CARGO DENSITY VARIATIONS --
A CHALLENGE TO AIR TRANSPORT

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INTRODUCTION[1]

My subject is cargo density, that is the ratio of cargo weight to cargo volume. I will attempt to illustrate the significance of dealing with variations in cargo densities in several phases of air transportation and then, I shall propose what I think is a basic revision in our thinking about cargo density variations and what to do about them. In the past we have tended to think and plan in terms of average density; as if cargo densities were always and everywhere the same. I believe we can replace this conception of cargo density with a more realistic one.

Chart I is based on Air Force shipments lifted by MATS to the Pacific in May, June, and July of 1955. For each day during this period, the average density of Air Force cargo shipped was determined. The chart shows the frequencies that these average daily densities occurred. About 5 per cent of the time density was less than 8 pounds per cubic foot; about 4 per cent of the time it was more than 20 pounds per cubic foot. This by no means is a small range of variation!

Obviously, cargo densities vary. They vary continuously and over a wide range. It is to these variations that I will address the remainder of my remarks.

Chart II shows some of the phases of air transportation in which variations in cargo densities are important.

Aircraft capacity estimates (A) bear on first, the problem of comparing the performances of different aircraft and second, on matching airlift capabilities with airlift requirements. When we assign a given number of aircraft to do a job or an amount of cargo to be lifted by a given aircraft fleet, a mis-matching of capabilities and requirements leads to waste, in the form of unutilized airlift

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1/ This paper is based on a more extensive treatment of the subject presented in RAND Research Memorandum 1380, "Cargo Density and Air Transportation", 10 May 1955, by R. E. Bickner.

capacity on the one hand, or to frustration, in the form of airlift commitments unfulfilled on the other.

The aircraft design problems (B) are concerned with the size of the cargo compartment and with the amount of weight-lifting capacity which a transport aircraft should have. Specifically, I will review methods of estimating the effects which any change in cargo space or weight-lifting capacity would have upon an aircraft's accomplishments.

Airlift operations (C) covers a broad range of activities in which variations in cargo densities can be important. I will limit my remarks to routing aircraft, selecting aircraft fleets, managing cargo backlogs and selecting aircraft loads.

Comparisons of the cost of airlifting different commodities (D) are necessary if available airlift is to be allocated to its most profitable uses. No matter how efficiently we design transport aircraft and conduct airlift operations, if we are not using airlift to move the right commodities we are wasting money and resources.

AIRCRAFT CAPACITY -- HOW TO OVERESTIMATE IT

Let us now consider aircraft capacity on a given route, and see how easily it can be overestimated if variations in cargo density are forgotten.

Chart III protrays an aircraft making two flights; the upper flight when cargo densities are high (say, 20 pounds per cubic foot), the lower one when cargo densities are low (say, 5 pounds per cubic foot). The aircraft has 1,000 cubic feet of useable cargo space, after allowing for stacking, but the amount of space actually utilized is shown shaded. It has an allowable load of 10,000 pounds, shown on the other side of the scale, and the load actually carried is likewise shown shaded.

Now, if cargo density is 20 pounds per cubic foot, simple arithmetic tells us that 10,000 pounds of cargo will exhaust the weight-lifting

