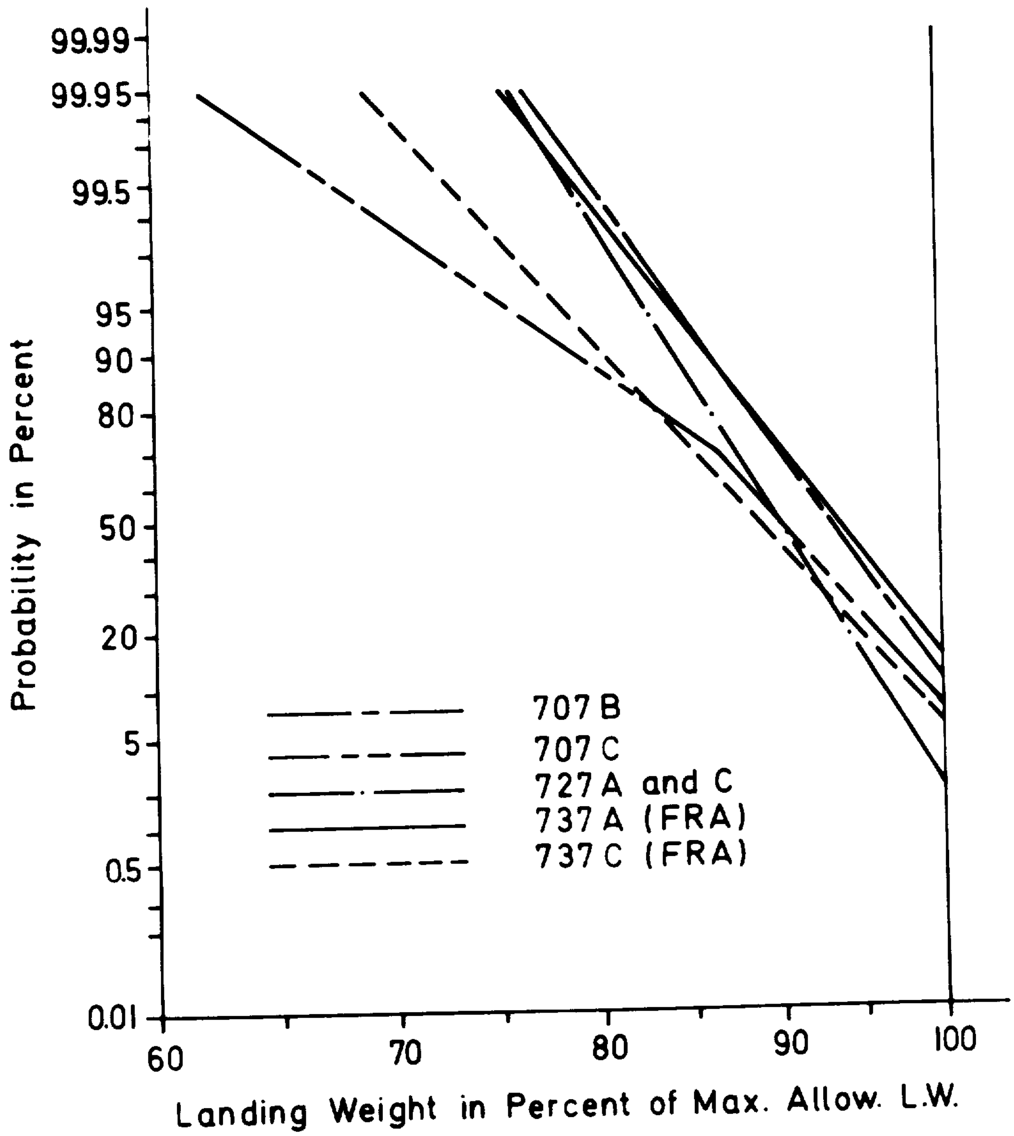

Figure 9.- Landing weights of jet-powered short-, medium-, and long-range airplanes.

