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PERSPECTIVE ON THE SPAN-DISTRIBUTED-LOAD CONCEPT FOR APPLICATION TO LARGE CARGO AIRCRAFT DESIGN

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16. Abstract

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SUMMARY

A simplified analysis of the span-distributed-load concept (in which payload is placed within the wing structure) has shown that a design based on these principles has a high potential for application to future large air cargo transport. Significant improvements are foreseen in increased payload fraction and productivity and in reduced fuel consumption and operating costs. A review of the efforts in the 1940's to develop all-wing aircraft shows the potential of transferring those early technological developments to current design of distributed-load aircraft. Current market analyses are projected to 1990 to show the future commercial demand for large capacity freighters. Several configuration designs which would serve different market requirements for these large freighters are discussed as are some of the pacing-technology requirements.

INTRODUCTION

The greatest opportunity for air transport growth and application of advanced concepts in design may be in the air cargo field, where projections indicate an eightfold increase in commercial air freight demand toward the end of the century (refs. 1 and 2). At this growth rate, air cargo revenue would surpass that of the passenger operation in the year 1990. The military logistics requirements present even more demands on future air cargo transport capabilities; the military missions, in contrast to the civilian cargo market, could use an improved logistics capability as soon as a cost effective design could be developed.

Current civilian jet freighters are derived from passenger design criteria; as such, their application to cargo payloads results in a loss in productivity. This loss is attributed to a reduced energy efficiency and to a less than efficient cargo handling system. Studies have shown, for example, that an airplane specifically designed for cargo transport (or dedicated cargo design) and which incorporates contemporary technologies would exhibit significant reductions in structural weight (ref. 3). Because current air freight density is about two-thirds the design payload density of current cargo aircraft (B-707, DC-10F), current cargo airplanes are limited in volume to a payload of less than

70 percent of their weight capability (ref. 4). The development of dedicated cargo transport systems, including ground-handling systems, offers the potential of improving system economics and minimizing total energy consumption. The projected demand growth, the large size and weight of some of the anticipated cargo units, the handling considerations, and the economic and energy-saving advantages of scale suggest the eventual development of air vehicles much larger than the wide-body transports flying today. The increased size alone presents a number of technical challenges, even if the vehicles are relatively conventional in design. Benefits in direct operating costs and fuel consumption and large increases in productivity can be shown to be possible through the implementation of advanced cargo transport concepts.

The concept of distributing the payload in the wing structure is a promising design approach applicable to the next generation of large cargo aircraft. Most of the payload would be carried in the wing to achieve a more uniform distribution of weight to balance aerodynamic loading. As a result of offsetting the aerodynamic forces in this manner, the structural weight of the airplane can be considerably less than the structural weight of a conventional fuselage-loaded airplane. Payload fraction, range, and fuel efficiencies are all improved for the span-distributed-load concept. Furthermore, the span-load concept lends itself to a modular structure and simplified design procedures which could reduce the design, engineering, and manufacturing costs.

This report discusses the potential of span-distributed-load cargo aircraft. Market predictions are summarized to show the future need for the high productivity available with this class of aircraft. Several basic design characteristics and options are reviewed, and the advantages and disadvantages of the concept are discussed. A brief description is given of some of the key research and technological requirements for the successful implementation of this design concept.

SYMBOLS

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

A	aspect ratio
C_L	lift coefficient
C_f	average skin-friction coefficient
c	wing chord

L/D	lift-drag ratio
M	Mach number
R	range, km (n. mi)
S	wing, area m^2 (ft^2)
t	wing thickness, m (ft)
W_F	fuel weight, Gg (lb)
W_G	gross weight, Gg (lb)
W_O	operating empty weight, Gg (lb)
W_P	payload weight, Gg (lb)
W_U	useful load, $W_F + W_P$

Acronyms and abbreviations:

ACLS	air cushion landing system
CAB	Civil Aeronautics Board
C.R.A.F.	Civilian Research Air Fleet
D.O.C.	direct operating costs
FAR	Federal Air Regulation
ICAO	International Civil Aviation Organization
LFC	laminar-flow control

HISTORICAL PERSPECTIVE

The concept of distributing fuel and payload in the wing to reduce structural weight originated during the 1930's. The design advances pioneered by J. K. Northrop in his

