STUDIES OF ADVANCED TRANSPORT AIRCRAFT

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SUMMARY

Studies have been made of several concepts for possible future airplanes, including all-wing distributed-load airplanes, multi-body airplanes, a long-range laminar flow control airplane, a nuclear-powered airplane designed for towing conventionally powered airplanes during long-range cruise, and an aerial transportation system comprised of continuously flying "liner" airplanes operated in conjunction with short-range "feeder" airplanes. The studies indicate that each of these concepts has the potential for important performance and economic advantages, provided certain suggested research tasks are successfully accomplished. Indicated research areas include all-wing airplane aerodynamics, aerial rendezvous, nuclear aircraft engines, air-cushion landing systems, and laminar flow control, as well as the basic research discipline areas of aerodynamics, structures, propulsion, avionics, and computer applications.

INTRODUCTION

Studies of concepts for future aircraft are a continuing activity at Langley Research Center. This paper reports on studies of advanced cargo airplanes, long-range laminar flow control airplanes, a nuclear tug, and a transportation system comprised of a continuously flying airliner that is loaded and sustained with the aid of feeder airplanes.

Motivations for these airplane studies include the hope of identifying promising areas for research or evaluating various applications of new technologies, and uncovering voids that may exist in related technologies. An example of the latter might be a need for aerodynamic data for implementation of active control systems.

In the examples that follow, the discussion centers around the airplane concepts, potential performance, and research that would be required if the concepts were to be considered more seriously. Energy comparisons are given. However, while energy considerations are obviously very important, the most difficult challenge to continued growth of air transportation may well be terminal-area congestion and related problems. It is not the purpose of this paper to discuss this aspect of new airplanes, but it should be kept in mind that large size and long range are features that tend to reduce the number of terminal-area operations.

SYMBOLS

Values are given in both SI and U.S. Customary Units. Calculations were made in U.S. Customary Units.

A	area
AR	aspect ratio
c_d	section drag coefficient
c_l	section lift coefficient
L/D	lift-drag ratio
M	Mach number
M_{CR}	cruise Mach number
M_{DD}	drag divergence Mach number
R_e	Reynolds number
W_G	gross weight
W_P	payload weight

DISTRIBUTED-LOAD AIRPLANES

Historically, the gross weight of new airplanes entering service has doubled every eight years. The driving force behind this trend is the "economy of scale"; that is, the fact that generally it is more efficient to do things on a large scale. Although there have been important improvements in technology throughout the history of aviation, much of the outstanding efficiency of current jet transports is due to their large size. Hence, the trend to ever larger aircraft can be expected to continue.

However, there may be changes in configuration with very large airplanes as a result of trends illustrated in figure 1. The figure shows that the available volume within the wing increases more rapidly than the volume required for fuel and payload. As indicated on the figure, there is a size below which a fuselage is required to provide adequate volume. Above that size, the wing volume alone is sufficient and no fuselage is required, at least on the basis of volume.

This trend arises from the aerodynamic requirement for approximately constant wing loading, a condition set by landing and take-off considerations. The wing area then must grow in proportion to the gross weight. For geometrically similar wings, the volume increases as the three-halves power of wing area and hence as the three-halves power of the gross weight. The fuel and payload, on the other hand, are roughly proportional to gross weight, so their required volume is approximately linear in figure 1. In the scaling study from which figure 1 is taken the fuel and payload fractions were found to decrease slightly with increasing gross weight; therefore, the "volume-required" curve is actually slightly concave downward and must fall below the wing volume curve at some point.

The trend shown is very general and is not likely to be reversed by technological advances, although any specific numerical results are dependent on technology level. For example, the allowable wing loading has increased from 1200 Pa (25 lb/ft^2) for the DC-3 to well over 4800 Pa (100 lb/ft^2) for current wide-body transports, changing wing volume by approximately 8 times for an airplane with a given gross weight. There are other factors that complicate the trade-offs, but the figure is correct in indicating that for very large airplanes there should be sufficient volume in the wings to meet all requirements.

Carrying payload in the wings provides another potential advantage illustrated in figure 2. In a conventional wing-body configuration, the payload weight is concentrated in the fuselage and must be supported by the wing acting as a beam. If the payload is distributed along the wing span, its weight is largely balanced by the local lift. The result is much smaller bending moments, which permits a lighter structure. Of course, the cruise equilibrium condition illustrated here is only one of many structural design conditions, so even the complete elimination of bending moments in flight would not eliminate all the structural weight. However, design studies have shown important weight savings for large airplanes loaded in this fashion, as indicated in the figure.

With these thoughts in mind, large payload-in-the-wing airplanes, called distributed-load freighters (DLF), have been studied for about four years now, both in-house and under contract. Industry has also conducted studies of similar airplanes, some of them preceding the NASA studies. Figure 3 is an NASA DLF concept devised by Thomas A. Toll of Langley Research Center several years ago. It is about 794 000 kg (1 750 000 lb) all-up weight, and has a wing span of about 107 m (350 ft). It may or may not be desirable to add cargo pods as shown in this figure, depending on the density of the payload. Such pods make it easier to achieve a proper wing loading for best performance, and also make it possible to arrange a landing gear in a way that permits rotation for take-off. Most DLF studies have assumed take-off without rotation because of constraints imposed by the landing gear arrangement.

Figure 4 shows a series of DLF's studied by the indicated firms. The configurations of The Boeing Company and McDonnell Douglas Corporation were developed in NASA-funded studies. The airplanes shown in figure 4 are all approximately twice the gross weight of current wide-body airplanes. Some specific data are given in table I. Each of these airplanes carries its payload in the wing, which tends to drive the configurations toward low aspect ratios and wing loadings. Although the Douglas configuration looks more conventional than the others, its fuselage exists primarily to provide a support for the tail.

Lockheed-Georgia Company, which conducted its study without NASA funding, coordinated its study in timing and ground rules with the NASA studies, and so provided an additional comparison. Lockheed began with an all-wing configuration, but added a fuselage and canard as a means of accommodating outsize cargo and to improve balance and control.

In this first series of NASA studies, it became evident that DLF configuration trade-offs, particularly wing design, are much different than for conventional airplanes. One aspect of the new considerations is illustrated in figure 5 (based on information in ref. 1). A series of wing cross sections is presented showing the internal arrangement of the cargo, which would be carried in standardized 2.4- by 2.4-m (8- by 8-ft) containers of either 3.05- or 6.10-m (10- or 20-ft) length. The figure shows the cargo containers with shading, and the cargo bays are shown in dotted lines. The cargo bays are somewhat higher than the container height in order to accommodate occasional outsize cargo or military equipment. As shown, the airfoil thickness ratio depends on the number of rows of cargo containers. For three rows of containers, the airfoil has a very high thickness ratio, 0.24, which is accompanied by a low drag divergence Mach number. This indicates the speed beyond which drag becomes unacceptably large, and so (for a given sweep) determines the speed of the airplane. As the number of rows of containers is increased, the airfoil thickness ratio is reduced and drag divergence Mach number increases, which permits higher flight speeds. Also shown in the figure is the cross-section utilization; that is, the ratio of payload (not payload bay) cross section to total wing cross section. This ratio increases from 36 percent for the 3-row wing to 41 percent for the 7-row wing, which indicates a significant improvement in volumetric efficiency. Hence, on the basis of figure 5, one expects that a large number of rows is advantageous.

However, if one considers the best overall design for a given payload, it is obvious that the span of the airplane must also be considered. For a given payload, the span tends to vary linearly with payload and inversely with the number of container rows (assuming the payload extends to the wing tip). This aspect of DLF configuration selection is illustrated in figure 6. This figure illustrates two possible configurations for the case of 340 000-kg (750 000-lb) payload, one with three rows of containers and the other with five rows. The 3-bay configuration is seen to have a high aspect ratio, which should give a high L/D at speeds well below M_{DD}. At some speed, however, the advantage of high aspect ratio will be more than offset by the aerodynamic penalty of its high thickness ratio. The DLF studies highlighted the fact that there is relatively little applicable wind-tunnel data for properly trading off the opposing trends of span and thickness ratio.

The most recent of the DLF's studied under NASA contracts is shown in figure 7, along with a Boeing 747 to illustrate the scale. It is a very large airplane, with a wing span of 153 m (503 ft) and a gross weight of about 1 361 000 kg (3 000 000 lb). This airplane has swept wings, which permits increased cruise speed and provides sufficient overall length to eliminate the need for a separate tail. The figure also shows how the DLF span compares with a 61-m (200-ft) wide runway, which is the width of the runways at JFK International Airport and several other large airports, although most current airports have 46-m (150-ft) wide runways. In order to distribute landing and taxi loads, this DLF has a 7.32-m (24-ft) landing gear with a tread of about 122 m (400 ft). This airplane would therefore require special runways, but the cost of runway widening is not large in the overall cost equation if the airplane is presumed to operate out of only a small number of major airports. Hence, this airplane is visualized as operating in a hub-spoke fashion from a small number of dedicated airports, with smaller airfreighters bringing cargo to it from conventional airports. It may be that with further development, an air-cushion landing gear would offer a significant advantage by making it easier to operate out of more airports.

Figure 8 illustrates the method of loading.

An economic comparison is shown in figure 9. The economic parameter chosen is the direct operating cost (DOC) normalized by the DOC of a current wide-body airplane. An advanced technology conventionally configured airplane is shown for comparison with two DLF's of the same technology level. The swept wing DLF of figure 7 is about 27 percent lower in DOC than the advanced conventional airplane, and less than half that of a current airplane.

The smaller unswept DLF is only marginally better than the advanced conventional airplane at the size shown. This is partially due to the reduced cruising speed imposed by its unswept wing.

The enormous productivity of such a large and fast airplane as the swept-wing DLF raises the question of market growth. The current cargo market would not support development of such an airplane.

A smaller airplane that retains much of the structural benefit of span loading, without the extreme runway width requirements, could be attractive. Curve (b) of figure 10 suggests that a double fuselage airplane, such as that shown on figure 11, has these features. Although its cost per available tonne kilometer (ton mile) is expected to be higher than that of the DLF, it may save enough in handling costs to be competitive because of its compatibility with existing runways. Only very limited studies of this airplane have been made to date; however, there have been several quite successful twin-body airplanes in the past.