CHART I

DAILY DENSITIES OF AIR FORCE CARGO AIRLIFTED TO THE PACIFIC AREA, MAY, JUNE, AND JULY, 1955

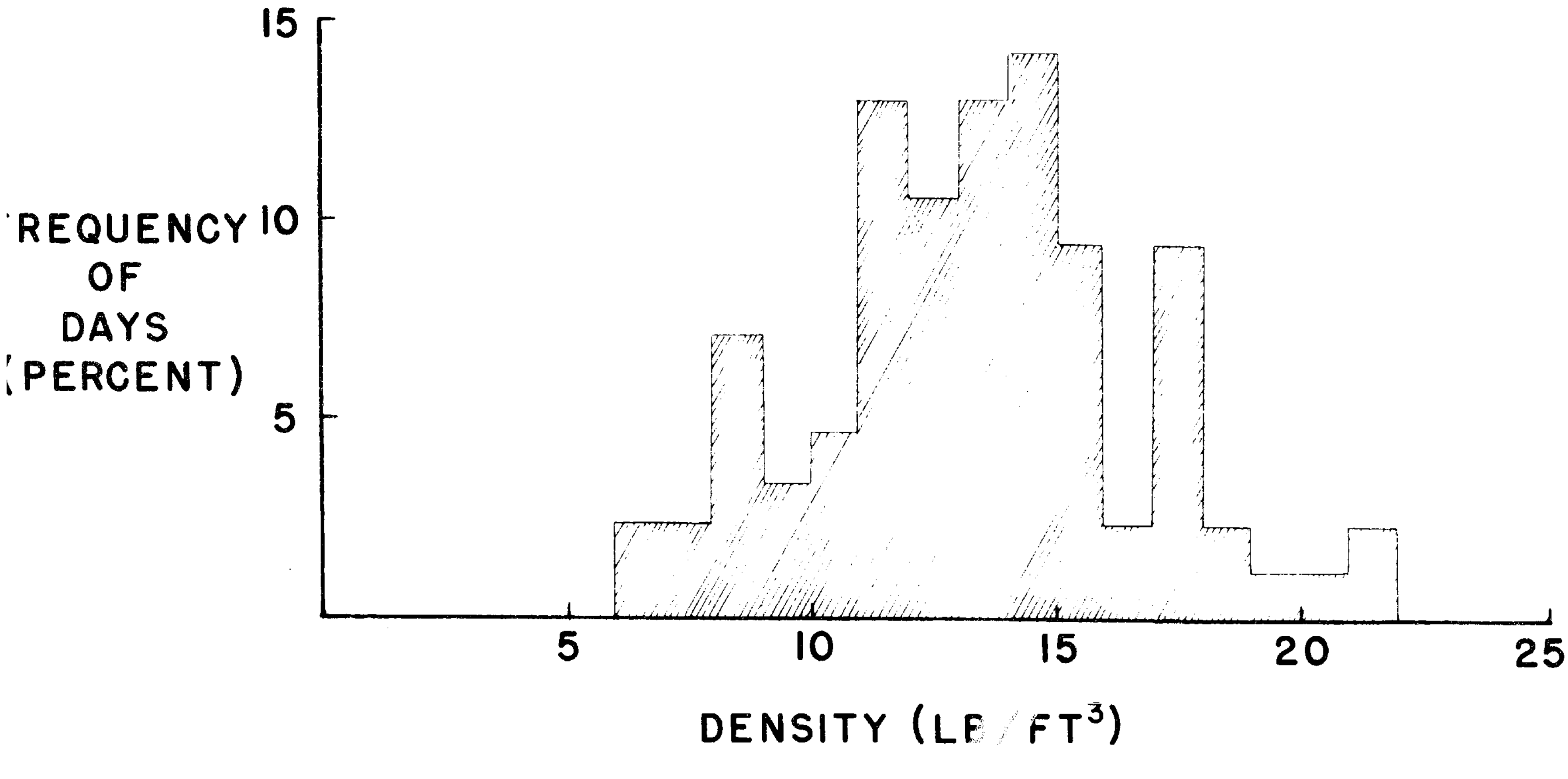


CHART II

CARGO DENSITY AFFECTS:

A. AIRCRAFT CAPACITY ESTIMATES →
- FOR COMPARING DIFFERENT AIRCRAFT
- FOR MATCHING AIRLIFT CAPABILITIES WITH AIRLIFT REQUIREMENTS

B. AIRCRAFT DESIGN →
- ESTIMATING THE VALUE OF CARGO SPACE AND WEIGHT LIFTING CAPACITY

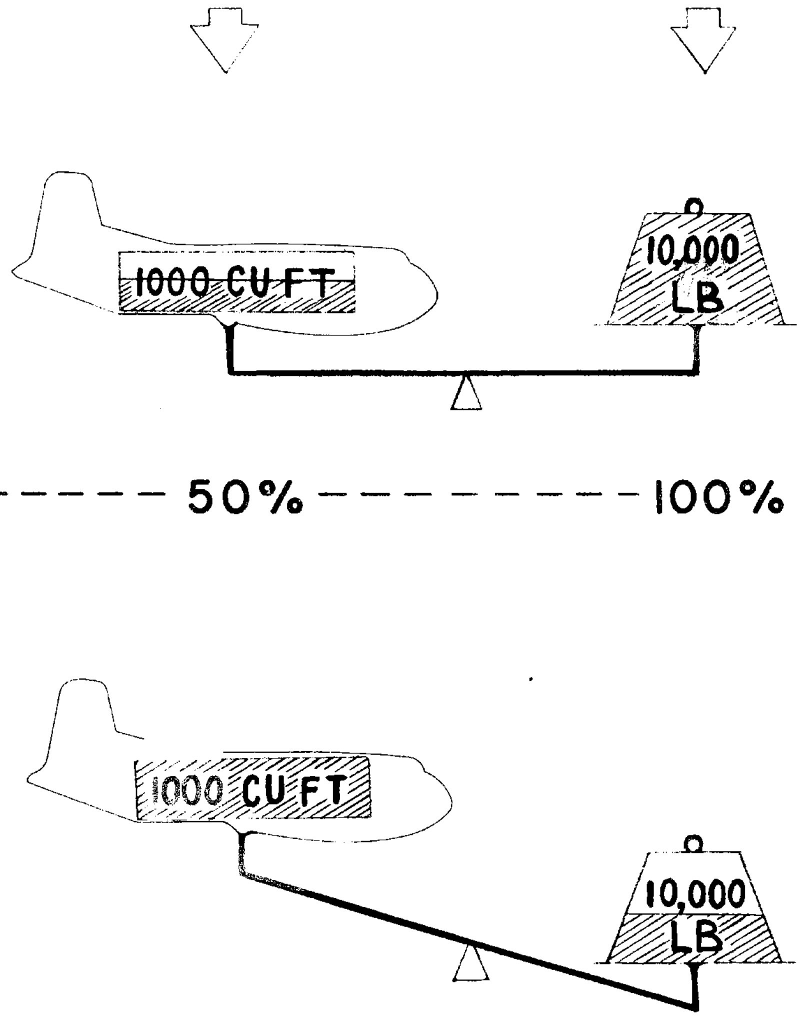
C. AIRLIFT OPERATIONS →
- ROUTING AIRCRAFT AND SELECTING AIRCRAFT FLEETS
- MANAGING CARGO BACKLOGS AND SELECTING AIRCRAFT LOADS

D. AIRLIFT COST COMPARISONS →
- FOR ALLOCATING AVAILABLE AIRLIFT TO MOST PROFITABLE USES

CHART III

CARGO DENSITY VARIATIONS AND AIRCRAFT CAPACITY

CARGO SPACE ALLOWABLE LOAD



FLIGHT I
20
LB/FT^3

TILIZATION ----- 50% ---------- 100%

FLIGHT II
5
LB/FT^3

TILIZATION ----- 100% ---------- 50%

	CARGO VOLUME	CARGO WEIGHT
FLT I	500	10,000
FLT II	1,000	5,000
TOTAL LIFTED	1,500	15,000
APPARENT CAPACITY	2,000	20,000

capacity, leaving 50 per cent of the "useable" space (500 cubic feet) unused. On this flight, the aircraft is "weight-limited".

