U. S. AIR FORCE
PROJECT RAND
RESEARCH MEMORANDUM

AIRCRAFT COMPARTMENT DESIGN CRITERIA
FOR THE ARMY DEPLOYMENT MISSION

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RM-2566

May 1, 1960

This research is sponsored by the United States Air Force under contract No. AF 49(368)-700 monitored by the Directorate of Development Planning, Deputy Chief of Staff, Development, Hq USAF.

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SUMMARY

This Research Memorandum is concerned with the design of cargo aircraft, particularly for their use in the army deployment mission. It suggests desirable relationships between compartment size and payload capacity for this mission, and thus aids in the design of future aircraft. The same criteria can also be used to assess capabilities of present aircraft.

As a basis for comparing the carrying capacity and efficiency of various aircraft, the study employs a list of equipment drawn up by the Office of the Deputy Chief of Staff for Logistics of the U. S. Army. This list, received in September 1959, is an estimate of the equipment required by a hypothetical planning force designated as the "A" Airborne Division Force, thought of as being used for show-of-force deployments. Final design decisions, must, of course, take other possible missions and lists of equipment into account.

The following are the study's principal conclusions:

(1) While cargo-compartment cubage may be an acceptable measure for measuring compartment space requirements for calculating peacetime airlift capability, the requirements of army deployment cargo demand a more accurate one. The bulk of this cargo is vehicular; peacetime cargo principally consists of small units which lend themselves to flexible arrangement.

(2) The best single measure of the space requirement for the equipment studied (which excludes the largest items required in an army deployment) is cargo-compartment floor area rather than cubage.

(3) The best estimate for floor space utilization is that about 51 pounds of this type of cargo can be loaded on each square foot of the compartment floor. This finding has direct implications for future cargo-aircraft design, and can also be used to assess present aircraft: (a) if
these aircraft are designed with a payload over the relevant range which is greater than 51 lb/ft$^2$ of compartment floor area, the constraint on aircraft capacity for the deployment mission will be floor space, not payload; similarly, (b) if the design is for payloads of less than 51 lb/ft$^2$ of floor area, the aircraft will typically be weight-limited.

(4) This planning factor was applied to the payload-range curves of aircraft presently in the fleet, and yielded revised curves which more accurately portray the results which would be obtained if these aircraft were used in a deployment mission. The adjustment imposed only a minor change in the curve for the C-124, but reflected a significant reduction in the capability of both the C-130 and C-133.

(5) If new aircraft are to have characteristics similar to those of the C-130 and C-133, mere reduction of vehicle weight will only slightly lower the amount of airlift required to support a deployment. More effective actions would be to reduce the length or width, or both, of army vehicles, and to rely on fewer vehicles relative to ammunition and smaller cargo.

On the basis of this analysis alone, however, it is not possible to suggest which should undergo the greater change — army cargo or the aircraft. The proper policy will depend on the extent to which changes for deployment purposes harm the efficiency of the vehicles or the aircraft in meeting their other requirements, and the importance of the deployment mission in comparison with those requirements.
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I. INTRODUCTION

The past year has seen considerable interest, both military and civilian, in the deployment of ground forces and their equipment to potential or actual war areas. It is generally agreed that the United States should be able to deploy its forces rapidly enough to gain significant military and psychological advantages. That such speed requires at least some airlift capability is seldom disputed; a common opinion is that it should be increased. This Research Memorandum examines an important element in the deployment mission: our cargo airlift capability, which may have to be increased to move the equipment and resupply necessary to make ground forces effective.

Opinions differ considerably on the best way to obtain that capability. Some of the disagreement arises from private convictions on who should own and operate the aircraft, but opinions also differ on the more objective question with which this study deals: the desirable characteristics for aircraft which are assigned the army deployment mission. We will examine a representative list of army cargo which might be deployed in response to a war threat, and evaluate the capability of a number of possible aircraft designs to move the cargo.

Aircraft loading problems are intimately connected with design criteria, which will dictate both the preferred loading technique and the maximum amount of materiel the aircraft can transport over any given route. One of the most persistent problems in air transportation has been how to determine the capability of cargo aircraft to perform various tasks. It has long been recognized that it often may be either impossible or impractical to load aircraft with the maximum payload allowable over the chosen
route; when this is so, some measure other than weight must be used in calculating airlift capability. Cargo cubage appears to be an acceptable measure for the type of materiel airlifted by commercial carriers and for most equipment moved by the military in peacetime; in both cases, most of the cargo consists of small units which lend themselves to flexible arrangement, so that the cargo compartment space can be efficiently used in all three dimensions. Under these circumstances, cubage may be used as the sole measure of space requirements in airlift planning.

The important relationship for peacetime cargo is between its weight and its cube. If an aircraft's allowable payload over a route exceeds the weight of the cargo which will fit into the cargo compartment, cubage is the constraint on airlift capacity.