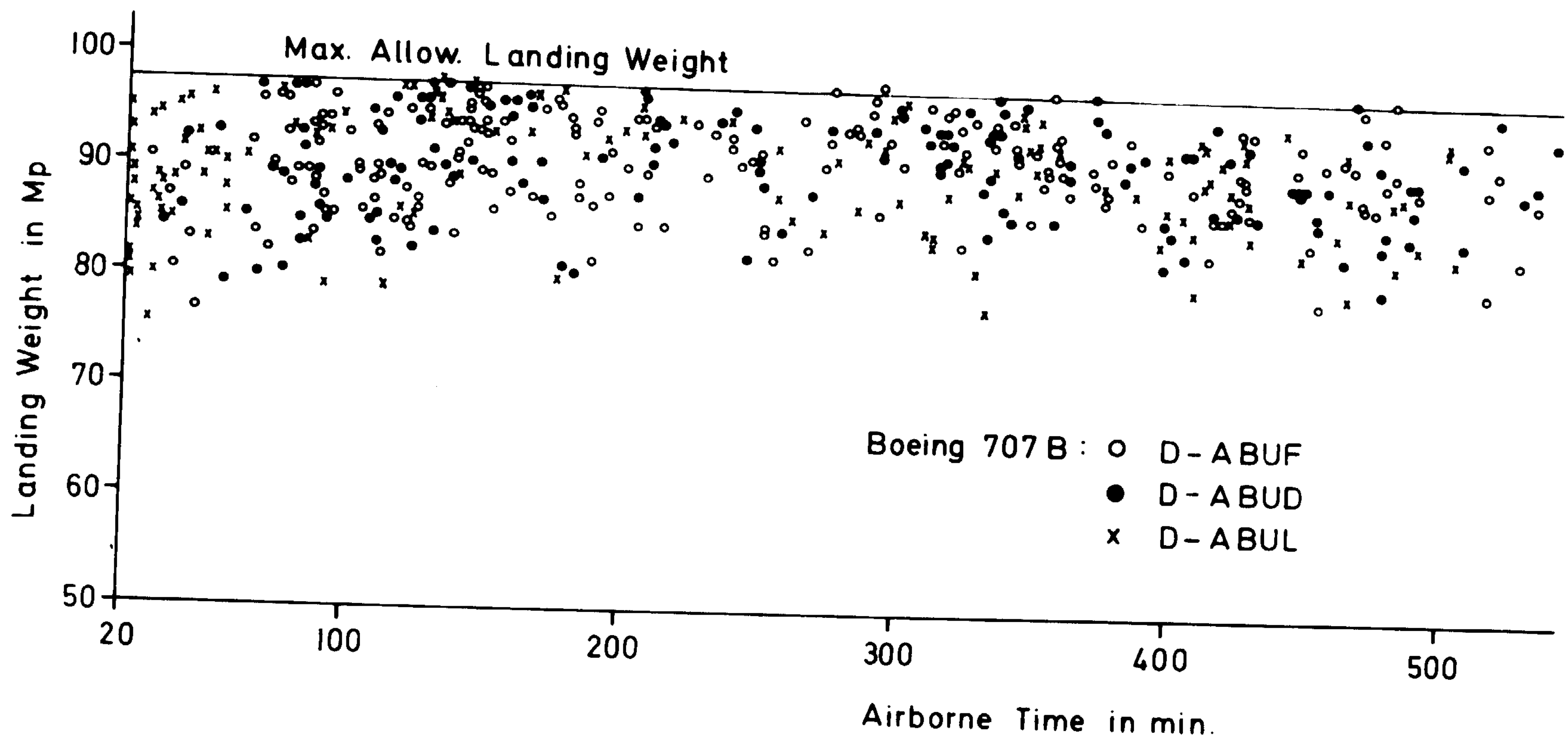

Figure 10.- Relation between landing weight in megaponds and flight time as observed for three long-range airplanes in passenger service.