The DLF studies indicate that the concept is promising and offers advantages for very large airplanes. A number of areas for technology research have been identified. These are discussed in references 1 to 7 and include thick airfoils, low-aspect-ratio untapered wings, wing-tip devices, control schemes (aerodynamic and electronic aspects), propulsion integration, structures, aeroelastics, and handling qualities. Possible advanced technologies include LFC (see section entitled "Laminar Flow Control Airplanes") boundary layer control on thick airfoils (see ref. 8, ch. VI), jet flaps, and the various propulsive lift concepts (see ref. 9, e.g.). The application of these advanced technologies to DLF's obviously involves all the airplane design and economic trade-offs, but basic disciplinary research is needed before the design trade-offs can be addressed.

Considerations of the size and productivity of DLF's show a need for better market information than is now available. At present growth rates, it would be several decades before there would be sufficient cargo traffic to make such airplanes economical. NASA is therefore conducting a number of studies aimed at providing a better understanding of possible future conditions. Among these studies are

CLASS (Cargo logistics and systems study) - a worldwide survey of users, airports, and carriers to determine the current outlook, the possible role of advanced technology for stimulating the growth of air cargo, and indications of desirable airplane characteristics.

Developing countries - a study of the potential use of advanced airplanes (including cargo) in countries that have no well-developed transportation infrastructure. A preliminary survey of all such countries has been made. A study of Brazil and Indonesia in greater depth is now under way.

Civil/military relations - NASA cooperates with USAF in searching for civil airplane concepts that could be used directly or with minimal modification for military airlift.

LAMINAR FLOW CONTROL AIRPLANES

Laminar Flow Control (LFC) is the subject of references 10 to 15. Briefly, however, LFC is a technology for reducing airplane drag by maintaining laminar boundary layers. The laminarization is accomplished by sucking a small amount of the external boundary layer flow through the skin. As shown schematically in figure 12, an LFC system requires a perforated or slotted skin and a compressor to expel the sucked air. Figure 12 is highly simplified; there must also be a system of internal ducting so that suction air from various regions of the airfoil (which will have a wide range of pressures) can all be processed efficiently.

The motivation for adding all this complexity is shown in figure 13. As shown, the drag of a fully laminarized airfoil is almost ten times smaller than that of a modern turbulent flow airfoil. The LFC curve of this figure includes the equivalent drag of the suction power.

The basic trade-off involved in LFC is then between the large drag reduction in the laminarized areas, and the weight and complexity of the suction system. LFC also requires closer tolerances on surface smoothness than current practice, which implies additional care in manufacture and additional care to keep the laminarized surfaces clean. Additional maintenance is therefore to be expected.

Studies show that the overall trade-offs are very favorable as far as fuel consumption is concerned. For fairly conventional long-range passenger airplanes, fuel consumption reductions of up to 29 percent have been reported (ref. 16). The economic benefits are smaller and are subject to great uncertainty because there is no applicable experience with maintenance costs. It is an objective of the LFC element of the Aircraft Energy Efficiency (ACEE) project to provide better information about maintenance costs.

In this section, examples are given of advanced configurations designed to maximize the benefits of LFC. Some of the important considerations involved in configuring with LFC are as follows:

(1) Laminarization becomes increasingly difficult as the length Reynolds number is increased. LFC has been achieved in wind tunnels with Reynolds numbers up to about 60 million and in flight up to about 47 million. Additional experiments are needed to show that laminarization can be obtained at higher Reynolds numbers.

(2) Smoothness constraints became more severe with increasing unit Reynolds number.

(3) Other forms of disturbance, such as engine noise, must be minimized.

(4) Wing sweep increases the difficulty of laminarization. On swept wings, both positive and negative pressure gradients are usually destabilizing because an unstable cross flow is produced within the boundary layer.

(5) Benefits of LFC increase with range because the basic saving is in fuel, which is a larger fraction of total airplane weight and operating cost for long ranges than for short ranges.

(6) Aerodynamic disturbances originating from ice crystal clouds can cause temporary loss of LFC. The probability of encountering such clouds decreases with altitude, and is essentially zero above 12.2 km (40 000 ft) in the U.S. latitudes.

These considerations are discussed in more detail in reference 17.

From the foregoing discussion, it would be expected that a potentially attractive LFC airplane is therefore one that operates at long ranges and high altitudes (low unit Reynolds number), has LFC applied to wings and tail (maximum possible area), has high aspect ratio (short chord and low length Reynolds number), and has comparatively low sweep. Such an airplane is shown in figures 14 and 15. This type of airplane concept has been evolved over a period of many years by Werner Pfenninger, currently at Langley Research Center, who is well known for his work in LFC.

Among the unusual features of this configuration are struts, external fuel nacelles, split wing tips, and a rearward location for the wing-mounted engines. The calculated performance is much better than that of conventional airplanes, 30 percent payload fraction at a range of 11 000 n. mi. With laminarization applied to the wings, struts, empennage, engine nacelles, and wing-tip fuel nacelles, the lift-drag ratio is 48. With the struts, the optimum aspect ratio is very high, 16.3 for this particular configuration.

The use of struts may seem like a step backward since this once-common feature has almost entirely disappeared. The reason for their disappearance is that, although for a given wing span weight can be saved through the use of struts, a penalty is incurred in the form of strut drag. The minimum drag of a well-designed strut is comparable to that of a wing of the same area, and at high speeds great care is needed to avoid premature drag rise due to flow interferences. These trade-offs are such that, for turbulent flow, struts have not been shown to "pay their way," although there has not been much research on modern strut-braced configurations.

With laminarized struts, the weight-drag trade-off is much different. Figure 13 indicates that the drag of well-designed laminarized struts could be reduced to almost negligible levels. The theory and some limited experimental data (unpublished) indicate that strut bracing offers a significant performance advantage for LFC airplanes (a comparison is given later).

The chord of the struts is large, about one-half of the wing chord, in order to provide torsional stiffness. Structurally, it is important that the struts provide torsional stiffness as well as bending strength, otherwise the weight penalties required to provide flutter margins could be excessive.

The laminarized tip tanks contain the reserve fuel. Under all normal conditions, these tanks will be full and provide appreciable bending moment relief. Flutter analyses have been made showing that the tip tanks significantly increase the flutter speed to well above the airplane cruise speed without considering any active controls. With additional fins on the nose of the tip tanks, active control technology could be applied to reduce both bending and torsional loads, as from gusts, on the wing.

The split wing tips were analyzed by Werner Pfenninger some thirty years ago. He was stimulated to do so by observations that some kinds of birds have similar features. The results of analysis of induced drag for such configurations are presented in figure 16. According to these theoretical results, the split tip configuration is almost as effective as vertical end surfaces in reducing induced drag. The total wing drag is calculated to be less than that for a wing with vertical surfaces, because the wetted area is smaller. The dot on the curve of figure 16 indicates that for the dimensions chosen for the airplane shown in figures 14 and 15, the induced drag is about 14 percent less than the minimum for an ideally loaded planar wing. Since, at optimum cruise conditions, the induced drag is nearly one-half of the total drag, the split tips increase the airplane lift-drag ratio by about six percent.

The wing-mounted engines are placed to the rear to reduce noise disturbances to the boundary layer. This location is undesirable from structural considerations, but the penalties are minimized by the design of the strut.

With the wing drag reduced by laminarization, and the wing weight reduced by external bracing, the optimum performance LFC airplane will tend to have higher aspect ratios and lower wing loadings than all-turbulent airplanes. These trends are also favorable for LFC because they lead to lower chord Reynolds numbers, lower unit Reynolds numbers, and higher cruise altitude. The various parameters are compared in table II.

Strut bracing permits thinner inboard wing sections and hence less wing sweep is needed, which makes laminarization easier. The unit Reynolds number is seen to be much lower for the LFC airplane, increasing tolerances of roughness and waviness, and increasing the allowable slot size and spacing.

Many variations of the configuration in figure 14 have also been analyzed. A range performance comparison at a constant gross weight of 454 000 kg (1 000 000 lb) is given in figure 17. The symbols on the figure are front view sketches of the configurations actually studied. The "partial fuselage" laminarization points are calculated assuming LFC can be maintained to a length Reynolds number of 120×10^6. This is about twice what has actually been demonstrated experimentally, but is thought to be attainable.

Numerous research areas are suggested by this series of configurations, including

Wing-body strut aerodynamics and structures; various truss arrangements

Flutter, considering struts and tip tanks

Tip devices

Active control applications

High Reynolds number laminarization

NUCLEAR TUG

The success of composite vehicles assembled from specialized modules, such as the tractor-trailer truck and the railway train, has stimulated a number of investigations of the potential of airplane-glider combinations. Reference 18 reports some recent NASA efforts.

To date, NASA studies have not shown a performance advantage for a tug-glider system as compared with an airplane designed for the same mission and ground rules (technology level, field length, safety and noise regulations, etc.). Reference 18 actually finds a significant gain in overall energy efficiency by adding engines to the glider. However, tug-glider systems may offer advantages in other ways, such as extending the capability of an existing airplane at less cost than acquiring an all-new airplane, or by making use of a technology that is otherwise not applicable. An example of the latter is the nuclear tug.

The unique potential of nuclear powered airplanes is for almost unlimited range and endurance, a capability of little interest for commercial applications but of considerable importance to the military for missions such as station keeping or a missile launch platform. A traditional difficulty with nuclear powered airplanes has been in providing adequate take-off power. For this reason, many nuclear airplane concepts have assumed that the engines would use JP fuel for all or part of the power in portions of the mission other than cruise. This suggests using the nuclear airplane as a towing airplane for the cruise portion of a long-range flight, with the towed airplanes operating independently in all other portions of the mission. The towed airplanes would carry the payload and only enough fuel for take-off, climb, descent and landing, plus reserves. Sizing of the nuclear propulsion system for towing in cruise would give adequate power for the tug alone to take off and climb, eliminating the need for an auxiliary power system.

A system of this type is illustrated in figure 18. The nuclear tug, shown in the foreground, has a gross weight of about 900 000 kg (2 000 000 lb), of which the reactor constitutes approximately 40 percent. Characteristics of the complete nuclear propulsion system are obtained from references 19 and 20.

The general arrangement of the tug is shown in figure 19. It is configured as a seaplane and would be constrained to always operate over water. A significant saving in reactor crash protection weight is possible if it need not be designed to survive a crash on dry land.

In the studies conducted so far, the towed airplanes are assumed to be C-5's, and the tug is sized for towing two airplanes. With the long-range military resupply mission in mind, the cruise Mach number has been selected as 0.70.