If the allowable payload is less than what the plane could carry, weight is the constraint. Considerable research has been devoted to this important problem area and the implications for airlift planning and aircraft design have been examined in some detail.*

Unfortunately, the procedures for studying peacetime cargo airlift do not appear applicable to army deployment, which involves a different kind of cargo. The bulk of it consists of vehicles which cannot easily be arranged to fill the cargo compartment. They cannot be stacked to take full advantage of compartment height; most of them are longer than the compartment width, so they cannot be turned sideways; and it is impractical to turn them on their sides. Cubage alone, then, is not an adequate measure.

in this case. This study investigates the space requirements of army deployment cargo and suggests a more accurate measure. It then examines the relationship between cargo weight and the space requirements, in order to indicate fruitful design criteria for this mission.
II. MATERIEL STUDIED

No single force can be ideal for meeting every conceivable war threat, nor can any single list of army deployment cargo. Ideally, we would like to obtain a number of such lists, each designed for a likely contingency, study each list and then examine the range of results. Such lists are not readily available at present, however; consequently, this study is restricted to the examination of one particular list of equipment.

The equipment studied is that required by a hypothetical planning force designed by the Office of the Deputy Chief of Staff for Logistics of the U. S. Army.* This force, designated as the "A" Airborne Division Force, is thought of as being used for show-of-force deployments. It is composed of elements of an airborne division augmented by portions of 45 supporting organizations. The cargo required to support the 16,123 personnel in the force weighs slightly under 13,600 tons; Table 1 shows its composition.

Table 1
CARGO REQUIRED FOR DEPLOYMENT OF AIRBORNE FORCE "A"

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight (tons)</th>
<th>% of Total Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles</td>
<td>8,770</td>
<td>64.5</td>
</tr>
<tr>
<td>Other Organizational Equipment</td>
<td>2,420</td>
<td>17.8</td>
</tr>
<tr>
<td>Basic Load of Ammunition</td>
<td>732</td>
<td>5.4</td>
</tr>
<tr>
<td>Accompanying Resupply (6 days)</td>
<td>1,670</td>
<td>12.3</td>
</tr>
<tr>
<td>Total</td>
<td>13,592</td>
<td>100.0</td>
</tr>
</tbody>
</table>

The results of the analysis performed in this study will apply to deployments similar to those of Airborne Force "A," of course. Moreover, although it cannot be said for certain that other deployments will have

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* A copy of this list of equipment was made available to The RAND Corporation in September, 1959.
similar requirements, it is extremely likely that they will, since most of the vehicles studied are standard equipment for almost every sizable army organization and make up a relatively constant percentage of any major force. The analysis should thus apply to a number of alternate mixes.

If additional equipment lists become available, it may be useful to repeat the analysis to see if the new results agree with those in this study; but since decisions on cargo-aircraft design must be made in the meantime, we will proceed on the likely assumption that our results are typical of army deployment cargo.
III. COMPARTMENT CROSS-SECTION

Items of army equipment to be moved vary markedly in all three dimensions, length, width, and height. Some items will not fit at all in a number of present aircraft compartments, but since no compartment under active consideration is shorter than the longest item in the list, we will assume that width and height are the only constraints.

Figure 1 summarizes a body of information derived from the equipment list and applied to the evaluation of compartment cross-section. The curve labeled "90%" indicates a number of combinations of item width and height; the weight of all items narrower and lower than any one of these combinations makes up 90 per cent of the total weight to be moved. The other percentage-curves indicate analogous combinations of dimensions. If no allowance is made for clearance, each of these curves can be interpreted as indicating the various rectangular compartment-cross-sections which are just able to carry a particular percentage of the total weight to be airlifted. It would be wise, however, to allow for clearance by entering the diagram with somewhat smaller than actual dimensions of each compartment under consideration.

One important qualification in using Fig. 1 must be noted here: it can be used only for compartments of rectangular cross-section, even if the items to be carried are not rectangular. Non-rectangular compartments must be analyzed in more detail; and in general, each particular compartment-size has to be examined separately to determine the items which can be carried.

No simple rule can specify the number of aircraft types which should be employed in the army deployment mission. It may be, for example, that
Fig. 1—Capacity of various aircraft compartment cross-sections
the best policy is to use two aircraft sizes: one very large aircraft which can carry any of the equipment, and a medium-sized one which can carry 90 per cent of it. Or perhaps a preferable combination would be the large aircraft plus one which can carry only 70 per cent of the equipment. Or perhaps a desirable fleet should include all three. The correct answer hinges on a number of factors outside the scope of this study, which in the broader problem represents only one of many inputs required for the final decision.* But it is an important input, worthy of considerable analysis.

In this paper we choose a particular group of equipment and evaluate the efficiency of various compartment sizes for moving it. All the equipment selected is less than 108 inches wide and 110 inches high. While this group is only one of a number which might be studied, several reasons make it particularly interesting for this illustration.

We have suggested that some number of aircraft with a compartment cross-section large enough to carry any item in the list must be assigned to the army deployment mission; however, it may be wise to procure only enough of them to carry a small portion of the total cargo. Two aircraft which can carry the larger items (the C-124 and the C-133) are already in the military fleet. Thus it appears that future aircraft development and procurement might best concentrate on aircraft which can carry an appreciable amount of the total army cargo, but not necessarily every item.

*The analysis described in this report was undertaken to aid in estimating the productivity of cargo aircraft in performing the army deployment mission. This study is part of a larger research project now in process at RAND. For a description, see William A. Niskanen and Richard B. Rainey, Jr., A Structural Approach to Military Air Transportation, The RAND Corporation, Paper P-1826, October 23, 1959.
The group of equipment chosen for this illustration constitutes approximately 85 per cent of the total weight to be moved, and thus requires a relatively large compartment cross-section. Further, it could be carried in a number of aircraft which major manufacturers have proposed in recent months; thus the results of this analysis should prove of considerable interest.