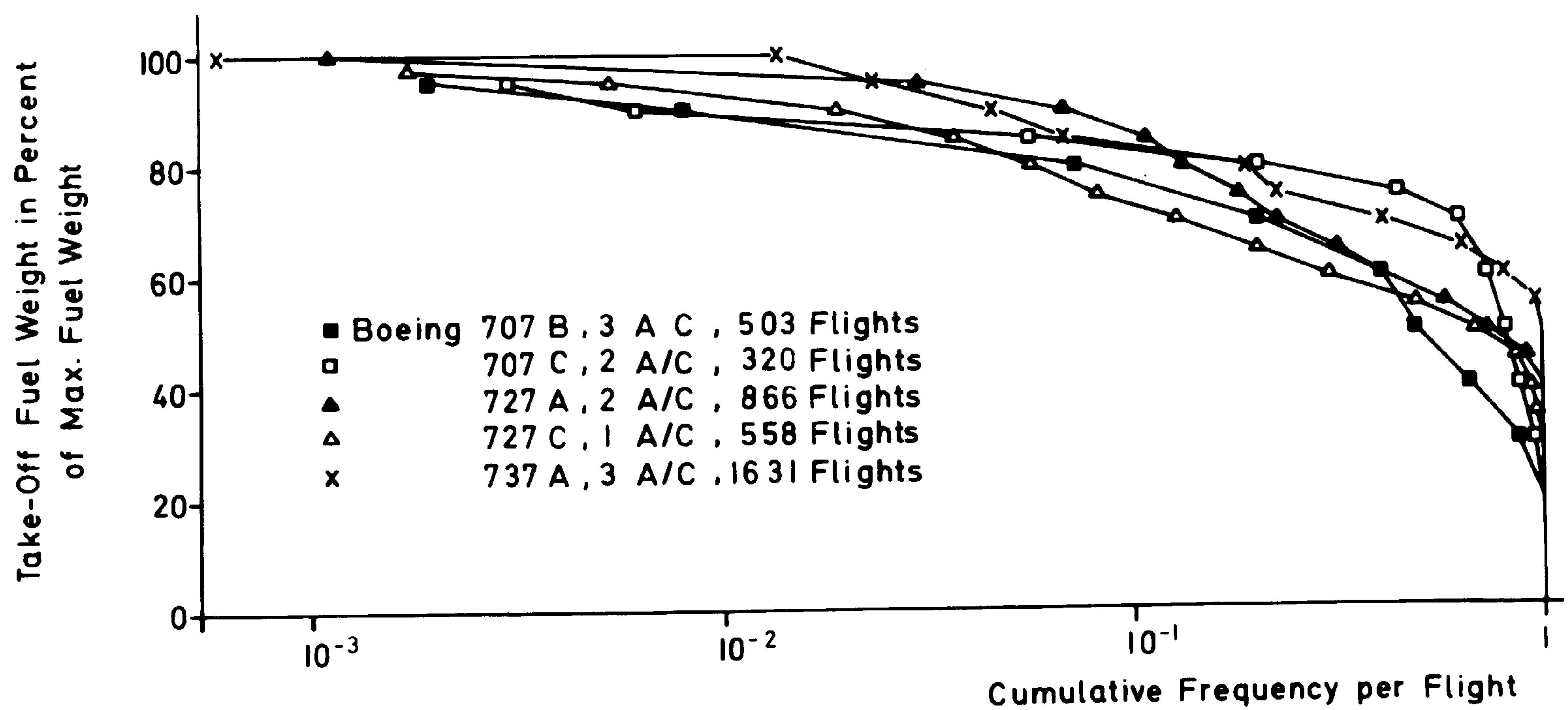

Figure 11.- Cumulative frequency distributions of take-off fuel weight for different types of transport airplanes.