An energy comparison is presented in figure 20, using information on the C-5 from reference 21. The nuclear tug is seen to use much less jet fuel at all ranges, which is probably the most important comparison. The existence of a nuclear airplane implies an advanced nuclear technology such that nuclear fuel should be much less critical than petroleum. At very long ranges, the tug system uses less total energy (per unit weight of payload) as well. This is partly because energy is used in carrying the fuel in a conventional airplane, and that penalty increases with range. The largest effect, however, is a reduction in payload capacity for the conventional system at long ranges due to the large fuel weight that must be carried. There is, therefore, an added plus for the nuclear system; the total payload capability of a specified number of C-5's is maintained undiminished at all ranges.

Possible commercial applications of the nuclear tug would be transoceanic missions, either passenger or cargo. The economics of commercial operations are such that it would probably be desirable for the tug to remain aloft for extended periods, shuttling back and forth continuously for as long as maintenance or crew replacement requirements would permit. While modifications of existing airplanes could be used with the nuclear tug, it is probable that a better system could be obtained with an all-new design for the towed airplanes.

From the preliminary studies so far conducted, the concept of a nuclear tug appears to merit further study. The primary new technology need is for the nuclear power plant, but eventually an entire technology of large-scale tug-and-glider systems would have to be developed. Studies of fuel requirements, including reserves, for towed airplanes having points of origin and destination at various distances from the limits of the towed course would be useful. For maximum utilization in a commercial environment essentially continuous operation of the tug is desirable. Eventually, it may be desirable to develop a technique of rendezvous for crew replacement.

AERIAL RELAY

If, in the previous example, the payload could be transferred in flight to the nuclear tug, a better overall system might be obtained, since only the tug would be needed for the cruise leg. Preliminary studies of a system that makes use of in-flight transfer of payload, fuel, and crews have been made by Albert C. Kyser of Langley Research Center. The system is called the aerial relay transportation system (ARTS).

The motivations for the study are to explore the potential benefits of using specialized airplanes for the two distinct phases of any airplane trip: the terminal-area operations of take-off, climb, descent and landing, and the cruise portion. The possible benefits foreseen were superior performance, comfort, service, and reduced congestion. Studies to date indicate possible gains in all these areas, but extensive research will be required to confirm these benefits and preclude serious obstacles.

The basic features of ARTS are illustrated in figure 21. The system consists of large continuously flying "liners" that operate in conjunction with smaller "feeders." The function of the feeders is to carry passengers or other payload, fuel, and replacement crews to and from the liners. The function of the liners is to carry the payload from the vicinity of the trip origin to the vicinity of the destination. The liners would operate continuously along prescribed paths.

Several versions of the liner have been studied. In most of the versions, including that shown here, the liner itself is a system of airplanes that may be regarded as modules. The modules would take off and climb as individual airplanes and link up once they reach cruising conditions. In this way, extremely large wing-span liners could be built-up without requiring runways of equal width. The modular approach has other potentially useful features, as discussed later. The manner in which the feeder rendezvous with the liner is indicated on the third module in figure 21. This module has been shown in phantom to indicate that there is no prescribed number of modules in the liner. The wing-tip mechanism for holding the modules together is also an air lock designed to permit passengers to move from one module to another.

The general arrangement of an 800-passenger liner module is shown in figure 22. The configuration has been chosen with laminar flow control in mind. With turbulent flow, the large wetted area and low wing loading of this all-wing configuration would not be desirable, and a more conventional arrangement would probably be chosen. The liner modules are unswept because, to date, no satisfactory swept-wing modular configuration has been identified. The wing thickness is established largely on the basis of internal space and height required for the passengers, with considerations much like those discussed in the section entitled "Distributed-Load Aircraft." This type of configuration tends to have a large amount of floor space when adequate height is provided for the passengers. The configuration shown has approximately 1.4 m^2 (15 ft^2) per passenger, rather than 2.1 or 2.4 m^2 (7 or 8 ft^2) as with current wide-body airplanes, and therefore could have greatly enhanced passenger comfort.

The resulting configuration has a large thickness ratio (0.15) that restricts its cruise speed to a Mach number of around 0.75, considerably less than for current airplanes. However, as discussed later, the capability for in-flight transfer between modules would often avoid layovers on the ground, in which case the overall travel time could be less than with the current system.

The rudimentary fuselage contains the flight deck and accommodations for feeder docking and in-flight transfer of passengers, cargo, fuel, and crews.

The structural weight of the liner module shown in figure 22 is partially based on the results of DLF studies (refs. 1 to 5), with allowances for docking and tip coupling equipment, and passenger accommodations. The module would not be required to take off or climb fully loaded. Rather, it is assumed that the modules would take off only when nearly empty - no passengers and minimal fuel - in order not to compromise cruise efficiency, add weight, or increase cost. For example, it should not be necessary to provide high-lift devices on the modules.

Powering the liner poses a number of interesting design problems. The modules must be capable of flight alone, perhaps with the LFC system inoperative. The difference in thrust required between sustained flight as a single, turbulent airplane, and as part of a multimodule LFC liner is a factor of 5 to 10. Even if it is assumed that sustained loss of LFC is a rarely occurring emergency condition (similar to loss of thrust for current airplane) under which the module would be permitted to descend, the thrust required for individual flight may still be more than twice that required when joined to several other modules. In order to accommodate the large variation in required thrust without incurring very large drag penalties from engines which have been shut down, the configuration shown in figure 22 has buried engines and retractable "sugar scoop" inlets (visible in the front view).

The feeder characteristics (fig. 23) are based on study airplanes from reference 22. The nose and flight deck arrangement have been modified to permit docking with the liner and transferring passengers through the nose.

In order to get some assessment of the numbers of airplanes ARTS might involve, a simple initial route was assumed (fig. 24) and an examination made of the potential ARTS traffic. The feeders are expected to fly about 240 to 400 km (150 to 250 miles) in climbing to rendezvous with the liner, so that a single ARTS liner could serve a region about 500 km (300 miles) wide without requiring additional cruise distance for the feeders. The region served by the assumed liner route is indicated by the hatched band in figure 24. Counting only the applicable city-pair traffic among the major cities in this band, the traffic for which ARTS would be appropriate amounts to about 65 000 seats per day. If the ARTS has the same load factors as current airplanes, this indicates a minimum fleet of about 42 liner modules and 130 feeders. Such a fleet could provide hourly round-the-clock service within the 500-km (300-mile) band if operated as 3-module liners. Since the bulk of the existing traffic occurs during the daylight hours, a larger fleet would be needed. A reasonable projection might be 200 to 300 liners from 1990 to 2000 for this one initial route. The existing traffic is remarkably uniform along the route (fig. 25), so the liners could be well utilized.

As the route network develops, the service could improve in both frequency and flexibility. After a number of major routes have developed, so that major intersections occur in the route network, it may be desirable to carry the in-flight transfer concept another step by having the multimodule liners exchange modules en route, as shown in figures 26 and 27.

Figure 26 indicates schematically that in the case of three routes meeting at a point, three liners could be scheduled to arrive simultaneously, separate and recombine in such a way as to comprise three new liners leaving that point. The value of such a maneuver is that passengers could be transferred from one route to another. For example, figure 27 shows the path of a passenger who leaves Houston, transfers in flight to another module and eventually arrives in New York, even though no single module makes that particular trip.

The significance of this in-flight transfer is that some of the airport function is accomplished aloft. For the passenger, this means reduced total travel time by avoiding layovers on the ground. It also means reduced airport congestion. On the average, today's passenger must now make two landings and take-offs per flight. With ARTS, only one take-off and landing per trip is needed. Ideally, then, this should lead to a reduction of roughly 50 percent in total airport traffic. The travel time and airport congestion aspects of ARTS seem to justify further study, independently of any cost or efficiency considerations.

Our studies of ARTS have been encouraging. Performance analyses indicate considerable improvement in terms of fuel efficiency and weight fractions over current airplanes. In order to substantiate these conclusions, research is needed in the basic disciplines of aerodynamics, propulsion, and structures (table III). However, the principle research needed relates to the operation of such a system, including routine rendezvous, tip coupling maneuvers, response of the multimodule liner to gusts, weather effects in general, fuel reserves, emergency conditions (e.g., inadvertent separation of liner modules), and automatic control of the entire liner fleet as a system.

CONCLUDING REMARKS

In this paper, a number of unconventional aircraft concepts have been presented. Each has attractive features according to the preliminary analyses that have been made.

The depth of the analysis varies. For the distributed-load freighters (DLF), there have been several design studies over a period of several years by several companies, plus NASA in-house and contract studies, with a samll amount of wind-tunnel testing. The laminar flow control (LFC) configurations have had several years of study, but there has been no wind-tunnel testing. The nuclear tug and aerial relay transportation system concepts are in very early stages of study.

Much further analysis and disciplinary research would be needed to determine if these concepts actually have merit. However, since the NASA purpose of these and similar studies is to identify potentially productive areas of research, they are considered to have served their purpose.

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TABLE I.- COMPARISON DLF CHARACTERISTICS

Agency	Range, n. mi.	W_P		W_G		Span	
		kg	lb	kg	lb	m	ft
Boeing	3000	320 000	700 000	760 000	1 670 000	95.7	314
Douglas	3000	287 000	618 000	610 000	1 350 000	86.9	285
Lockheed	3000	270 000	600 000	700 000	1 540 000	100.9	331
NASA	3200	270 000	600 000	620 000	1 360 000	88.4	290

TABLE II.- FLIGHT PARAMETER COMPARISON

	Turbulent Airplane	LFC Airplane
Wing loading, $\frac{kg}{m^2}$ $\frac{lb}{ft^2}$	683.5 (140)	415.0 (85)
Aspect ratio	7.0	16.3
Cruise lift coefficient	0.50	0.55 to 0.60
Altitude, km (ft)	10.36 (34 000)	13.72 to 14.02 (45 000 to 46 000)
Mean aerodynamic chord, m (ft)	8.32 (27.3)	7.32 (24)
Chord Reynolds number	57.4×10^6	30×10^6
Unit Reynolds number, per meter (per foot)	6.89×10^6 (2.10×10^6)	3.65×10^6 (1.11×10^6)

TABLE III.- DISCIPLINARY RESEARCH NEEDED FOR ARTS

Aerodynamics

Wing/airfoil:

- Low aspect ratio
- High thickness ratio
- Low design lift coefficient

Interference effects for vehicles in proximity:

- Liner-module
- Liner-feeder

Induced drag of modular configurations:

- Lift constraints on each module
- Moment constraints on each module

Control concepts

Structures and mechanisms

- Pressurized noncircular passenger compartment
- Low-weight LFC suction surfaces
- Tip-coupling mechanism and air lock
- Docking mechanism
- Mechanism for in-flight transfer

Propulsion

- Cruise-specialized engines
- Retractable inlet design
- Air starting
- Long run times between inspection