If cargo densities are 5 pounds, the situation is obviously reversed. Then the 1,000 cubic feet of useable space is filled with cargo weighing only 5,000 pounds. Another 5,000 pounds of supposed payload cannot be used because there is no empty space for more cargo. On this flight the aircraft is "space-limited".

Thus there are two possible limitations to an aircraft's cargo capacity: a weight limit and a space limit. On each and every flight either one of these limits may be the effective one. On high density flights, an aircraft will be weight-limited, and in a sense will be "wasting" space. On low density flights it will be space-limited, and it will not be utilizing all its payload potential. But the same limit -- weight or space -- may not be the effective constraint over a series of successive flights.

The important thing to remember about this chart is simply this: if cargo densities on some flights are "high" and on some flights "low", this aircraft cannot always utilize fully its allowable load, nor can it always utilize fully its cargo space. To assume that it could do either, would be to exaggerate its capacity.

This is illustrated numerically on the right hand side of Chart III.

On the high density flight, the aircraft carried 500 cubic feet and 10,000 pounds of cargo. On the low density flight it carried 1,000 cubic feet and 5,000 pounds of cargo. Its total accomplishments on these two flights would be 1,500 cubic feet and 15,000 pounds. But if we assumed it could always utilize fully its cargo space, we would have estimated its accomplishment at 2,000 cubic feet. Or if we assumed it could always fully utilize its allowable load, the estimate would have been 20,000 pounds. Either assumption would have exaggerated capacity.

Perhaps this is obvious: but if so, why then is everyone so interested in the <u>average</u> density of air cargo?

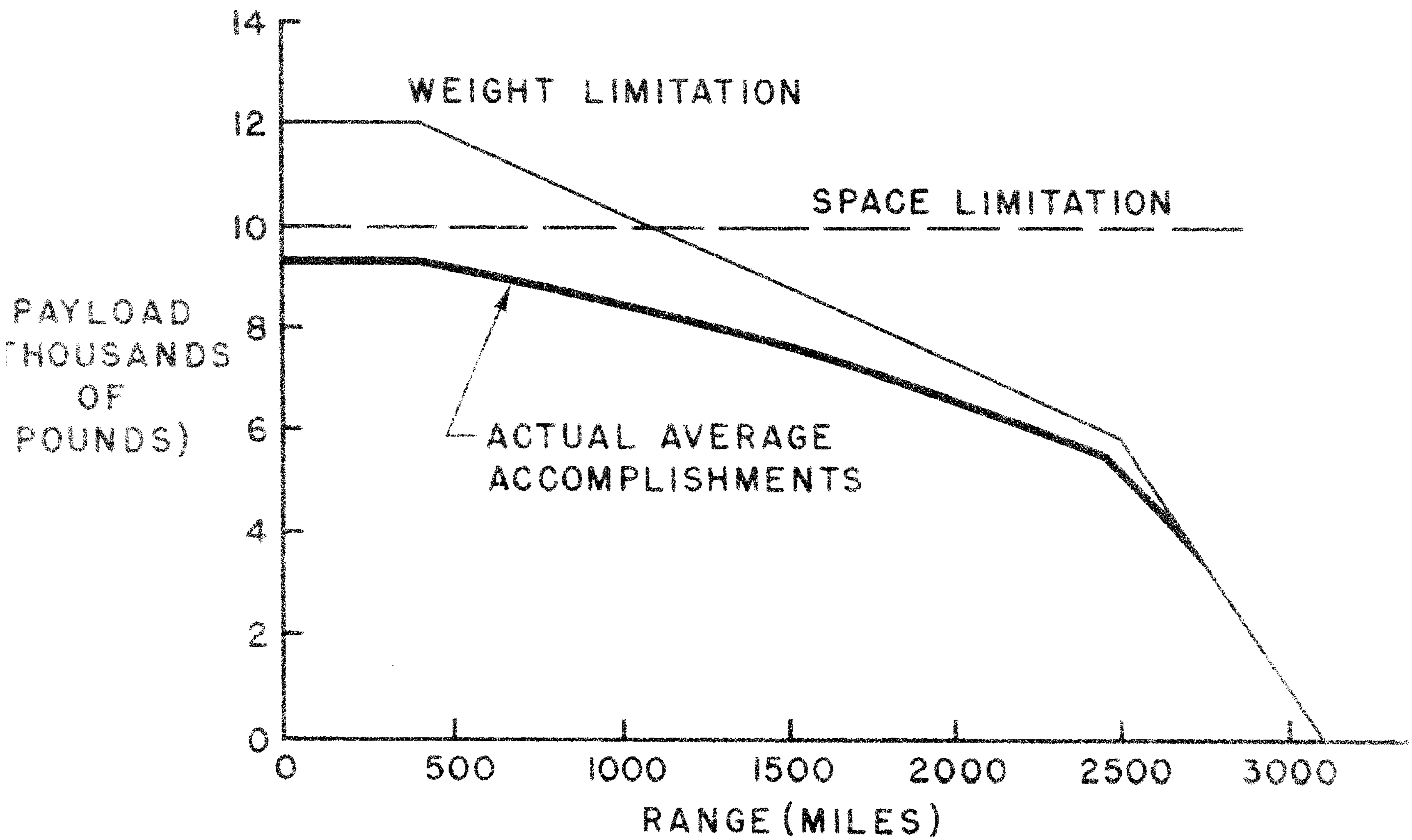
Payload range curves, for the same reasons, often exaggerate an aircraft's supposed weight lifting capacity over a series of flights. Chart IV shows a typical payload range curve, the upper (thinner) curve showing the maximum payload weight (vertical axis) that can supposedly be lifted at each range (horizontal axis). Unfortunately, over a series of flights, there will be occasions when the cargo has rather "low" density. In these cases the fuselage will not contain all the cargo that would have to be loaded for the weight limitation to become effective. On these flights the aircraft takes off with a lighter payload than indicated by the upper curve. The disparity between estimate and actuality is more likely to occur on short range flights when the payload weight limit is high but the available space is, of course, unchanged. In any event, it is important to realize that the actual average accomplishment <u>must</u> lie below the weight limited payload range curve if the performance of a given cargo aircraft type over a <u>series</u> of flights is being considered.