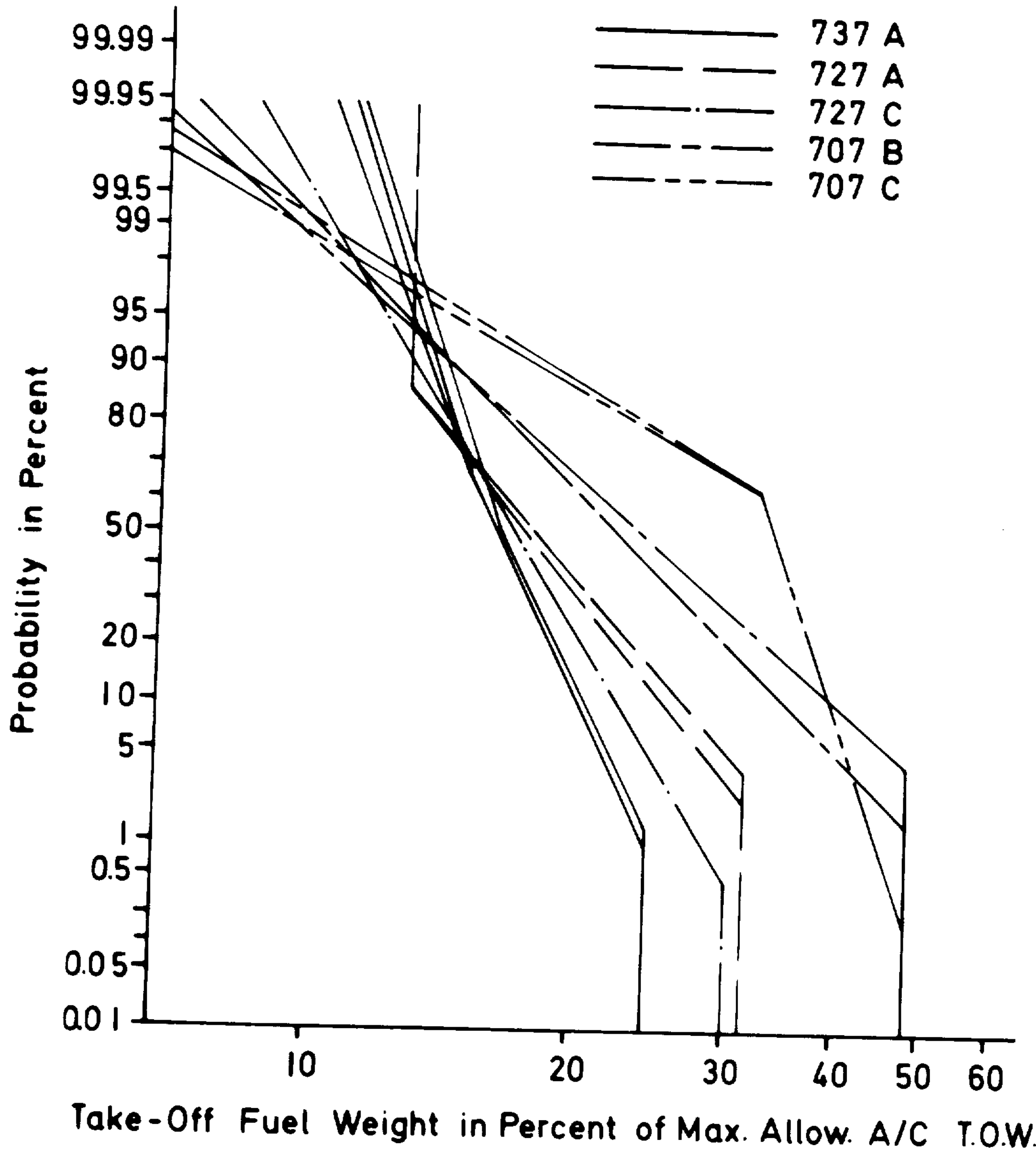

Figure 12.- Ratio of take-off fuel weights to airplane take-off weights for 10 airplanes during the same period of observation. Each line indicates a different airplane.