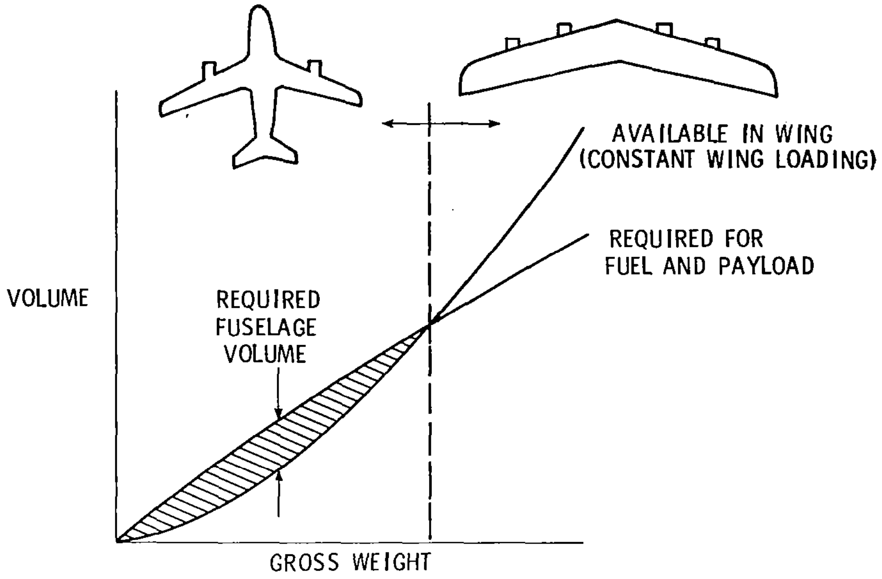


Figure 1.- Airplane size-volume trends.

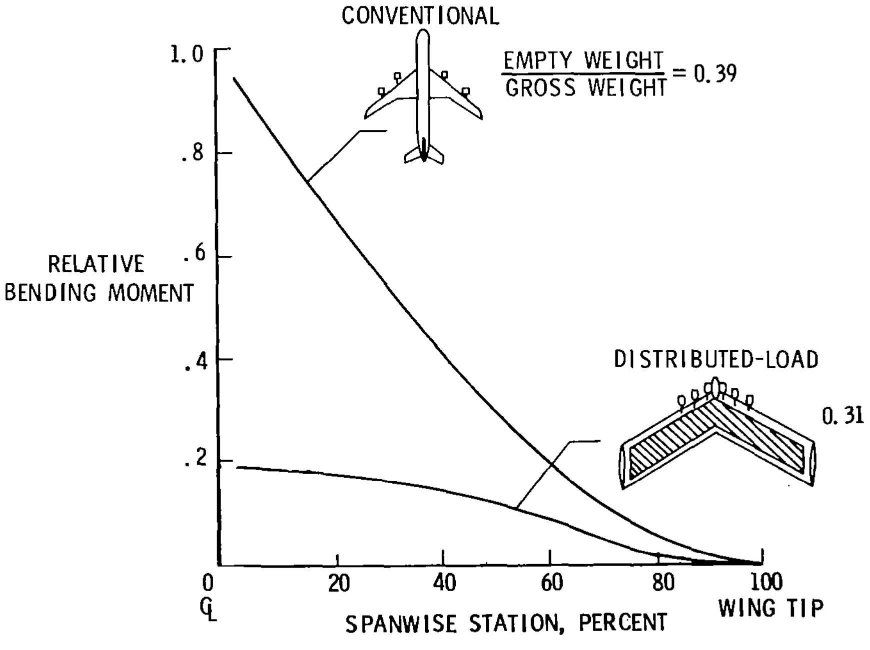


Figure 2.- Wing bending moments.

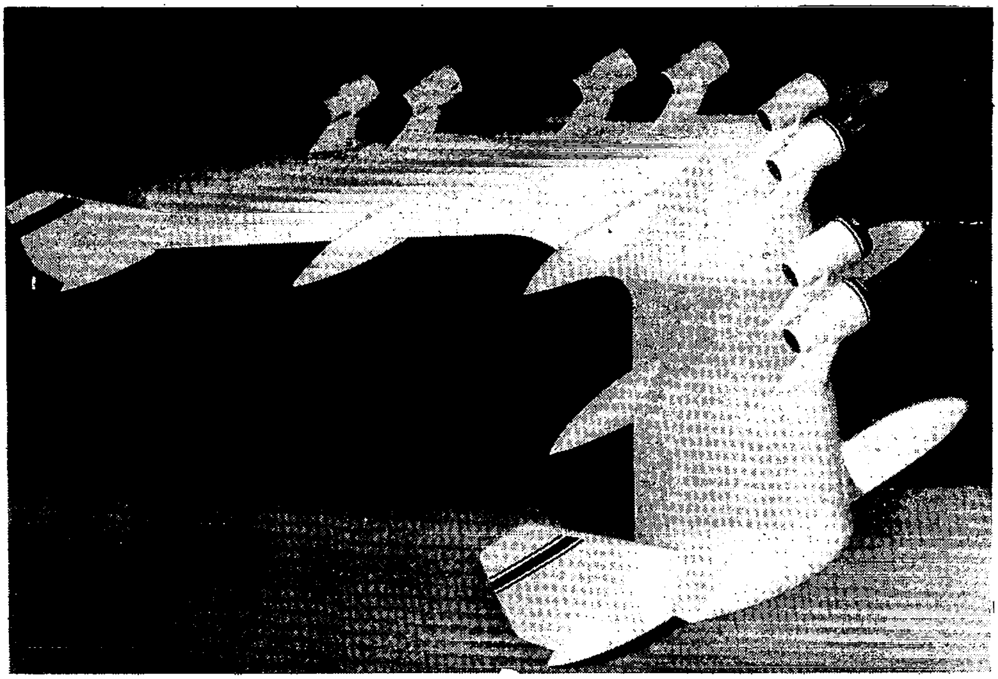


Figure 3.- Early NASA distributed-load airplane.

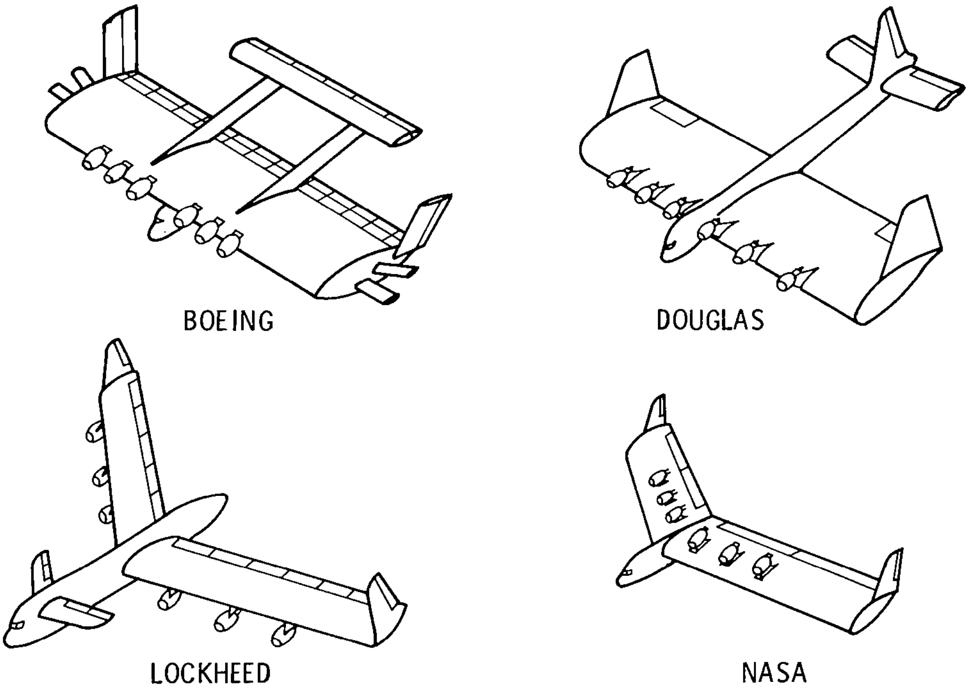
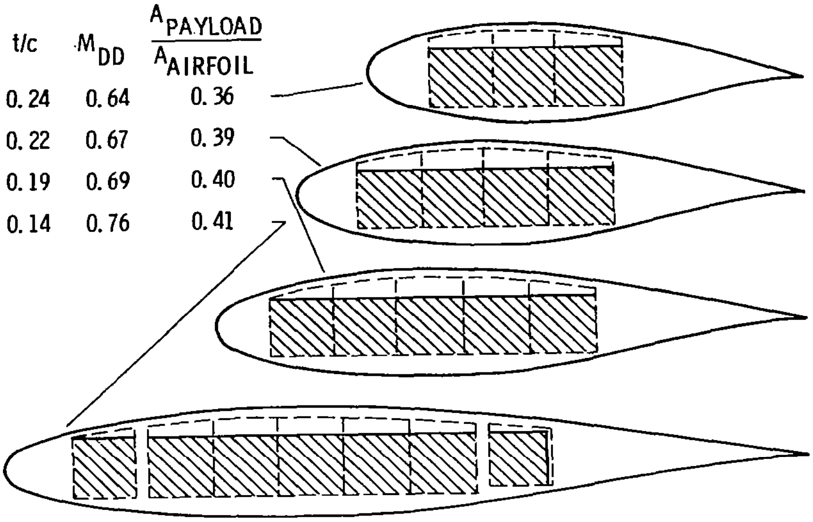


Figure 4.- DLF's studied by organization indicated.



t/c	M_{DD}	$\frac{A_{PAYLOAD}}{A_{AIRFOIL}}$
0.24	0.64	0.36
0.22	0.67	0.39
0.19	0.69	0.40
0.14	0.76	0.41

Figure 5.- DLF airfoil trade-offs.