1940 development of the flying-wing bombers could serve as a guide for tomorrow's distributed-load cargo transports. Northrop was drawn to the "all-wing" design because of the potential reduction in drag. He stated (ref. 5) that "It has been the goal of airplane designers to produce a plane in which every part exposed to the airstream would contribute to the lift of the machine in return for drag caused." Northrop recognized the possibility of reduced structural weight through the distribution of payload and fuel in the wing section. His calculations showed that the range of the all-wing design could exceed the range of contemporary conventional aircraft by more than 50 percent (ref. 6). According to Kohn (ref. 7), "Early in World War II the United States had to think in terms of British defeat, and therefore a bomber was needed which would reach Germany from the North American continent and return." Northrop's XB-35 design lost in the competition with the Convair B-36 to fulfill that mission requirement. Northrop built numerous versions of the flying wing. Two reached the prototype stage and were serious contenders for production: the XB-35 which used pusher props and a later version, the YB-49, which employed turbojet engines. These two aircraft are shown in figure 1(a). The exterior dimensions of the two aircraft are nearly identical; the jet-powered YB-49 employed four inboard vertical fins to replace the directional stability provided by the propellers of the XB-35.

Several problems were encountered in the design and operation of these aircraft. The first was the problem of achieving satisfactory unaugmented handling qualities and control and dynamic stability, particularly in the lateral-directional modes (refs. 8 and 9). Second, a span-distributed-load airplane must be very large (in excess of 0.5 Gg (one million lb)) or carry very dense useful loads in order to operate efficiently (ref. 10). The Northrop aircraft were too small to meet this criterion for a civil application; Northrop all-wing transports were suited primarily for long-range and high-density payloads such as fuel and bombs. Yet, because of the pioneering advances applied in this unique design, these 1940 aircraft could provide a substantial technological base for the advanced cargo aircraft of the future.

Another noteworthy effort in flying-wing design never progressed beyond the development state (ref. 11). In 1942, the British were enthusiastic about the compounded advantages of the flying-wing design and laminar flow. It was desirable to maintain laminar flow over most of the surface of the airplane by the use of laminar-flow airfoils which had the potential of providing significant drag reductions. Three prototypes were constructed under the direction of Armstrong Whitworth. The failure of the airplane to maintain laminar flow was attributed to the rather severe wing sweep required to maintain satisfactory longitudinal control characteristics. The final version, the AW 52, is shown in figure 1(b). Specifications for the Northrop airplanes and the AW 52 are given in figure 1(c).

Market demands and technological advances since the 1940's have resulted in the production of larger aircraft with higher wing loadings. Airplanes with gross weights four times that of Northrop's B-35 flying wing are now accepted by the general public, the manufacturers, and the pilots. Automatic control and stabilization technology is now routinely used in large transport aircraft. If landing and taxiing very large aircraft present structural design problems attributed to the wheeled gear system, then an air-cushion landing system may offer a solution (ref. 12). The air-cushion system would also relieve the loading imposed on airport runways. Analysis has shown (ref. 10) that for aircraft with a gross weight exceeding 0.5 Gg (one million lb), the distributed-load design is probably the best choice for achieving maximum economy and productivity. It appears, then, that a reexamination of this concept in today's more favorable environment is appropriate.

Several aircraft manufacturers have conducted design studies and economic analyses of the span-distributed-load concept. There is a wide diversity of mission objectives and states of technology defining the design criteria in these studies. One of the recent publications resulting from these studies (ref. 13) discusses the significant weight and cost savings with the "Spanloader" concept and urges the pursuit of research and the development of technology required to establish the necessary technological base and to optimize the benefits.