A typical and erroneous way of introducing this aspect of the problem is to add a so-called space limitation line to the payload range chart. In Chart IV this is the dashed line. Thus, if the cargo space is 1,000 cubic feet, it might be said that the average density of cargo is 10 pounds per cubic foot and that, therefore, the space could hold, on the average, 10,000 pounds of cargo. But it could not actually carry, on the average,

CHART IV

PAYLOAD – RANGE CURVE

AIRCRAFT SPACE: 1000 CU FT
AVERAGE CARGO DENSITY: 10 LB PER CU FT



10,000 pounds of cargo unless its cargo space were fully utilized on <u>every</u> flight. Since there will be many occasions in which cargo densities are rather high, and in which the aircraft's allowable load will restrict us from fully using its space, this assumption is unrealistic. The actual average accomplishment must lie below the "space-limitation" line when a series of flights is considered.

CARGO AIRCRAFT DESIGN -- WHAT'S EXTRA CAPACITY WORTH?

How valuable is it, in designing a cargo aircraft, to give it an increment in, say, payload, or alternatively in useable cargo space? Clearly this important question can only be answered if, in addition to a knowledge of tariff rates and other things, the designer has some idea of the frequency with which extra useable payload would in fact be used, or the probability that extra cargo space would in fact be filled. If an aircraft's density factor is 5 pounds per cubic foot, an increment in useable space will be used only infrequently.

All these aspects of the utility of increases in the cargo weight, or alternatively cargo space limitations, seem erroneously to have been eliminated when analysis runs in terms, not of <u>variations</u> in cargo density, but rather in terms of some unique and invariant <u>average</u> cargo density. Thus, if it is pretended that cargo density will be 12 pounds on each and every flight, and the space and weight allowables are respectively 1,000 cubic feet and 10,000 pounds, an increment in cargo space would appear to have no value on any flight. However, a 20 per cent increase in the allowable payload would seem to have value on every flight. We have said enough already to show that such a conclusion is nonsense and rests on a spurious approach to the problem. Now for some hypothetical numbers.