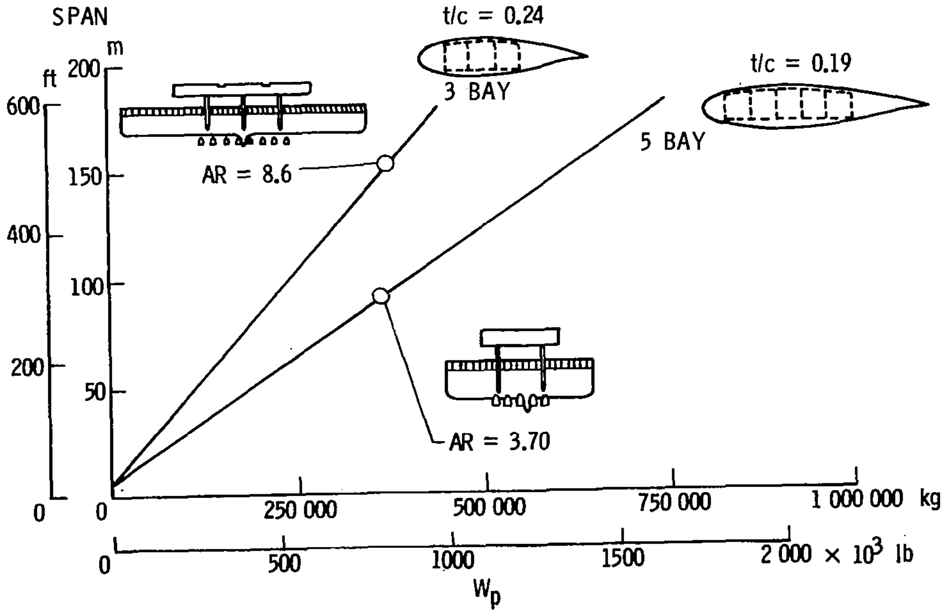


Figure 6.- Distributed-load airplane geometry constraints.

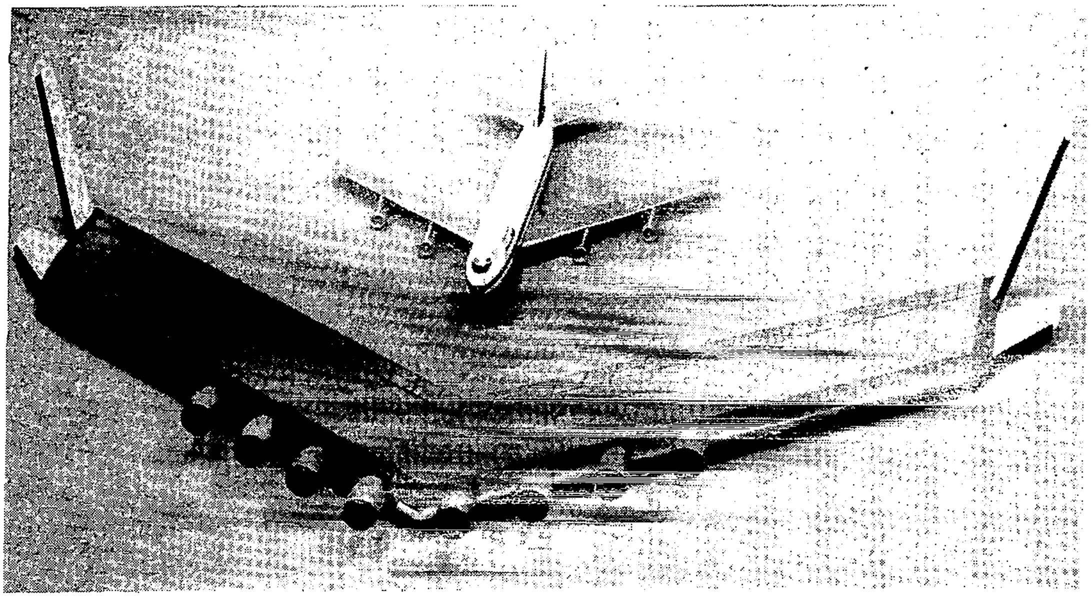


Figure 7.- Distributed-load freighter (NASA-Boeing study).

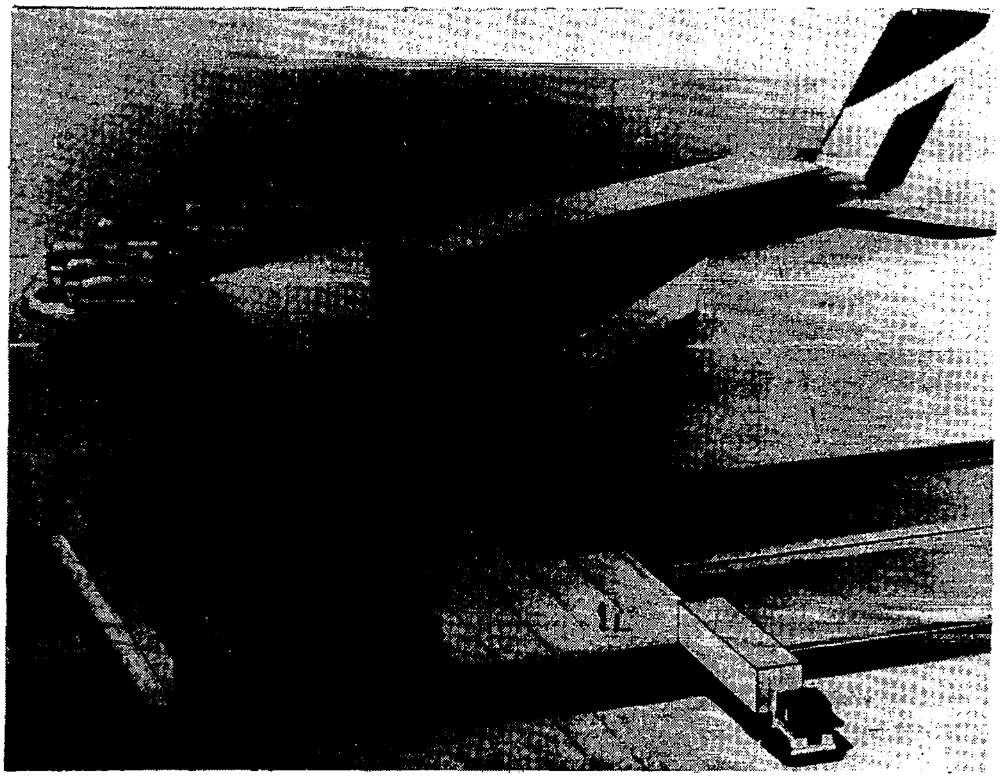


Figure 8.- Loading a distributed-load airplane.

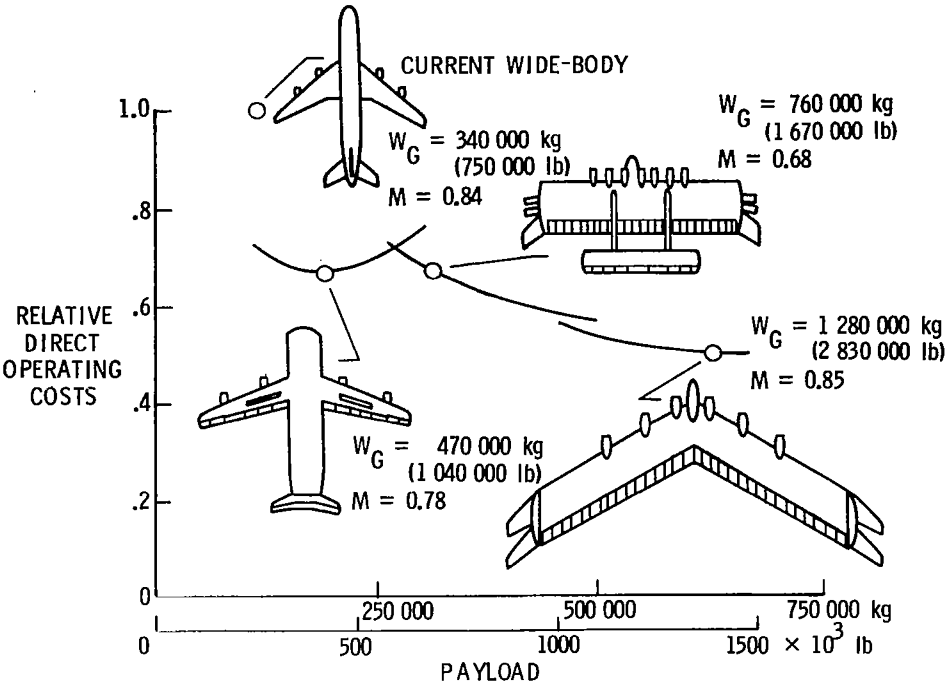


Figure 9.- Economic comparison of advanced cargo airplanes.

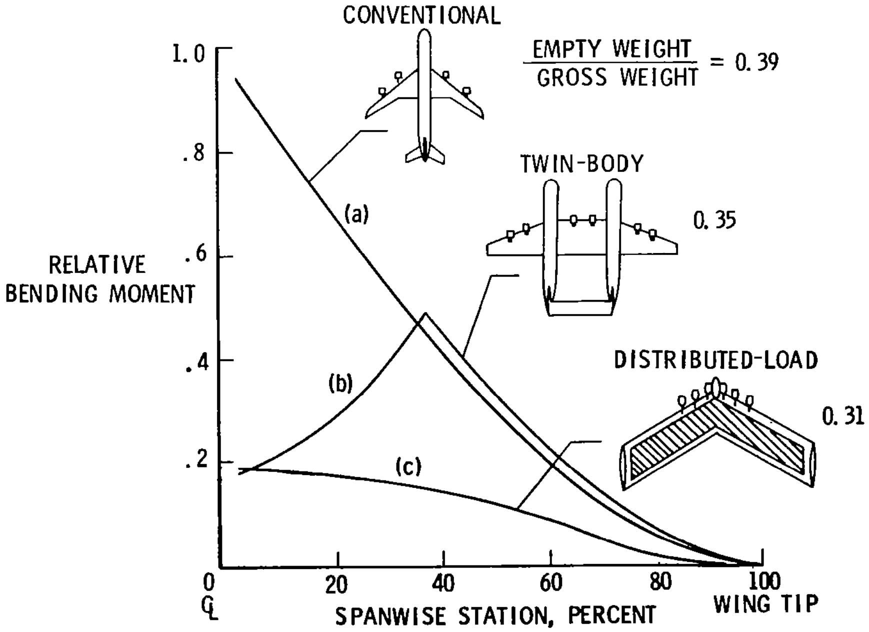


Figure 10.- Wing bending moment comparison.