MARKETING ANALYSIS

Figure 2 shows tentative projections for future air cargo demand for the world markets (not including Russia and China). The data and projections for the total air cargo revenue ton-miles are from the International Civil Aviation Organization (ICAO) (refs. 1 and 2). The projected growth rate of about 15 percent per year is based on an extrapolation of the experience from the past five years. The ICAO predicts a 14-percent growth for 1973 to 1985 (ref. 2). The most significant portion of this growth most probably would occur in the international market. International cargo activity should continue to grow at an ever accelerating rate as developing nations move directly into the air age (ref. 14), bypassing development of rail, highway, and port facilities (because of prohibitive capital costs). The analysis reflected in figure 2 omits any consideration of the explosive potential of trade opportunities that could develop with mainland China and the Soviet Union. If the introduction of a highly efficient, dedicated freighter could lower direct operating costs (D.O.C.) and freight rates by only 25 to 35 percent, then an impressive array of major consumer lines (for example, refrigerators, automobiles, air conditioners, etc.,) might appear as "air-eligible" products (ref. 4).

The first generation cargo aircraft, for example, DC-8F, are currently the workhorses of the air cargo carriers; they are no longer in production and, as suggested by the trend in figure 2, will disappear from the fleet by the turn of the century. The belly space on passenger aircraft will continue to be used and will show a moderate growth with time; this capacity, however, is limited by the growth of the passenger market. The balance of the cargo market must then fall to large dedicated freight carriers as indicated in the figure. Some of this load would be carried by the wide-body freighter: the DC-10F and 747F. By 1990, a new cargo aircraft design with greater payload efficiency and lower operating costs than the wide bodies could capture the major share of this market which would amount to 12.3×10^6 Gg-km (73 billion revenue ton miles) by 1990 (84 percent of total market in that year). Actually, the development and introduction into service of an advanced freighter could accelerate this growth and could secure for air freight a far larger share of the total freight market.

An analysis was made based on the method in the appendix to determine the number of large cargo aircraft required to meet the future market demand. The results are shown in figure 3 for four different airplane payload capacities. The large cargo aircraft traffic projections were obtained from figure 2. The lowest payload corresponds to the capacity of a 747F for a range of 4630 km (2500 n. mi). By 1990, if no advanced freighters were introduced, 500 wide bodies would be required. Assuming that a span-distributed-load airplane with the same range could carry a payload of about 0.3 Gg (700 000 lb) (ref. 13) and that such a vehicle would transport 80 percent of the large aircraft cargo traffic in 1990, the equations of the appendix show a fleet demand of 146 aircraft (based on a utilization of 4400 block hr/yr). Utilization rates of current all-cargo freighters average about 3600 block hr/yr. Using the last figure as a basis, the fleet demand would rise to about 178 airplanes. Because of the cost-saving design and construction features (discussed later), a fleet demand of around 150 distributed-load airplanes may be sufficient to warrant production.

This analysis pertains only to the civilian market requirement. The military need for a high payload logistics aircraft with long-range capability creates a greater sense of urgency. World crises such as the 1973 Israeli-Arab conflict can require massive airlift capabilities for men and material. The strategic success of such operations could well be dependent upon the length of time required to accomplish the airlift mission. Furthermore, a long-range capability may be needed since intermediate fueling stops may not be available for many emergency scenarios. The span-distributed-load aircraft can be designed for an exceptionally long range and can carry about three times the payload of a wide-body freighter. Because of the rising costs projected for developing new transport aircraft (ref. 14), a single dedicated carrier design may have to serve both military and civilian requirements. One operational option would provide for the joint use of new cargo aircraft by both sectors through the Civilian Reserve Air Fleet (C.R.A.F.) arrangement. The combined needs of the military and commercial interests should be anticipated in defining new concepts and mission capabilities.

AIR CARGO TRANSPORTATION SYSTEM REQUIREMENTS

As many experts can attest, the air cargo business has many "built-in" impediments to growth. (See, for example, refs. 4, 15, and 16.) Among those problems more frequently cited are: (1) a repressive and highly complex commodity rate structure, (2) inefficient interaction with surface transportation, (3) inadequate handling operations at the terminal, and (4) historical lack of aggressive promotional efforts in selling air cargo.

The successful integration of a fleet of large cargo transports into the air freight system requires at least partial solution of these problems and others that can arise because of the unique character of these new airplanes. On the other hand, the advanced cargo airplane exhibits certain characteristics which could reduce the impact of these and other "system" problems. For example, interaction with ground modes in transferring cargo can be greatly simplified by using intermodal containers designed to be transported by land and air without reloading the containers. The large capacity, distributed-load airplane can have as a design criterion the requirement to house, in an optimal way, multiple units of 8- by 8-foot intermodal containers. The span-loaded airplane can more easily be adapted to an automated ground-handling system (than can current freighters) for rapid disposition of the cargo. For example, access to the cargo bay of the distributed-load design would be on one level; access to two levels is required to load current commercial freighters.