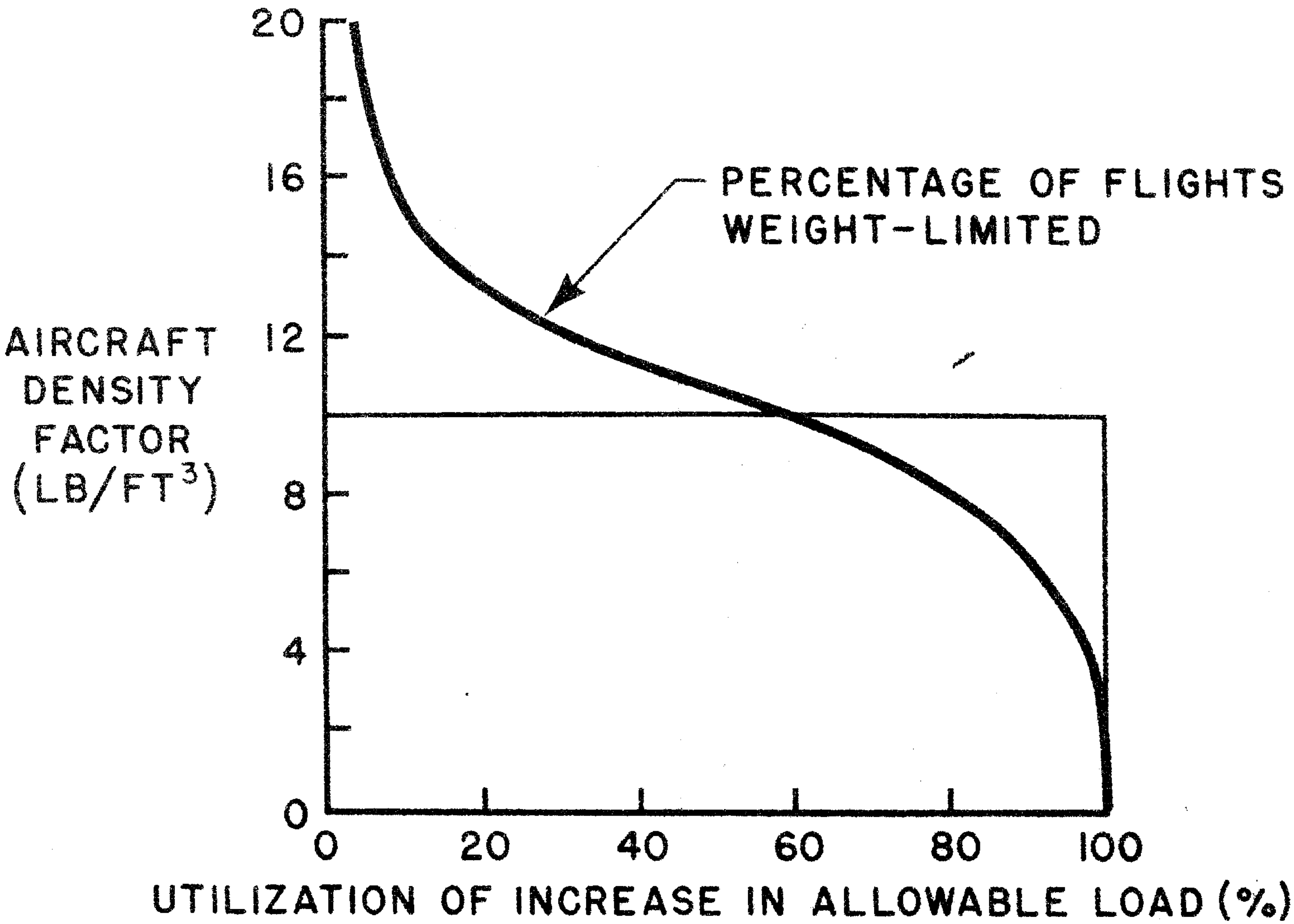
Chart V relates density variations to aircraft design in a more realistic fashion. The vertical scale on this chart shows aircraft density factors. An aircraft's density factor is its ratio of allowable load to cargo compartment volume. The horizontal axis is a percentage scale. The curve indicates for any aircraft the percentage of flights on which actual cargo densities might exceed the aircraft's density factor; i.e., the frequency with which it is likely to fly weight-limited. Those with low density factors will often fly weight-limited.

But this curve also indicates the utilization rate which can be expected of any increase in an aircraft's allowable load. If an aircraft has a density factor of 11 pounds per cubic foot, for instance, the curve suggests that 45 per cent of its flights would be weight-limited. That is, 45 per cent of its flights will have cargo densities exceeding 11 pounds per cubic foot. If its allowable load is increased, the increase could be utilized on 45 per cent of its flights. Thus the average increase in the aircraft's accomplishments resulting from, say, a 100 pounds increase in allowable load would be 45 per cent times 100 pounds, or 45 pounds. The curve shows the expected increase in airlift accomplishments due to an increase in weight-lifting capacity.

This same curve shows the effects of changes in cargo space on the aircraft's accomplishments. Since it indicates the percentage of flights which will be weight-limited, it also indicates the percentage which will be space-limited. If 45 per cent of the flights are weight-limited then 55 per cent are space-limited. If the horizontal percentage scale is simply reversed it will show percentage frequencies of <u>space</u>-limited flights, and the frequency with which any increase in cargo space would be utilized.

CHART V

AIRCRAFT DESIGN FACTORS



Once again, it should be emphasized that these utilization rates depend, not upon average cargo density, but upon variations in cargo density. To assume that all cargo loads are of average density would lead to gross miscalculations of the value of increased space or allowable load. Such an assumption, shown graphically by the horizontal straight line in the Chart, would lead to obviously wrong conclusions. Thus, for any aircraft with a density factor greater than the average, the value of increased allowable load would seem to be zero, despite the fact that there is always some finite probability that an increment in useable payload will be wanted on some flight.