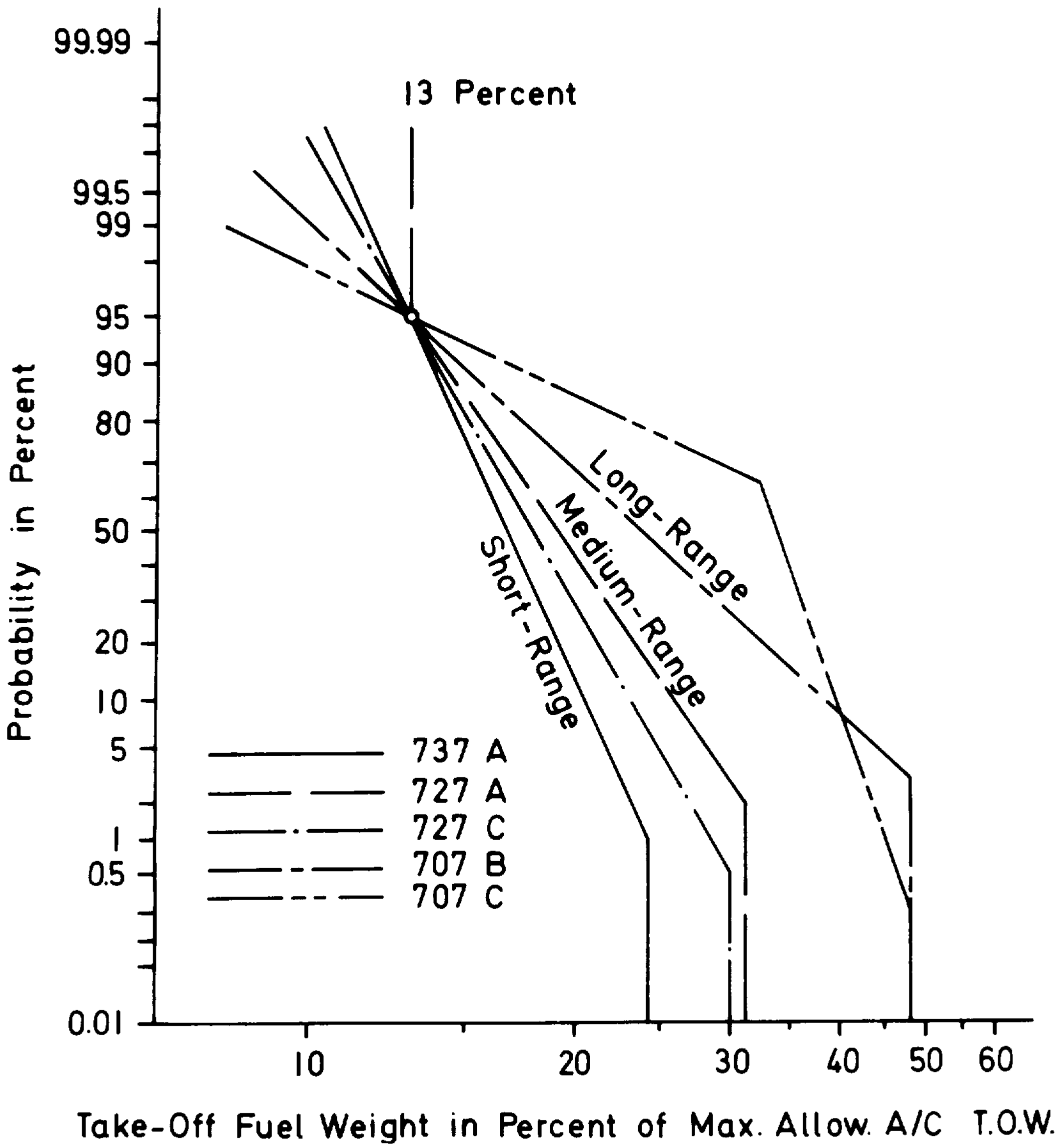

Figure 13.- Take-off fuel weights of jet-powered short-, medium-, and long-range airplanes.