An operations scenario of the future which could best accommodate the large cargo freighter would probably include the "gateway" concept, that is, a large distribution and collection center with modern automated handling equipment, computerized cargo control and pricing, dedicated air freighter runway facilities, and efficient access to surface transit modes. Such a system would reduce damage and pilferage, provide accurate records of cargo characteristics, and reduce unit costs in processing and loading freight. Whether these facilities would be provided as a satellite operation adjacent to a passenger airport or whether a separate cargo airport would be required is as yet unanswered (ref. 4). The investment capital required to underwrite the development and construction of these gateway facilities may require major funding from the public sector. Studies are required to assess the overall cost-benefit of this cargo transportation concept. The gateway concept may require concentration of the bulk of air freight operations in a few cities around the world, sixty at most (ref. 17). As previously noted, the international markets are growing at a faster rate than the domestic, and thus may be more amenable to the gateway methodology.

GENERAL ANALYSIS

Description of Span-Distributed-Load Concept

The structural benefit derived from distributing the payload in the wing is described in figure 4. On a conventional airplane, the cargo weight is concentrated in the fuselage. The aerodynamic lift forces on the wing structure produce large bending moments at the root. In the span-distributed-load concept, the cargo is placed within the wing so that the payload weight can partially offset the lifting forces and thereby reduce the wing bending moments. Most transport designs benefit from this principle by placing fuel in the wings. Figure 5 from reference 18 shows the distribution of this bending moment along the span for several methods of payload distribution. For the distributed-load airplane, the wing-root bending moment has been reduced by a factor of 7 compared to the fuselage-loaded airplane.

This reduced bending moment permits a significant reduction in the structural weight of the airplane. In comparison to a fuselage-loaded configuration, a typical span-distributed-load design exhibits a significant reduction in the ratio of empty to gross weight. As shown in the analysis in figure 6 (from ref. 10), this increased structural efficiency permits an increase in the payload fraction and/or range compared to the conventional, fuselage-loaded concept. This improvement in efficiency provides the most significant factor in reducing operating costs. A second factor is the declining influence of certain D.O.C. elements as size increases: crew, avionics, and instruments (refs. 19 and 20). A third contribution of the distributed-load design to cost saving is the adaptability of the concept to cost-effective design and construction. The wings could be composed of modular units of identical characteristics, with no changes such as twist or taper in section characteristics. The D.O.C. for current dedicated freighters are shown in figure 7 and are compared to the projected value for the distributed-load design (ref. 12). The cost data have all been adjusted to the 1973 base. The distributed-load design could have as much as a 50-percent reduction in operating costs over the same costs for today's typical wide-body freighter.

The fuel efficiency of the span-distributed-load concept is another particularly favorable benefit in today's environment. In figure 8, fuel efficiency is compared for span-loaded and wide-bodied airplanes. The wide-body data are derived from industry sources and the span-loaded aircraft data from reference 12. Not only is the efficiency greatly improved at moderate ranges, but the ultimate range is greatly extended. The extended range is an important factor in military applications.

Two span-distributed-load concepts are shown in figure 9 and are compared to the conventional fuselage-loading feature characteristic of current cargo airplanes. The unswept concept which uses a conventional tail illustrates a low-technology design that can take advantage of the reduced structural weights and increased payload fractions offered by the span-loading feature. The "flying-wing" proposal offers even higher benefits through greater reduction of parasite drag. Because of the stability and control problems associated with all-wing aircraft, however, this concept may require more sophisticated technologies.