Approximately 85 per cent of the total vehicle weight is contributed by vehicles smaller than the maximum width and height dimensions we have chosen. The larger ones constitute 15 per cent of the vehicle weight but only 10 per cent of the total weight. Thus it is possible to load 90 per cent of the total weight in the aircraft considered in this study, if we assume that the excluded vehicles are transported without any accompanying items. But since the aircraft in which these excluded vehicles would be carried are no more likely to be weight-limited than are those examined in this study, it would appear more reasonable to assume that a proportionate amount of the non-vehicular weight would be moved with the excluded vehicles. Thus we will include only 85 per cent of the weight of the remaining items in the equipment list to be studied. Table 2 gives the resulting list.

Table 2

CARGO INCLUDED IN THE STUDY

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight (tons)</th>
<th>% of Weight Included in the Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles</td>
<td>7,436</td>
<td>64.5</td>
</tr>
<tr>
<td>Other Organizational Equipment</td>
<td>2,052</td>
<td>17.8</td>
</tr>
<tr>
<td>Basic Load of Ammunition</td>
<td>621</td>
<td>5.4</td>
</tr>
<tr>
<td>Accompanying Resupply (6 days)</td>
<td>1,416</td>
<td>12.3</td>
</tr>
<tr>
<td>Total</td>
<td>11,525</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Before the analysis proceeds, two operations must be performed on this list.

First we segregate items which must go on the floor of the aircraft because they cannot be loaded in truck beds, and require a large floor area whose shape cannot be altered. Virtually all of them are either wheeled vehicles (which are best loaded with their axles perpendicular to the compartment walls), or have one dimension longer than the width of the widest aircraft considered. For ease of exposition we will refer to all such items as vehicles. They account for $2/3$ of the total weight to be moved. In Secs. V and VI we develop a method for determining the efficiency of various aircraft compartment sizes in moving these vehicles.

There will probably be some lost space due to tie-down requirements, room for maneuvering, etc. Accordingly, the second operation on the list attempts to account for the loss by increasing the dimensions of the vehicles. The length of each item is increased by 12 in.; the width of items over 65 in. wide is increased by 12 in., while that of items under 65 in. is increased only by 6 in. to account for their greater maneuverability. In the remainder of this paper, width and length will thus include the actual dimensions plus these clearance requirements.
IV. AIRCRAFT STUDIED: COMPARTMENT WIDTH AND LENGTH

Our specifying the materiel which must be carried by the aircraft to be evaluated in turn places certain restrictions on aircraft size.

First, it demands compartments at least 110 in. high. We assume here that all aircraft compartments to be studied meet this constraint, and exclude compartment height from the remainder of the analysis. This approach is adopted since vehicle stacking is not current practice, and increasing compartment height above 110 in. would therefore not increase the capability of a given compartment to carry the equipment selected.

Secondly, the equipment selected restricts compartment width. The widest vehicle in the study measures 108 in.; allowing for clearance gives a minimum cargo width of 120 in. Since the widest compartment currently under consideration is slightly over 12 feet, we shall evaluate cargo compartments from 120 to 150 in. wide.

Finally, the equipment selected places a minimum constraint on compartment length: the compartment must be as long as the longest item. We shall consider compartment lengths from 500 in. (which more than meets this requirement) to 1000 in. (the length of some of the larger aircraft presently under consideration).

*However, it might prove extremely worthwhile to alter vehicle designs to enable stacking in aircraft with high cargo compartments.*
V. COMPARTMENT WIDTH

Compartment width claims our first attention; this Section attempts to specify the most efficient method of using it in loading vehicles. The problems of compartment length are disregarded here, to be taken up in Sec. VI.

For expository simplicity, assume it is possible to build an aircraft of any length but with a specified width; given this constraint we wish to determine the shortest possible aircraft which will just hold all the vehicles to be transported. The compartment is wide enough to hold some vehicles side by side, but no more than two, since the narrowest vehicle is more than 1/3 the width of the compartment (this applies to all compartment widths studied, since the narrowest vehicle is over 50 in. wide).

The technique is simple analytically and could be applied on the flight line. The vehicles are first lined up with their left sides against the left wall of a very long cargo compartment; the widest vehicles go in first. Graphically, this is merely the cumulative column length as a function of vehicle width. Figure 2 illustrates the function for the vehicles in this study. The horizontal axis gives the column length which can be made up of vehicles whose widths exceed the corresponding value on the vertical axis. Column lengths are expressed in terms of the total column length (the length of the vehicle column when no doubling of vehicles is permitted).

Next, the last — and narrowest — vehicle pulls out of the line and drives forward, with its right side against the right compartment wall. The next-to-last vehicle follows it. The process continues until one of the vehicles can drive no farther because the space is too narrow between the vehicle to its left and the compartment wall to its right. It is easy
Fig. 2—Cumulative distribution of vehicle width
to perform this process graphically by using a transparent overlay of the original distribution: the overlay is rotated 180°, with the original horizontal axis placed on the horizontal line corresponding to the compartment width; the overlay is then moved from right to left until the two curves touch. Figure 3 shows the result of applying the technique to a compartment width of 150 in. The total length of the new column is about 0.72 that of the original. The minimum column length has been attained because the vehicle represented by the shaded area can move no farther forward (to the left on the diagram).