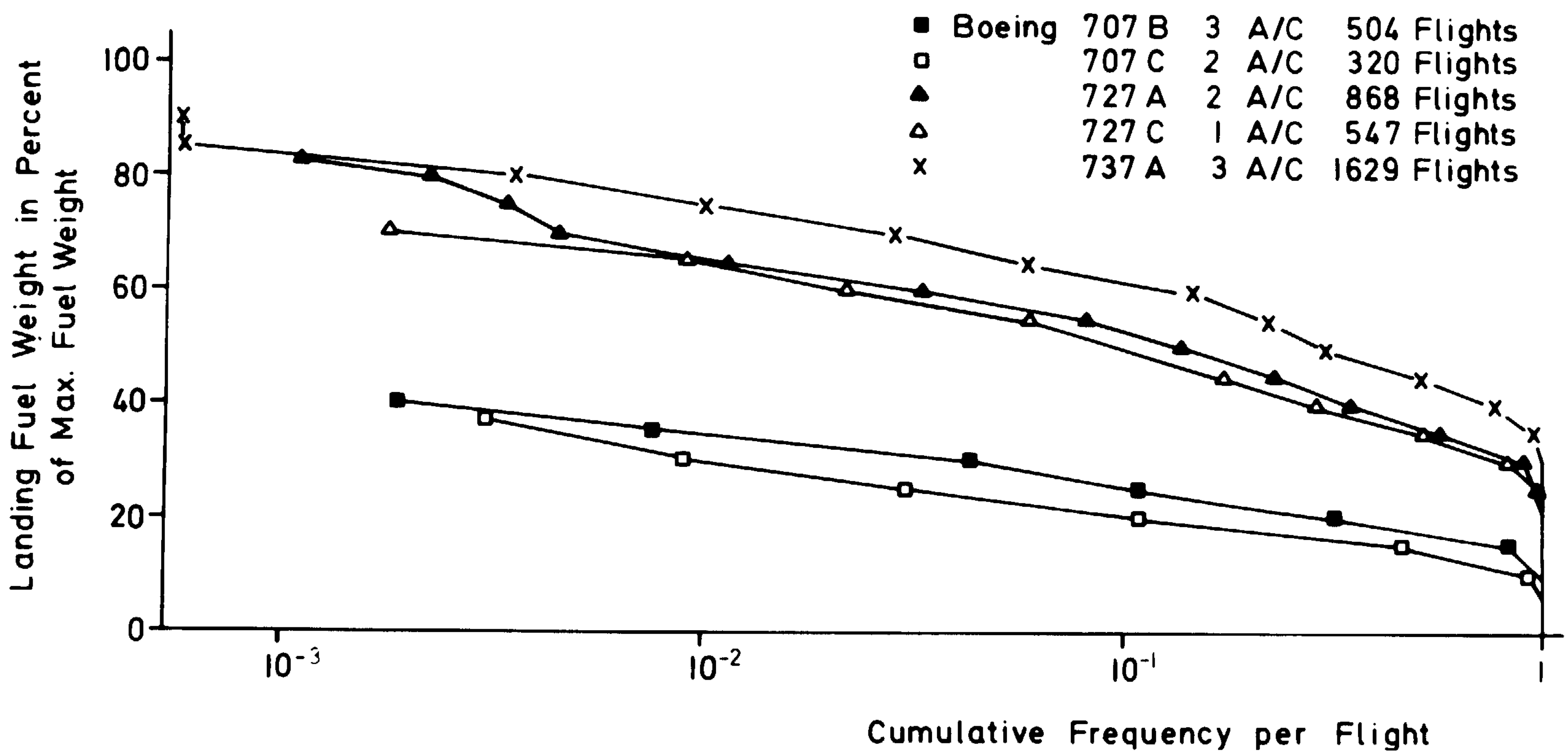

Figure 14.- Cumulative frequency distributions of landing fuel weight for different types of transport airplanes.