Figures 10 to 12 show three versions of the span-distributed-load concept under consideration. The first (fig. 10) is the Langley-conceived flying wing with the following characteristics:

Sweep, Λ, deg	30
Aspect ratio	7.0
Take-off weight, Gg (lb)	0.77 (1.7×10^6)
Take-off thrust to weight ratio	0.25
Take-off wing loading, kN/m^2 (lb/ft^2)	4.1 (85)
Wing area, m^2 (ft^2)	1858 (20 000)
Wing span, m (ft)	114 (375)
Thickness ratio	20 percent
Thickness, m (ft)	3.3 (10.7)
Approximate cruise lift-drag ratio	20

A wind-tunnel test program is planned at the Langley Research Center to evaluate this configuration and to establish stability and control characteristics using movable outboard and inboard flaps, elevons, and rudders. The pods shown on this model could carry fuel or passengers. In a full-scale version of this design, the diameter and length of these pods would be about the same as the fuselage of the Boeing 737 aircraft.

A straight-wing design requiring less research and development is shown in figure 11. This configuration is under study by the National Aeronautics and Space Administration (NASA) and an airframe manufacturer. The version shown in this figure was developed by the Boeing Commercial Airplane Company. An obvious advantage to this design is the design simplicity which permits the use of modular structural elements. The figure illustrates one loading technique in which the wing tip is rotated upward about a chordwise hinge for access to the cargo area.

The third version under study by the government and industry incorporates a novel propulsive-induced lift concept in which the exhaust from the forward-mounted engines is ducted beneath the wing to provide augmentation for lift-off from unprepared terrain or water. A wind-tunnel model of this concept is shown in figure 12. The aircraft would initially derive a performance advantage by flying within ground effect. As fuel is consumed, the airplane would ascend to altitude for greater efficiency. The forward engines could then be rotated to allow the exhaust to flow over the wing to increase circulation.

Perhaps the ultimate benefit from the distributed-load concept could be derived with the tailless "all-wing" design in which most of the surface contributes to the lift. As is discussed later in this section, this design is also favorable to the application of laminar boundary-layer control. One of the fundamental problems facing the designer of tailless all-wing aircraft is how the airplane can be satisfactorily trimmed with longitudinal control devices. To provide trim control on the tailless airplane, a segment of the wing trailing edge can be hinged to act as an elevator. With control of this type, the loss in lift caused by the flap deflection can be appreciable, and the greater the static margin, the greater is the loss in lift (ref. 9). These losses could be minimized by placing the control surfaces at the tips of swept wings of moderate aspect ratio or by reducing stability requirements through augmentation systems. Other concepts would lead to a departure from the tailless concept and could include the use of a horizontal tail supported by a tail boom or the placement of "T" tails at the wing tips. A potential problem of the tailless design is directional stability and control requiring an external surface to provide satisfactory flying qualities. Any fixed vertical stabilizer must be quite large because of the small moment arm, but the large stabilizer leads to adverse side forces. Current technology in active controls could probably resolve these problems. Northrop's wings employed a drag rudder composed of a double-split trailing-edge flap. Reference 9 reviews the stability and control problems associated with tailless aircraft.

Square-Cube Law

The "square-cube law" demonstrates that as a structure is scaled upward, its weight increases more rapidly than its strength. The law derives its name from the fact that the available cargo volume of an airplane grows as the cube of the linear dimensions, whereas the cross section which must support the load grows only as the square of the linear dimensions. Thus, by following this law, in designs scaled upward, the stress in the supporting members would increase with the growth in linear dimensions. (See ref. 21 for further discussion of the square-cube law.) For an airplane design representing a change in scale from a previous design which encompassed the same level of technology, the law would dictate that structural weight in excess of the scaled value would be required to offset the imposed stresses. Thus, the operating empty weight fraction would grow with gross weight. The presentation of this law in figure 13 is taken from reference 19, and the dashed lines show the approximate "square-cube law" trends.

Progress in aeronautical development through technological advances has permitted favorable deviations from the square-cube law for the aircraft shown in figure 13. Useful load fraction has grown historically in spite of the law because of the advances in configuration design, materials, structures, aerodynamics, propulsion systems, and subsystems. The allowable wing loading has also increased significantly. Clearly, to consider a viable aircraft design in excess of a million pounds, a design which would again improve the load fraction would require the implementation of a new design concept such as that of distributing the useful load in the span of the wing.

Effects of Increased Aircraft Size

Reference 19 presents an excellent summary of the many facets of aircraft design and operation that are affected by an increase in design gross weight beyond that of contemporary wide bodies. Only a few of the most pertinent effects which apply to the span-distributed-load aircraft are reviewed here.