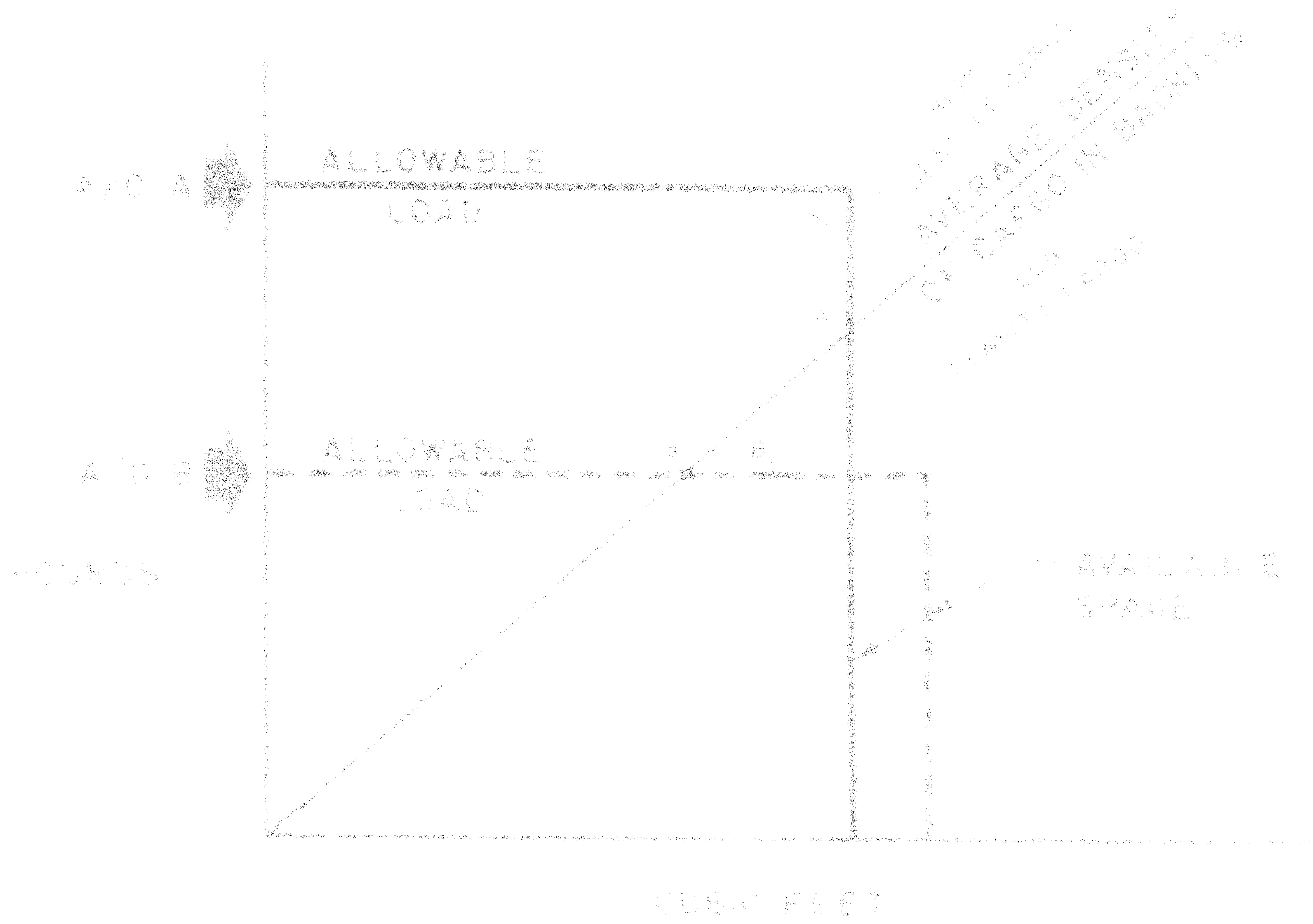
AIRLIFT OPERATIONS — OR, ONE PLUS THREE EQUALS FIVE

The management of cargo airlines and airlift operations is another field in which density variations can be neglected only at the risk of inefficiency. Let us see next how the capacity of a fleet of aircraft can exceed the sum of the capacities of the individual aircraft. Also let us understand how capacity depends upon the ingenuity of management.

In Chart VI, the vertical axis once again represents weight, the horizontal axis volume, and any diagonal represents a given density. Two aircraft are shown schematically. Their allowable loads are indicated by the horizontal lines and their cargo compartment volumes by the vertical lines. The "orange" aircraft (aircraft A) has a higher density factor than the "green" aircraft (aircraft B): i.e., A is comparatively space-limited, B weight-limited.

Suppose these two aircraft types are flying the same route, and that the average density of cargo in the backlog for the route is indicated by the solid diagonal. Loading aircraft B with cargo of this density,

DENSITY VARIATIONS AND AIRLIFT OPERATIONS



the aircraft's weight limitation would first be reached. The weight and volume of its load is indicated by the intersection of the density line and its allowable load line at B_1. Loading aircraft A with similar cargo, its space limitation would be reached, and the weight and volume of its load is indicated by the intersection at A_1.

However, there is likely to be considerable variation in the densities of the individual shipments in the cargo backlog. Instead of loading each aircraft type with cargo of the same density, the higher density cargo should be placed aboard aircraft A and the lower density cargo aboard aircraft B. Loading aircraft A with the higher density cargo, suggested by the upper diagonal, its load is now indicated by the new intersection (A_2). The volume of its load is the same as before, but the weight is greater. Loading aircraft B with the lower density cargo, its load is also indicated by a new intersection (B_2). The weight of its load is the same as before, but its volume is greater. Thus the airlift capacity of each of these aircraft can be greater when operating together than when flying over the route alone.

The airlift capacity of an aircraft is dependent upon the other aircraft types with which it is operating.

In scheduling aircraft, this should obviously be considered. When high density factor aircraft (such as Air Force C-97's) and low density factor aircraft (such as C-124's) fly the same routes, their airlift accomplishments will likely be greater than when either type alone operates on a given route. In selecting additional aircraft for a fleet this interdependence can be very important. If low density factor aircraft are added to a fleet of high density factor aircraft, the accomplishments of the latter are likely to rise. The total weight-lifting capacity of the fleet may increase by more than the weight-lifting capacity of the new aircraft. Aircraft comparisons should not neglect these hidden, but significant, benefits.