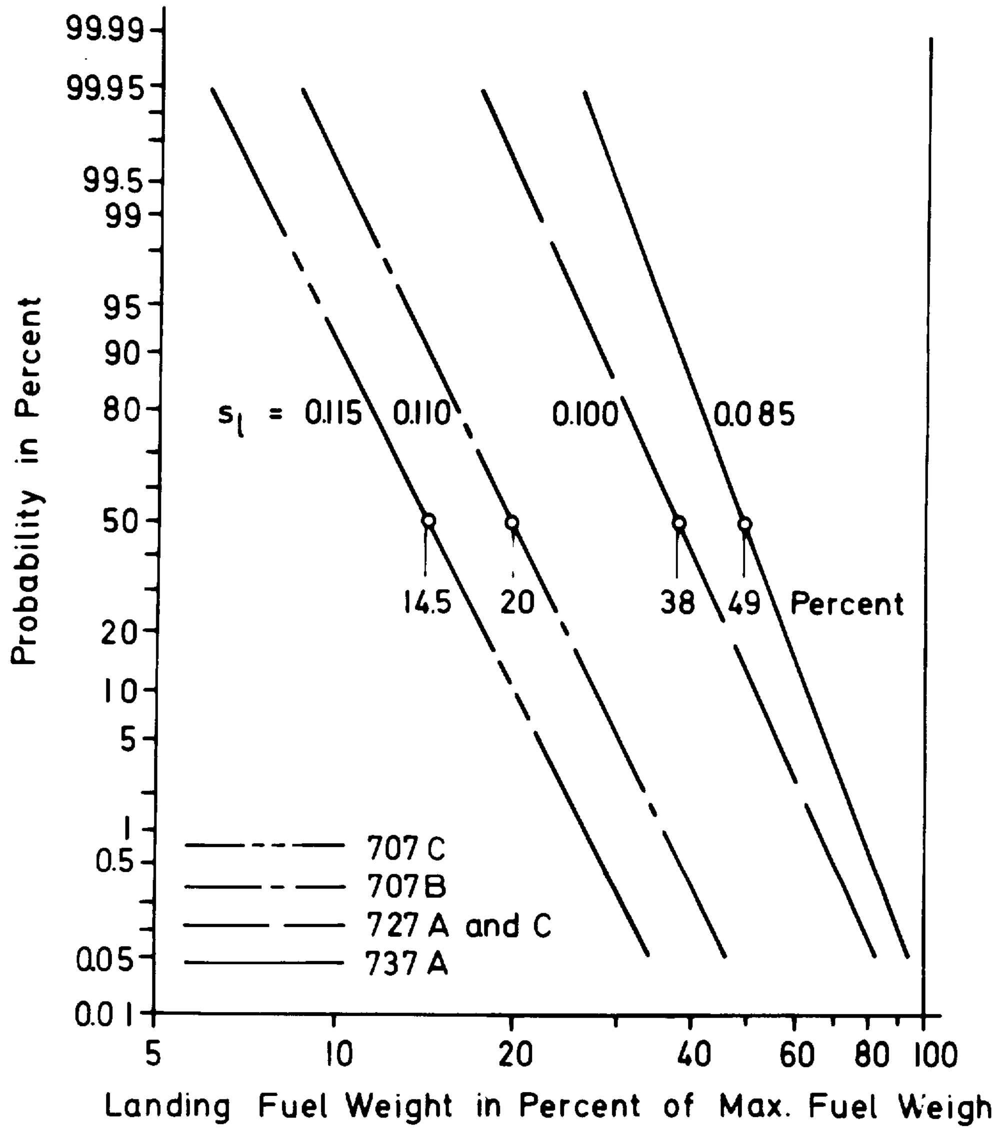

Figure 15.- Landing fuel weights of jet-powered short-, medium-, and long-range airplanes.