An intuitive argument for the use of this technique is relatively simple. The vehicle represented by the shaded area cannot move to the left of the line EF since the original vehicles (Groups I, II, and IV) do not leave enough space. But the vehicles in Groups VI and VII are at least as wide as the vehicle in the shaded area since we have arranged them in order of decreasing width. Thus they cannot be placed in the area to the left of EF. Therefore, the only vehicles which can possibly fit in this area are those in Groups III and V, which have already been placed there by the technique. Since no further rearrangement of vehicles can thus decrease the length of the column, the minimum column length has been attained.

By repeating this procedure for each of the compartment widths to be evaluated, we can find the corresponding minimum possible column length. This can be done in a matter of minutes once the transparent overlay of the initial distribution is made. In Fig. 4 the solid line indicates the minimum column length associated with each of the aircraft compartment widths. The column length is again expressed as a proportion of the length of the initial column.
Fig. 3—Aircraft loading: compartment width 150 inches
Fig. 4—Utilization of compartment width
The horizontal axis in Fig. 4 represents compartment width, while the vertical axis represents the total length of cargo compartment(s) required for the entire group of vehicles. Any rectangular hyperbola of the form $xy = K$ represents all combinations of compartment width and column length which have the same total floor area. Three such functions are shown by the dotted curves in Fig. 4 (note that since the axes do not start at zero the hyperbolae appear almost linear). We know the total floor area of the vehicles themselves, so any total compartment floor area can be related to the vehicle floor area by means of a load factor. Thus a load factor of 76 per cent means that the vehicles will cover 76 per cent of the total floor area; stated in another way, the total floor area equals $1/0.76$ times the required vehicle floor area.

For the vehicles included in this study, Fig. 4 shows that the simple rectangular hyperbola provides an excellent equation for estimating the relationship between aircraft width and column length. The function everywhere lies between the curve representing a 76-per-cent load factor and that representing an 83-per-cent factor, and is well approximated by that representing a 79-per-cent factor. Within the range considered, we may conclude that aircraft width is irrelevant: 79 per cent of the compartment floor area is covered with vehicles regardless of compartment width.

There is no a priori reason that a constant floor-area load-factor should adequately summarize the effect of varying compartment width. Its use will simplify the remainder of the analysis, but the analysis could also be performed with some less convenient estimating-equation for this relationship. Other lists of equipment might yield a curve which could
be better approximated in some other manner.* But the list under study here was selected because it was thought to be typical of army cargo to be deployed in contingency missions, and it is likely that many alternative lists would exhibit the same relationship between aircraft width and column length.

*If, for example, we were to study the 15 per cent of the original list which has been excluded in this analysis, the best estimating equation would be of the form, Column Length = Constant, since the vehicles are all so wide that little or no doubling would be possible.
VI. COMPARTMENT LENGTH

In the preceding Section we minimized the length of the total column of vehicles to be airlifted, subject to various constraints on the compartment width. We concluded that if compartment length could be perfectly utilized, 79 per cent of the total floor area could be covered with vehicles. This is an impossible ideal; to assess the real possibilities we must now examine the effect of compartment length on aircraft loading.

The same physical fact prevents perfect efficiency in using either compartment length or width: vehicles cannot be chopped into convenient sizes. But compartment length is more likely to be used efficiently than is width, because compartment lengths are greater in comparison with the average vehicle length than compartment widths are in comparison with the average vehicle width. Moreover, we would expect longer compartments by nature to be more efficient than shorter ones. Obviously, the approximate magnitudes of these relationships need to be determined.

There are no simple rules for the optimum use of compartment length; and in assessing the capability of various aircraft, no rule should be considered at all if it cannot be applied with some speed on the flight line. A further complication arises when we attempt to reconcile a technique for obtaining optimum use of compartment length with the technique described in Sec. V for optimum use of compartment width. We shall initially disregard width (as we did length in Sec. V) and return to it later.

Since there is no simple optimum rule for length, we will have to look for some simple and fairly efficient working-rule. Tentatively, we will use the following technique.
We are given a group of vehicles to be loaded in single file, none side by side. The aircraft have a given compartment length. The goal is to load the vehicles but use as few aircraft as possible.

The vehicles are first lined up in order of decreasing length. The longest vehicle goes on the first aircraft, then the second longest, and so on until the remaining space is too short for the next vehicle in line. At this point, the longest vehicle which will fit is loaded.

The general rule is to load no more than one vehicle of any particular length on any single aircraft. The rule must be broken toward the end of the process, however, since one each of the few remaining vehicle lengths cannot fill the aircraft. In such a case it is permissible to load more than one vehicle of the shortest available length in a given aircraft.

When the vehicles are all loaded, we count the aircraft used; this quantity, times the compartment floor-length of the individual aircraft, gives the total compartment floor-length required. The total length of the vehicle column, divided by this total compartment floor-length, gives a loading-efficiency ratio with respect to compartment length.

The rule suggested has virtues other than simplicity. It imposes at least a small degree of combat loading; that is, it makes the loss of any one aircraft somewhat less crucial since the great majority of the aircraft contain only one vehicle of any given model. Further, it will tend to reduce the distribution of weight per aircraft.* Finally, it may prove fairly efficient.