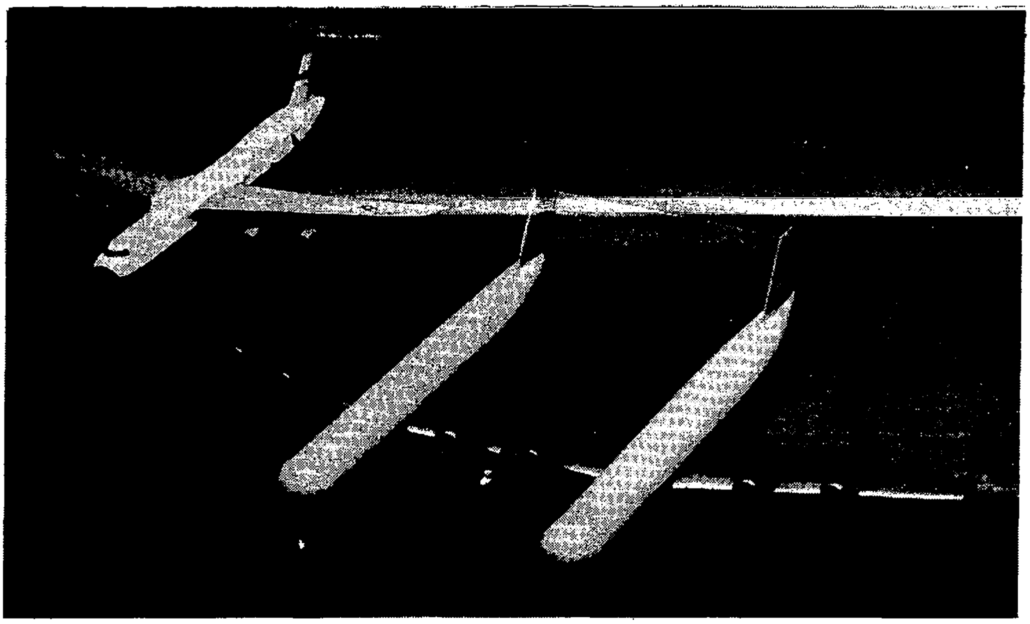


Figure 11.- Twin-body cargo airplane.

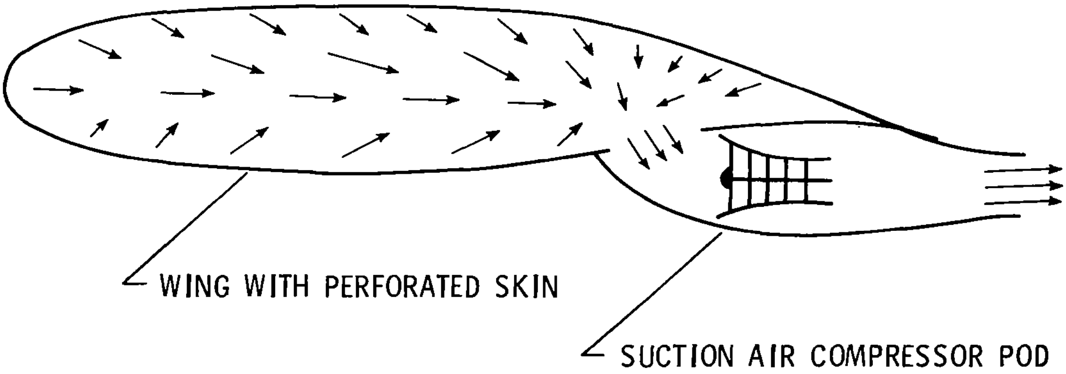


Figure 12.- Laminar flow control system.

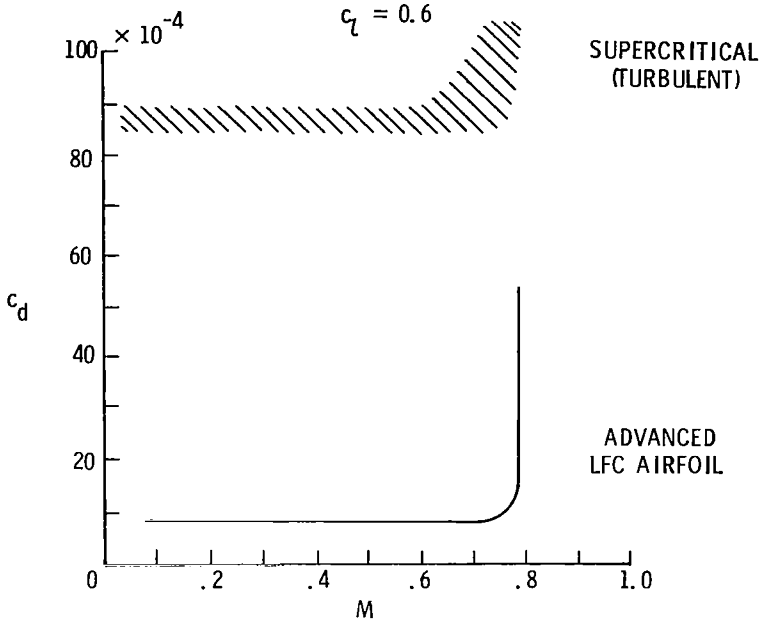


Figure 13.- Airfoil drag comparison.

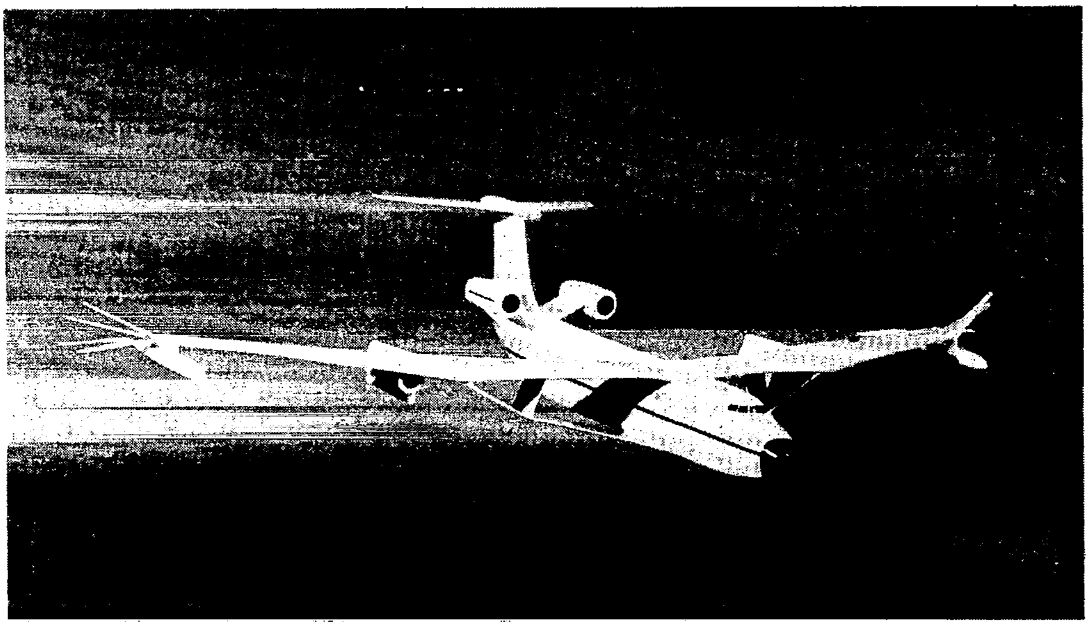


Figure 14.- Long-range LFC airplane.

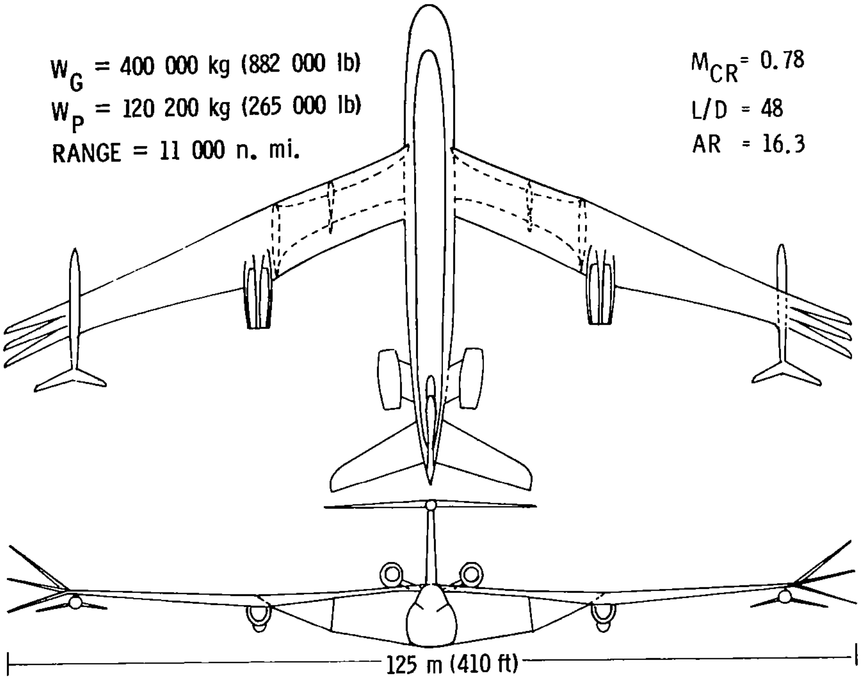


Figure 15.- Long-range LFC airplane general arrangement.

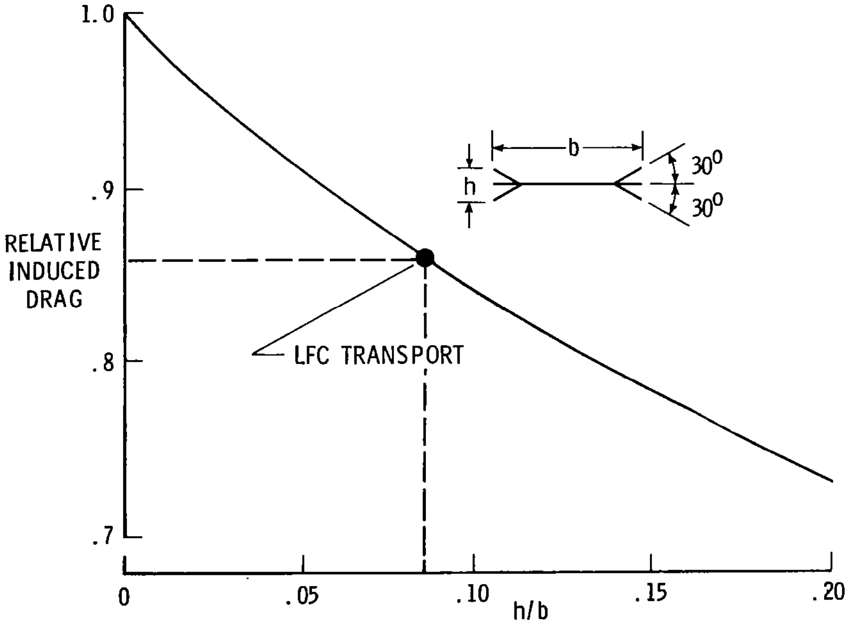


Figure 16.- Induced drag factor of wing with tip devices.