Clearly, the same principle can be applied to the situation in which only one type of aircraft is flying a route but, due to variations in density, the aircraft becomes alternately weight limited and space limited. When the aircraft is weight limited, it is important that it be loaded, so far as possible, with the lower density cargo in the backlog, increasing the volume of its load. The higher density cargo can then be placed on space-limited flights increasing the weight of such loads. Thus, a higher utilization rate of both allowable load and cargo space could be attained.

Obviously, cargo density variations are of significance to all those concerned with efficient airlift operations, whether their concern is in scheduling aircraft, or in aircraft procurement, or in air terminal operations.

AIRLIFT COSTS -- WHAT SHOULD WE LIFT?

The last phase of air transport I want to mention is that of allocating airlift; or more specifically, that of comparing the cost of airlifting different commodities. Unless we can compare such costs -- unless we know how much of one commodity we could airlift instead of so much of another -- we cannot allocate airlift to its most profitable uses. Even this knowledge, while necessary, is insufficient to tell us what to lift and what to leave behind.

Suppose we compare the cost of airlifting two different items each weighing the same. On the first flight, when, let us say, cargo densities are high and the aircraft is weight limited, the costs of carrying the different items are equal, regardless of their densities. Even if one item occupies twice as much space as the other, there is plenty of extra space aboard the aircraft. A pound of the high density item would displace exactly as much other cargo as would a pound of the low density item.

But on the other flight, in which densities are low and the aircraft is space limited, a different picture exists. On this flight it is volume which determines cost. If the low density item takes up twice as much space as the high density one, it would displace twice as much other cargo. It will cost twice as much to carry, even though the two items weigh the same. On weight-limited flights costs are proportional to weights, and on space-limited flights costs are proportional to volumes.

The "opportunity cost", that is the lost capability of lifting one thing because something else has been lifted, is always measured in terms of space or weight, depending which is the effective constraint.

However, over a series of flights, unreliable cost comparisons result if either weights <u>or</u> volumes are disregarded, for both are relevant.

Chart VII gives some of the reasoning. Two items, each weighing 500 pounds, are compared. Item "A" occupies 50 cubic feet of space and item "B", 100 cubic feet. The cost of airlifting "B" is shown as a per cent of the cost of "A". On the weight-limited flight the cost of "B" is 100 per cent of the cost of "A", since it weighs exactly as much. On the space-limited flight the cost is 200 per cent of the cost of "A", since it occupies twice as much space. On the average, over these two flights, the cost of "B" is half again as much as the cost of "A". On the average, "B" would displace half again as much cargo as "A".[1/]

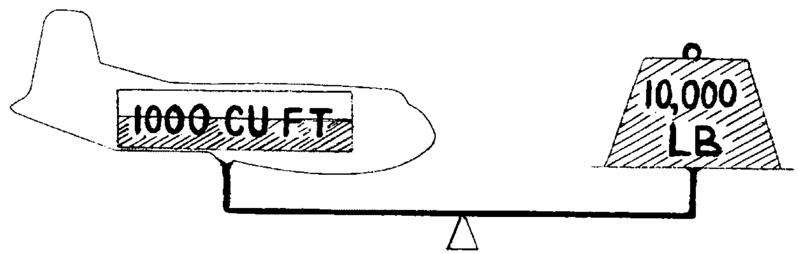
1/ This does not mean that the total cost of "B" over a series of flights is 150 per cent of the total cost of "A", however, since the cost of "A" may be much greater or much less on weight-limited flights than on space-limited flights. The more sophisticated formula on the next chart takes this possibility into account.

CHART VII

CARGO DENSITY VARIATIONS AND AIRCRAFT CAPACITY

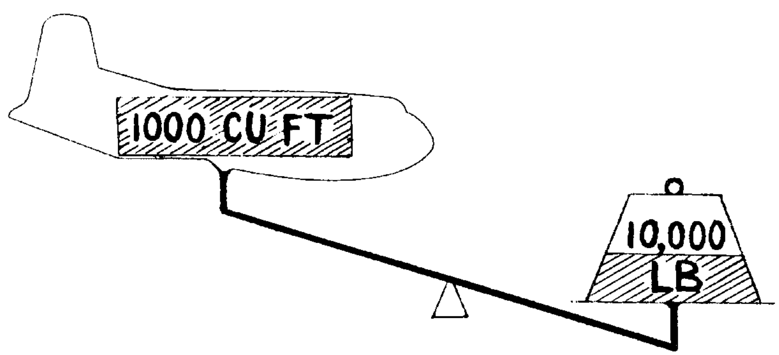
CARGO SPACE ALLOWABLE LOAD

FLIGHT I
20
LB/FT^3



TILIZATION------ 50% ----------- 100%

LIGHT II
5
LB/FT^3



ILIZATION----- 100% ----------- 50%

ITEM A 500 LB 50 CU FT
ITEM B 500 LB 100 CU FT

	COST OF B AS A % OF A
FLT I	100 %
FLT II	200 %
AVERAGE	150 %
ESTIMATE	100 %

A more exacting assessment of the opportunity costs can be obtained according to the scheme of Chart VIII.

The cost of airlifting a commodity over a series of flights depends upon (1) its volume, (2) the frequency of space-limited flights, (3) its weight, and (4) the frequency of space-limited flights. This formulation appears at the bottom of the chart and it permits cost comparisons to be made very quickly. It is necessary only to multiply the density factor of the aircraft serving a route by the relative frequency of space-limited flights to weight-limited flights over the route. A comparative cost index for airlifting any commodity over the route can then be obtained simply by adding its density to the product. Such indices reveal at a glance the comparative cost of airlifting equal volumes of commodities of different densities.