*There are two constraints on aircraft capacity: the vehicle capacity (determined by the above analysis) and the payload capacity. The payload per aircraft loaded according to vehicle capacity is the ratio of these two dimensions for the equipment to be moved. The more this distribution clusters around its mean, the less inefficiency will arise because of the presence of the two constraints; and hence the smaller the number of aircraft of any given design which will be required to move the equipment.
To get a first approximation of the efficiency of this rule, it was tested on the full list of vehicles, assuming that none would be placed side by side. The longer compartment was more efficient, as we expected. Cargo compartments of 500 and 1000 in. were evaluated; the efficiency of the shorter compartment was 95.5 per cent, of the longer, 98.1 per cent. The size of these percentages indicates that the rule is surprisingly efficient and quite satisfactory for our purposes.

When we turn to a consideration of double columns of vehicles we once more encounter the problem of compartment width, whose optimization was discussed in Sec. V. Doubling also compounds the length problem, however, since the end of a vehicle in one column may come in the middle of a vehicle in the other column. If the resulting loss of length-efficiency is substantial it may even be wise to consider less efficient methods of using compartment width; but as a first cut at this problem, we will see how efficiently length can be used if we retain the doubling techniques described in Sec. V.

The method adopted can best be seen with the aid of Fig. 3, which shows the arrangement of vehicles in an aircraft 150 in. wide. In any aircraft, there will be some wider vehicles which will have no others alongside them (Group I, in this case). At the end of the column, there will also be a few pairs of vehicles with the same or nearly the same width (Groups VI and VII); we can regard these pairs as single vehicles and mix them at will with the wider vehicles (Group I). We can now apply our length-utilization rule to this composite group of vehicles to determine the number of aircraft required to hold them.

Next we take the remaining vehicles and divide them into groups according to the following criterion: the vehicles can be rearranged within a
group in any manner, without violating the width constraint. Groups II, III, IV, and V in Fig. 3 are examples of such groups. Next, we apply the length-utilization rule to each such group, obtaining the number of aircraft required. The aircraft required for two groups which go alongside each other is merely the larger of the aircraft required for the individual groups. Thus, if Group II requires more aircraft than does Group III, the aircraft required for Group II will suffice to carry both groups.

This technique allows us to determine a number of aircraft which can contain all the vehicles. We may express the efficiency of the technique by dividing the length of the initial (doubled) column by the total compartment length of the aircraft required. The results for the four extreme compartment sizes are as follows:

<table>
<thead>
<tr>
<th>Compartment Length</th>
<th>120 in.</th>
<th>150 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 in.</td>
<td>91.8%</td>
<td>89.4%</td>
</tr>
<tr>
<td>1000 in.</td>
<td>95.4%</td>
<td>91.2%</td>
</tr>
</tbody>
</table>

Again the efficiency is surprisingly high. The narrower compartment uses length more efficiently since relatively few vehicles have been doubled, while the wider compartment pays for its efficient use of width by achieving a slightly less efficient use of length. The advantage of longer compartments is evident for each compartment width.

These differences are not insignificant; they suggest that a really sophisticated analysis might profit from a study which applied several possible techniques to this problem, evaluating the efficiency of such techniques for a large number of possible compartment sizes. The remainder of this study, however, adopts the very simple assumption that length can be used
with 91.5-per-cent efficiency regardless of compartment size. This assumption has the virtue of simplicity and should not prove far wrong for most compartment dimensions under consideration, since compartment length and width are usually correlated. The efficiency of the short, narrow compartment is 91.8 per cent, while that of the long, wide compartment is 91.2 per cent. If a compartment is to be considered which sharply diverges from these proportions, the final values obtained in the analysis should be adjusted appropriately.

We may now summarize the analysis of Secs. V and VI. Section V found that vehicles would cover 79 per cent of the floor area in a perfect utilization of compartment length; if the policies suggested in Sec. VI are adopted, however, only 91.5-per-cent efficiency appears obtainable in terms of length utilization. In that event, only about 72 per cent of the floor area will actually be covered — 91.5 per cent of 79 per cent. Stated another way, the minimum number of aircraft required to hold the vehicles can be computed by dividing the vehicle floor area by 0.72 to determine the aircraft floor area required. This figure is then divided by the floor area of the compartment size in question, to determine the required number of aircraft. And this technique applies to the full range of aircraft under consideration.
VII. COMPARTMENT CUBE

Our analysis thus far has been concerned only with the vehicles to be airlifted. The study must now encompass the remaining materiel, which accounts for $1/3$ of the total weight to be moved. This Section deals with the requirements for cubage in which to place this equipment; Sec. VIII deals with its weight.

Having determined the minimum number of aircraft required to move the vehicles, we must now find out if enough cubage is available in those aircraft to carry the remaining equipment. Two sources of space are available for this purpose. First, there is the space not covered by vehicles. This amounts to 28 per cent (100 - 72) of the total aircraft floor area, or approximately 40 per cent of the vehicle floor area (28/72). The second source is the platform area of many of the cargo vehicles. This area is roughly 30 per cent of the total floor area of the vehicles. The total area available for the remaining cargo is thus equal to approximately 70 per cent of the vehicle floor area.