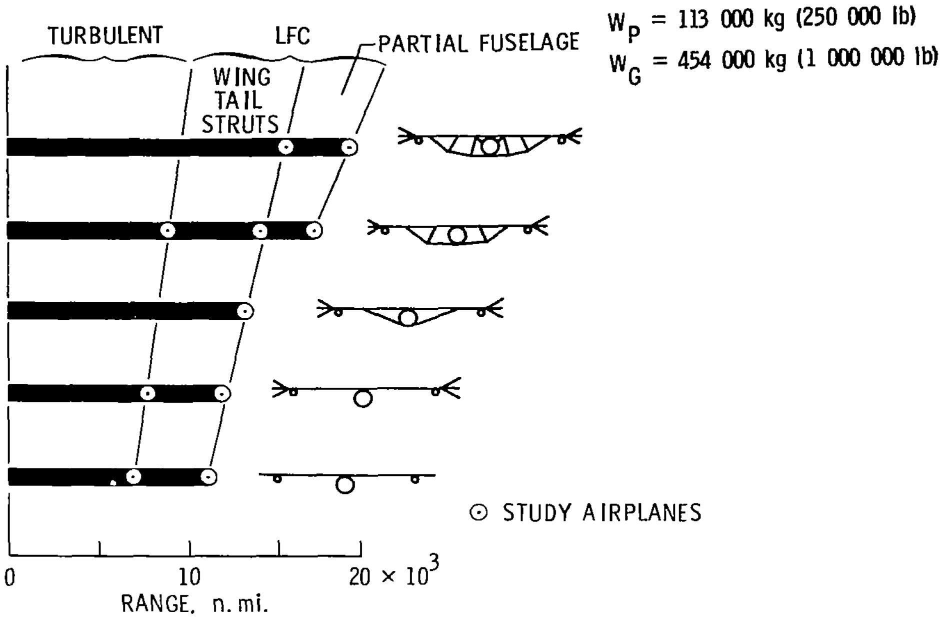


Figure 17.- Range comparison.

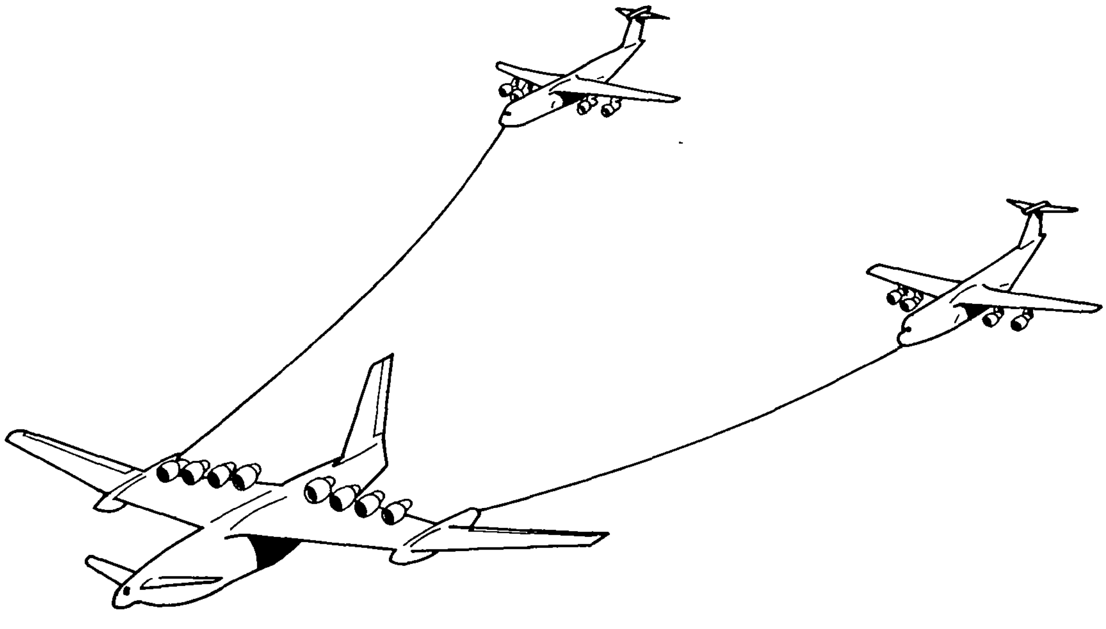


Figure 18.- Nuclear tug.

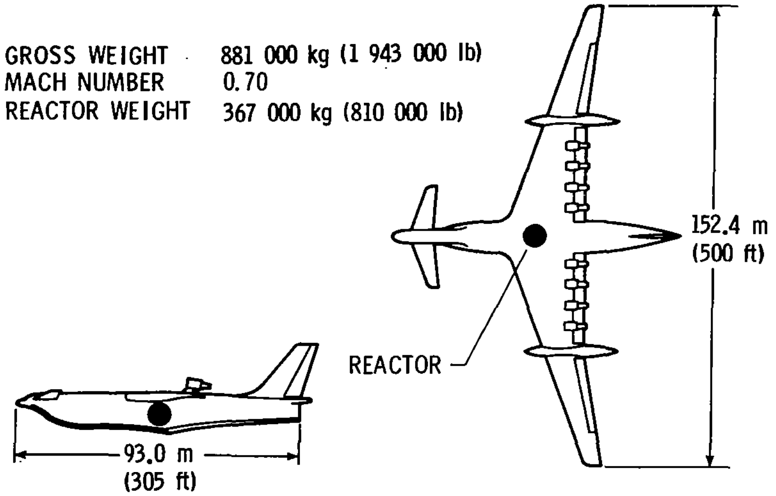


Figure 19.- Nuclear tug airplane general arrangement.

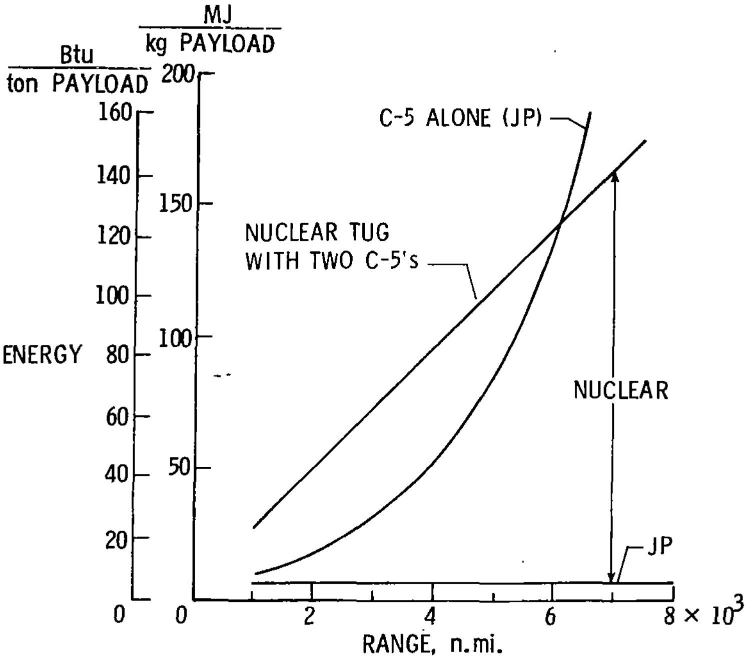


Figure 20.- Nuclear tug system energy comparison.

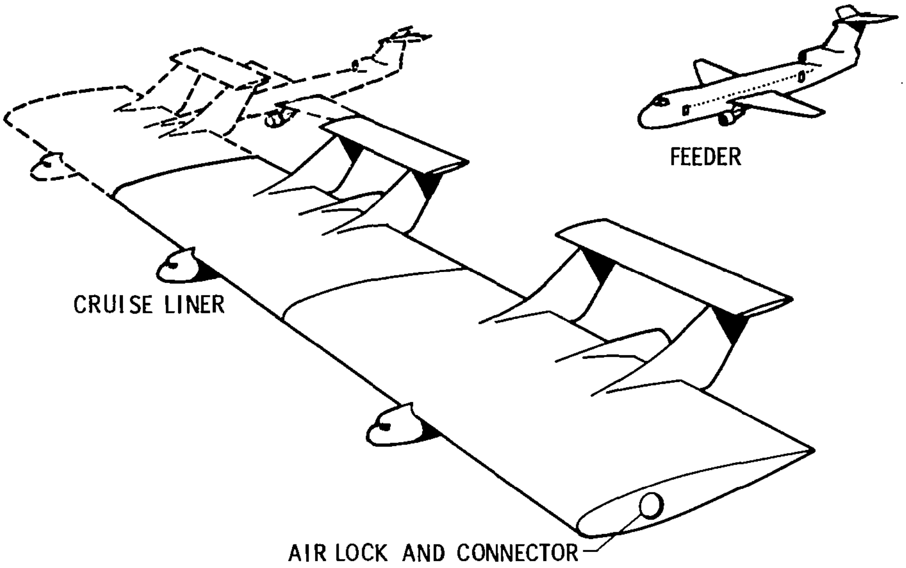


Figure 21.- Aerial relay transportation system.

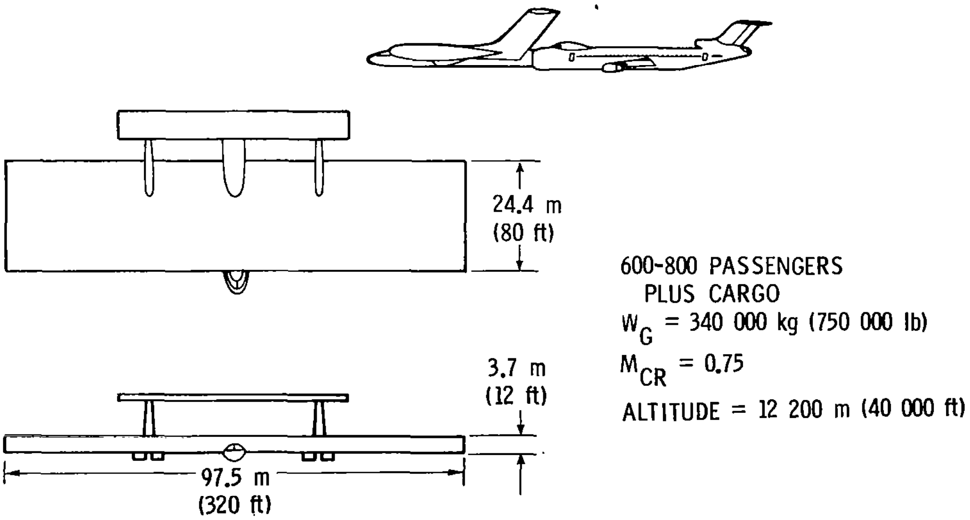


Figure 22.- ARTS LFC liner module.