The important thing to remember is that variations in cargo densities affect the costs of airlifting different commodities, and that reliable estimates of opportunity costs are necessary if airlift is to be allocated to its most profitable uses.

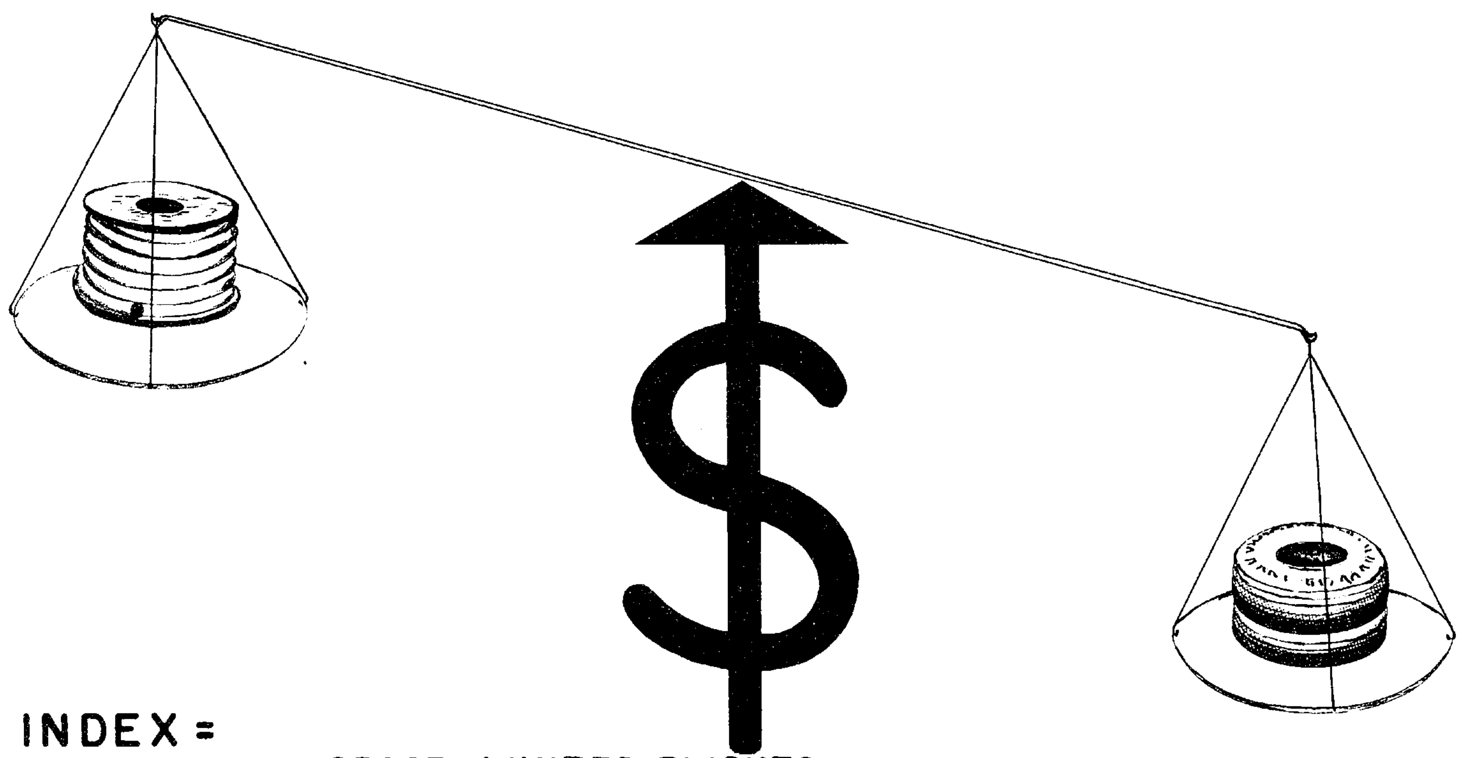
CONCLUSION

To summarize, I have tried to show that cargo densities, and particularly variations in cargo density from flight to flight, are important in many phases of air transportation. These variations affect the matching of airlift capabilities with airlift requirements; the designing of transport aircraft; the selecting of aircraft for a fleet; the routing of aircraft; and the allocating of airlift. Moreover, I have emphasized the fact that cargo densities vary considerably from flight to flight and from route to route. When we think and plan in terms of some average density, as if cargo

THE COST OF AIRLIFTING A COMMODITY IS PROPORTIONAL TO:

(A) ITS VOLUME,
AND THE FREQUENCY OF SPACE-LIMITED FLIGHTS

(B) ITS WEIGHT,
AND THE FREQUENCY OF WEIGHT-LIMITED FLIGHTS



COST INDEX =
A/C DENSITY X $\frac{\text{SPACE-LIMITED FLIGHTS}}{\text{WEIGHT-LIMITED FLIGHTS}}$ + COMMODITY DENSITY

BICKNER

densities were always the same, we run the risk of making wrong decisions and promoting inefficiency. In many instances these mistakes can be avoided and I have tried to give examples of how better estimates and decisions might sometimes be reached.