The cubage of such equipment in the lists used in this study was approximately 1.4 times the floor area of the vehicles (it is considerably denser). If it were spread evenly over the available area the average stack height would thus be 2 feet ($1.4 / 0.7$). Since the minimum aircraft height considered is over 9 feet from the floor, and between 5 and 6 feet from the average truck bed, there is considerable latitude in loading this equipment. For all practical purposes, cubage per se can be disregarded in the analysis which follows.
VIII. AIRCRAFT PAYLOAD

We have determined the minimum number of aircraft required to hold the vehicles to be moved, and we have found that this number can easily hold the remaining cargo. The next step is to examine the distribution of weight per aircraft which would result if aircraft were loaded in the way the preceding Sections have described. By comparing this distribution with current designs, we can determine which constraint is more important for such aircraft — weight or floor area; more important, we can suggest desirable design criteria for future aircraft.

We will begin with the distribution of weights which results from loading the vehicles, temporarily leaving the remaining items out of the analysis. First we must determine each vehicle's weight per square foot of floor area. For convenience we will use the term Area Load Factor (ALF) to indicate the ratio of weight to floor area. We then calculate the distribution of these ALF's, using floor area as the frequency measure.* In the particular case described in this study the mean ALF was 47.6 lb/ft² and the standard deviation of a fitted normal curve was 33.4 lb/ft².

The average floor area of the vehicles studied was 108 ft², and we have determined that 72 per cent of the floor area of any given aircraft can be covered with vehicles. Therefore, the average number of vehicles per aircraft (N) is a simple function of the aircraft floor area in square feet (A):**

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*This is the proper measure for the special case where floor-area utilization is constant. In the general case the particular measure which best represents the amount of an aircraft utilized by each vehicle should be chosen.

**In the general case N would have to be determined for each individual compartment size in accordance with the results of the analysis of length and width utilization.
If a large total number of vehicles is to be loaded, and randomly with
regard to weight per square foot of floor area, it is a simple matter to
estimate the distribution of the average ALF's of the individual aircraft.
Each aircraft represents a sample of size \(N\) drawn from the population of
mean 47.6 lb/ft\(^2\) and standard deviation 33.4 lb/ft\(^2\). The average ALF (per
square foot of vehicle floor area) in a given aircraft corresponds to the
sample mean, and the distribution of such average ALF's is merely the dis-
tribution of the sample means. This distribution has simple properties.
The mean is, of course, the mean of the population, or 47.6 lb/ft\(^2\). The
standard deviation is simply the standard deviation of the population di-
vided by \(\sqrt{N}\); i.e., \(33.4/\sqrt{N}\). *

Thus, we can easily determine the distribution of average weight per
square foot of vehicle floor area once we know the floor area of the indi-
vidual aircraft. The next step is to consider the effect of loading the
remaining cargo.

*Of course this will give a somewhat optimistic estimate of the actual
standard deviation, because \(N\) is merely the average number of vehicles
loaded in each aircraft; since the actual number varies around \(N\), the stand-
ard deviation of the resulting distribution will exceed the value calculated
by this method. In fact, however, the error resulting from the assumption
that \(N\) vehicles are loaded in each aircraft appears to be small. The actual
weights loaded in the smallest aircraft under consideration -- 120 in. wide
by 500 in. long -- were computed and compared with the distribution pre-
dicted by the use of this formula. Approximately 90 per cent of the aircraft
contained loads within the range which the formula predicted would contain
95 per cent of the cases; approximately 95 per cent of the aircraft loads
were within the range which the formula predicted would include 99 per cent
of the cases. While the error in this case was not insignificant, it appears
that using the formula will not seriously bias the study, for two reasons.
First, no attempt was made in the example to adjust loads so as to reduce
the range of vehicle weights; such a readjustment would have made it possible
Figure 5 illustrates the cumulative distribution of weight per square foot of vehicle floor-area for an aircraft of 450 ft$^2$ floor area. Area is expressed in terms of total vehicle-floor-area, the ALF is measured in lb/ft$^2$ of vehicle floor-area; the cumulative distribution is shown by the curve OPR. Now we must add to this weight another group of items which weigh half as much as the vehicles themselves. Since the preceding Section demonstrated that there can be considerable latitude in loading these items, they will be added here so as to yield a desirable weight distribution.

What weight distribution would be the best? If the aircraft is so designed that all aircraft loaded with vehicles already contain more weight than the allowable payload, weight will be the only effective constraint on aircraft loading; the manner in which we load the remaining items is irrelevant, since they will eventually have to be reloaded in other aircraft. However, it is much more likely that only a portion of the aircraft loaded with vehicles already contain more than the allowable payload weight. In these aircraft, weight will be the effective constraint on cargo carried, but vehicle loading will be the initial constraint in the remaining aircraft. Now if additional weight is added to the former aircraft, the number of aircraft required will likewise increase — weight being the constraining dimension. However, if we load the additional weight on the latter group of aircraft (those with a low initial ALF) the number of aircraft required will not be increased — up to a point, at least — since the initial loads to obtain a distribution much closer to that predicted by the formula. A second reason for regarding this error as acceptable is that the particular aircraft chosen for the test is the smallest considered, having a floor area of only 420 ft$^2$; the error for larger aircraft is likely to be considerably less important.
Fig. 5—Cumulative distribution of area load factors for aircraft of 450 ft$^2$ floor area, loaded with vehicles

are below the allowable payload. Thus the preferred loading policy for this remaining equipment is quite simple: each pound should be loaded in the aircraft with the (then) smallest average ALF.