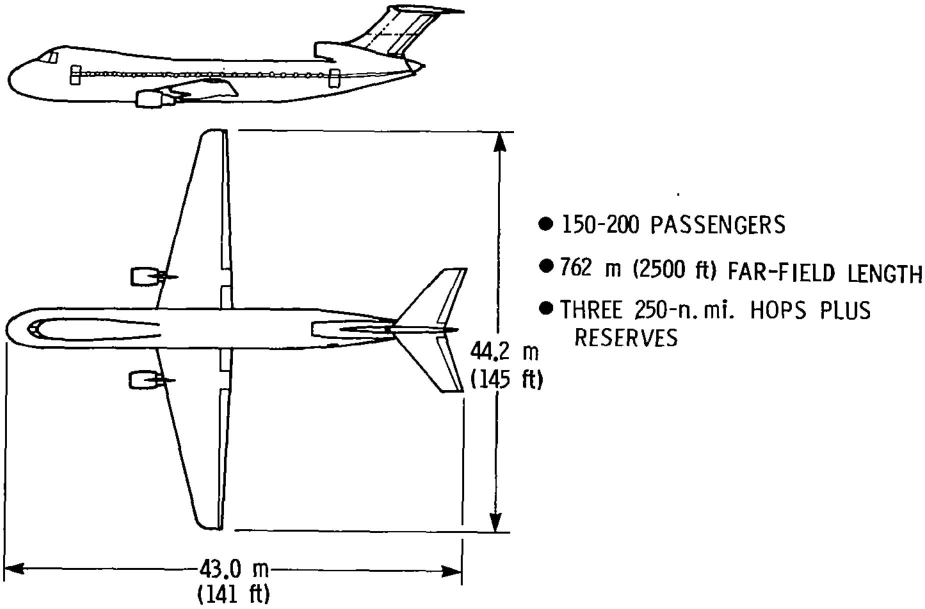


Figure 23.- ARTS feeder.

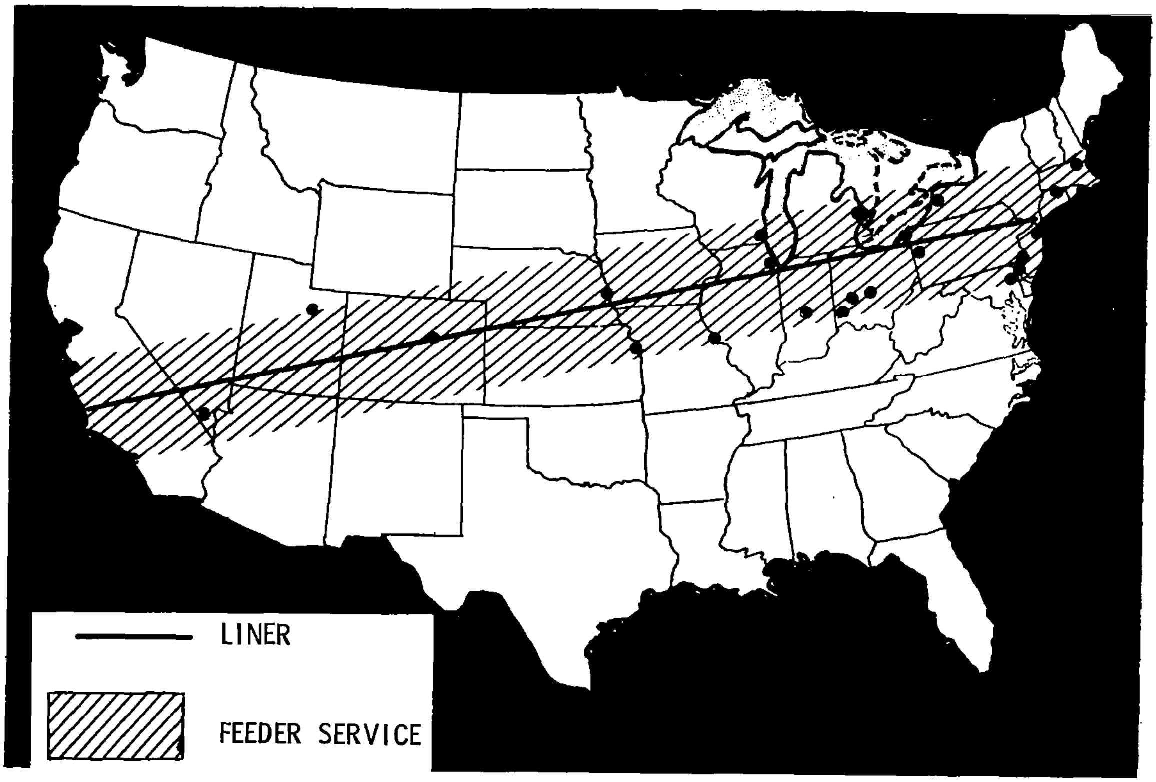


Figure 24.- Possible initial relay system route.

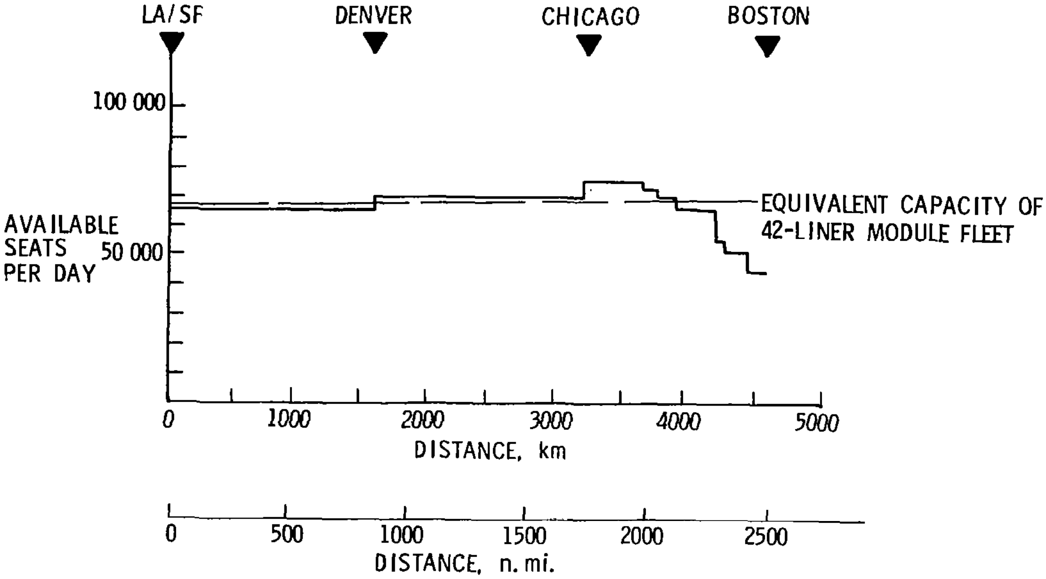


Figure 25.- Current scheduled airline traffic west to east.

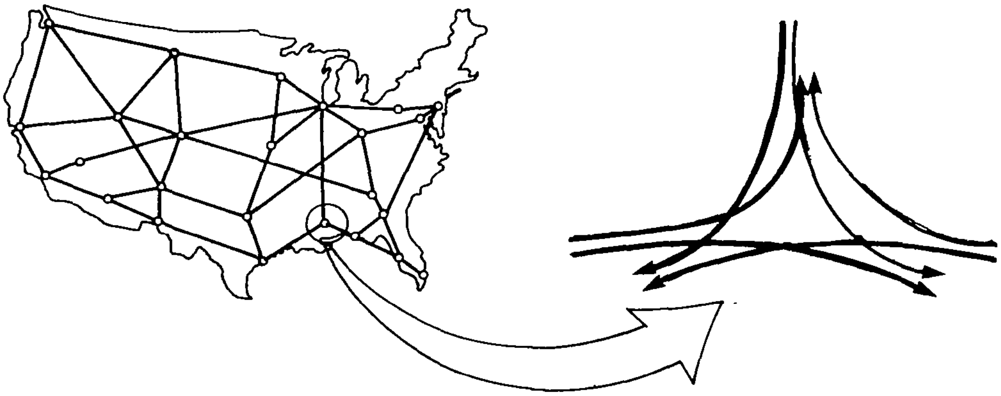


Figure 26.- Aerial relay transportation system enroute mixing at route intersection.

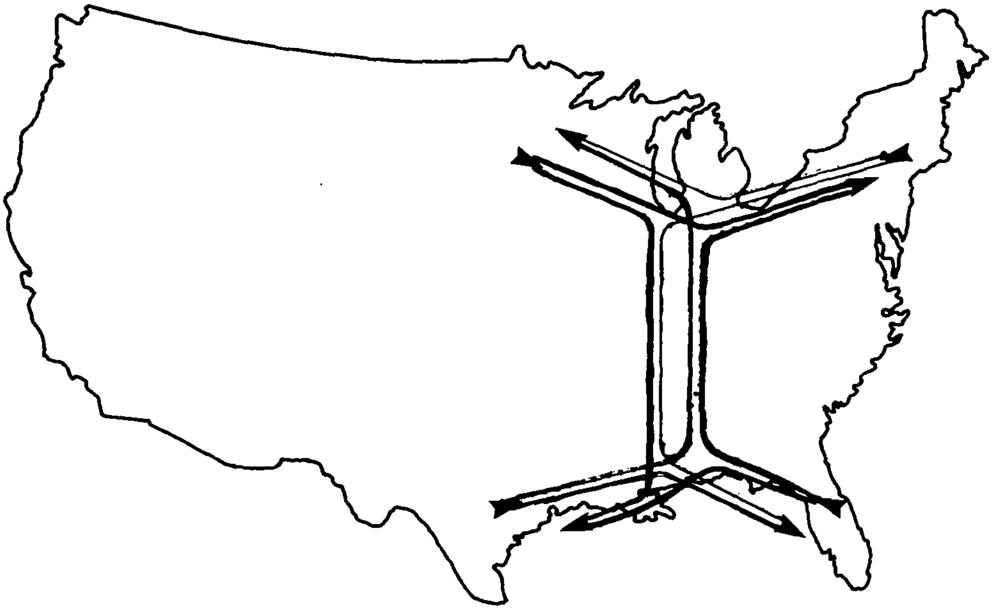


Figure 27.- Aerial relay transportation system enroute mixing of trip paths.