This rule can be easily performed graphically. Since the horizontal axis in Fig. 5 represents ALF's measured in lb/ft$^2$, and the vertical axis represents floor area measured in ft$^2$, an area of any given size on this graph represents some total weight. Since our task is to distribute a given total weight, we need only apply the specified rule until the required area is obtained graphically. The rule that each pound must be loaded in the aircraft with the smallest average ALF can be followed by merely moving a vertical line from left to right. The area to the left of such a line and under the curve will represent the weight added; the line is merely moved to the right until this area equals the total weight to
Fig. 6—Cumulative distribution of area load factors for aircraft of 450 ft\(^2\) floor area, loaded with vehicles and other cargo

be distributed. In Fig. 5 the final position is shown by the line MN, while the shaded area OPNO is equal to the weight of the additional cargo. The final distribution of ALF's is now given by the curve ONMR.

Thus far we have determined the distribution of weight per square foot of vehicle floor area. We must now convert this into the weight per square foot of aircraft floor area. This is a simple operation since the vehicle floor area equals 72 per cent of the aircraft floor area. By merely multiplying the ALF's already obtained by 0.72, we obtain the corresponding ALF's stated in terms of aircraft floor area.

Figure 6 represents the final distribution of weights per square foot of aircraft floor area, for a cargo compartment of 450 ft\(^2\) floor area. Consider an aircraft which can carry a payload over the relevant range equal to 52 lb/ft\(^2\) of floor area. From Fig. 6 it is evident that 90 per cent of
the aircraft loaded up to the floor-area constraint will not require the full payload available; for these aircraft, the limiting factor is their floor area. To determine the number of aircraft required to carry this equipment, the total vehicle floor area is divided by 0.72 and then multiplied by 0.9; the resulting figure is then divided by the floor area of the individual aircraft. Now the remaining 10 per cent of the aircraft (as initially loaded) contains cargo which weighs more than the allowable payload; thus some of the equipment must be offloaded and placed on additional aircraft.\footnote{But it cannot be placed in any of the aircraft which are floor-area-limited since this equipment also requires floor area.} Weight will be the limiting factor in loading this equipment. The total weight is shown by the shaded area in Fig. 6; the total number of aircraft required to carry these items can be determined by dividing the total weight by the relevant payload of the aircraft. This procedure, although somewhat cumbersome, can provide a rather accurate estimate of the number of aircraft of a particular design required to move such a group of equipment.

Let us now summarize the ALF relationships for aircraft of various floor areas. In Fig. 7, the minimum ALF in lb/ft$^2$ of aircraft floor area is shown by the curve labeled "0\%" for aircraft floor areas from 400 to 1100 ft$^2$. It has a very slight slope and is asymptotic to 51.4 lb/ft$^2$. The other three curves show the values below which lie the average ALF's of 95.0, 97.5, and 99.5 per cent, respectively, of the aircraft for each compartment size. The equations for these functions can be readily determined from the confidence limits of the normal distribution and the relationship among the aircraft floor area, the number of vehicles per aircraft, and the standard deviation of the relevant ALF distribution described earlier in this Section.
Fig. 7—Confidence limits of area load factors for various aircraft compartment sizes

One of the aims of this paper is to arrive at relationships which are simple but nonetheless take into account the more important factors to be considered in evaluating the capability of various aircraft in performing the army deployment mission. In keeping with the quest for simplicity, it seems reasonable to suggest that, at least for the larger aircraft, no great harm would be done if the distribution in Fig. 7 were represented by a single line at, say, 51 lb/ft².* If this simplification is made, a straightforward rule can be adopted. Any aircraft which is designed for a maximum payload (over the relevant range) of less than 51 lb/ft² of its compartment floor area will be weight-limited in performing this mission; and the total number of aircraft required can be determined by dividing the total weight to be carried by the aircraft payload. On the other hand, any aircraft which has a payload greater than 51 lb/ft² of floor area will be floor-area-limited in performing this mission, and the total number of aircraft

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*The slight loss of accuracy from such an approximation should be well worth the resultant gain in simplicity.
required can be determined by first dividing the total floor area of the vehicles to be moved by 0.72, and then dividing the result by the aircraft floor area.
IX. CONCLUSIONS AND IMPLICATIONS

As it is formulated here, the design criterion which indicates an aircraft's efficiency in performing the army deployment mission is fairly obvious. The most efficient design would provide for a payload capacity (over the relevant range) of approximately 51 lb/ft$^2$ of floor area. If the payload were greater than that, the payload limitation could be reduced down to 51 lb/ft$^2$ (thus reducing the total cost of purchase and operation of the aircraft) without decreasing the amount of cargo which the aircraft could in fact carry. On the other hand, if the payload were less than 51 lb/ft$^2$, the compartment floor area could be reduced until the ratio again reaches 51 lb/ft$^2$ (again reducing the purchase and operating cost) without decreasing the amount of cargo which the aircraft could actually carry.

Thus, the most efficient aircraft for this mission would have payloads (over the required range) equal to about 51 lb/ft$^2$ of compartment floor area. It is important to remember that, in fact, this will be but one of a number of criteria to be considered in selecting an aircraft designed to perform many missions.

What criterion would be proper if a number of aircraft designs were to be compared in terms of the cost of performing the army deployment mission? The cost per pound of cargo carried provides at least a partial measure of this capability.* For aircraft with payloads less than 51 lb/ft$^2$ of floor area, the cost per pound of payload capacity will suffice. But aircraft with payloads greater than 51 lb/ft$^2$ will not be able to carry the

*Speed, landing-field limitations, airdrop capability, and a number of other considerations would also have to be considered. The criterion presented here is only one factor which must be considered for this mission. The final design, of course, must take other missions into account.
allowable payload of cargo. The cargo they will be able to carry will weigh 51 lb/ft$^2$ of the aircraft floor area. Thus the appropriate measure of cost per pound carried would be $1/51$ times the cost per square foot of floor area. The comparison of such measures, derived from engineering and cost analyses, will enable planners to evaluate various aircraft designs in terms of their ability to carry cargo similar to that used in this study.

As suggested earlier, this study yields a number of implications for policies not directly connected with future aircraft design. In the analysis of space requirements, we developed a technique of loading vehicles and other cargo in the aircraft. It is possible to view this technique as an approximation of that which an experienced loadmaster would actually use. The average loadmaster may perform less effectively, however; if so, the techniques developed in this Research Memorandum could improve the utilization of scarce airlift resources. Perhaps the best policy would be to apply the techniques first, and then allow the loadmaster to rearrange the cargo in any way which further reduces the airlift required.

These techniques can also be applied to logistics planning. In drawing up a war plan, a logistician can use them to determine the number of various types of aircraft required for moving the cargo involved in the specific war plan. If detailed data are available on the weight and dimensions of each item of equipment, the entire analysis can be repeated in the same manner as it has been performed here. For more general planning, the results of this study can be used as a rough planning factor.

Any particular aircraft can carry varying amounts of payload weight, depending on the length of the mission to be flown, and the specified fuel reserves and wind and temperature conditions. This relationship is usually
Fig. 8—Hypothetical payload-range curve

represented on a payload-range curve, such as the curve ABFCD in Fig. 8. This indicates the maximum allowable payload weight which the aircraft can carry over the particular range, if the assumed conditions hold.* However, it may not be possible to weight-limit the aircraft with army deployment cargo over the shorter missions. Since the compartment floor area is known, it is possible to get a rough estimate of the maximum weight of the equipment which can be carried by assuming that each square foot of floor area can carry 51 pounds of equipment. Thus a maximum payload based solely on space limitations can be determined. If this exceeds the largest possible weight-limited payload (OA in Fig. 8), it can be disregarded; all flights will be weight-limited. If, however, the maximum weight which can be carried due to space limitations is less than OA, the effective payload-range curve will lie beneath the standard curve. Thus if the maximum which can be placed

*Similar relationships can be derived for radius missions. The principle described here will hold in both cases.
on the floor area is given by OE, the effective payload-range curve is EFCD. Aircraft will be space-limited on missions with a range less than OG; the cargo which can be carried will weigh OE regardless of the range, as long as it is less than OG. On missions with a range greater than OG, aircraft will be weight-limited and the cargo carried will vary with the length of the mission.

Figures 9 through 11 show the payload-range curves for the three aircraft in the present fleet which can carry all the items studied;* the assumptions used to derive each curve are indicated at the bottom of the figure. The dashed line indicates the space-limited weight, derived by multiplying the main cabin floor area by 51 lb/ft². Note that the effective payload-range curve thus derived diverges considerably from the initial curve for both the C-130 and the C-133, and that floor area will be the constraint over many interesting ranges. Only for the C-124 does space-limitation appear relatively unimportant.

Whenever possible, planners should examine in some detail the particular list of equipment to be moved before estimating the number of aircraft of a given type required to move it over a selected route. The use of general planning factors can be condoned only when time does not permit such an investigation. In such circumstances, however, adjusted payload-range curves, such as those shown in Figs. 9, 10, and 11, are likely to be a much better guide to aircraft performance in the army mission than are the unadjusted curves.

The payload-range curves reveal that the two newest cargo aircraft in operation today have payloads exceeding 51 lb/ft² of floor area, over ranges

*These curves do not apply, therefore, to the 15 per cent (by weight) of the cargo which was excluded from the study.
Fig. 9—Payload-range curve, C-124 C

ASSUMPTIONS: MIL-C reserves, 185,000 lb total weight;
            Normal operation;
            Cruise at 10,000 ft.

SOURCE: Standard Aircraft Characteristics, AF Guide No. 2,
Fig. 10 — Payload-range curve, C-130B

**ASSUMPTIONS:** MIL-C reserves, 2.5 load factor, optimum cruise altitude

ASSUMPTIONS:  MIL-C reserves, normal operation, optimum cruise altitude

which are likely to be chosen for army deployment. If new cargo aircraft continue to be designed in this manner (the better to perform alternative missions), no reduction in army-vehicle weight will decrease the airlift required for the deployment of any given force, unless vehicle floor area is also reduced. On the other hand, shorter vehicles, narrower vehicles, or vehicle stacking could reduce the amount of airlift required. It appears that substantial advantage is to be gained if vehicle weight and floor area on the one hand, and aircraft payload and floor area on the other, could be more closely related. On the basis of this analysis alone, however, it is not possible to suggest which should undergo the greater change -- the vehicles or the aircraft. The proper policy will depend on the extent to which changes for the purpose of this deployment will harm the efficiency of the vehicles or the aircraft in meeting their other requirements, and the importance of the deployment mission relative to those other requirements.