The square-cube law does not affect all airplane components to the same degree; cantilevered members such as the wing and empennage are most strongly penalized. If the airplane geometry, wing loading, allowable stresses, and load factor are held constant, then, according to Cleveland's analysis, the wing and empennage weight vary as the gross weight of a conventional airplane to the 1.4 and 1.2 power, respectively. By relieving the wing-root bending moment to a value one-sixth of that for a conventional design (fig. 5) and by eliminating or greatly reducing the weight of the empennage, the span-distributed-load concept can be seen as a suitable option for the next "defeat" of the square-cube law.

One benefit that results from increasing the size of the aircraft is the reduction of turbulent skin-friction drag. About half of the cruise drag is caused by skin friction. As Reynolds number based on wing chord increases, the value of skin-friction drag coefficient decreases. Figure 14 (adapted from ref. 20) shows the magnitude of the relative benefits. The decrease in C_f shown for the span-distributed-load airplane compared to that for the C-5 represents about a 3-percent reduction in cruise drag.

Assuming that the trend in useful load fraction predicted by the square-cube law can be reversed, the remaining potential disadvantages of increased size are in the areas of systems operations and handling qualities. The effect of very large airplanes on the terminal area operation could be severe. These large airplanes require dedicated and highly mechanized loading areas. If conventional wheeled gear systems are used, runways may have to be strengthened and widened. The speed of these freighters would probably be somewhat slower than passenger aircraft and would thus require special consideration for integration into the air traffic control system. Because aerodynamic noise increases with aircraft size, these vehicles may have difficulty meeting future noise restrictions. Because the span-distributed-load aircraft can carry a payload more than twice that of the current wide-body freighters, a large expansion in the market would be required to justify the production of these large aircraft and to justify funding for adequate terminal area facilities.

The deterioration in handling qualities with size has been well documented by the aircraft manufacturers who have built the civilian wide-bodied aircraft and the C-5 military cargo aircraft. (See refs. 19 and 22, for example.) Generally, as airplanes get larger, their ratio of moment of inertia to control moment increases. The increase in this ratio produces a more sluggish control response of the large aircraft to pilot command. Roll response, in particular, is adversely affected. A control quickening system may be required to provide desirable response characteristics in take-off and landing. One potential problem area not covered in the Federal Air Regulation (FAR) requirements could have serious implications for the distributed-load design; this problem is the response of the aircraft to asymmetric gusts.

One potential solution to the runway requirements and the design penalties associated with wheel gear could be the use of an air cushion landing system (ACLS). The landing impact loads could be distributed over a wider portion of the wing span and thus permit landing sites to be constructed from unprepared terrain or water. The taxi and landing loads of the distributed-load design would probably be more critical than those of the fuselage-loaded airplane. The concentrated load points resulting from wheel gear can be greatly relieved with ACLS. If load relief from load distribution and ACLS is considered in the design, then an unusually high proportion of the structural components can be sized by consideration of stiffness and aeroelasticity (ref. 8).

Application of Boundary-Layer Control

The span-distributed-load concept is a natural application for low-drag boundary-layer control such as laminar-flow control. Efforts at combining these concepts date back to the 1940's (ref. 11).

On a conventional airplane, the flow over the fuselage cannot easily be adapted to laminar-flow control (LFC), and the intersection of the wing and fuselage produces interacting flow fields which can initiate transition. The span-distributed-load wing volume is substantial and could suitably house the plumbing and pumping system required to meet the suction requirements. The power requirements for this system have not been examined and may be prohibitive, especially for swept wings. The LFC tends to drive down the optimal cruise lift coefficient since for cruise near maximum L/D, induced drag should be nearly equal to form drag. The lower design C_L could be a great benefit to the design because of the requirement for high thickness-ratio airfoil design. The resulting lower wing loading is entirely compatible with this design concept (ref. 10). Crossflow instabilities induced by sweep promote early transition of the boundary layer; therefore, the unswept configuration may be a more beneficial application of LFC.

Design studies such as those reported in reference 23 show that fuel savings of about 30 percent and a payload increase of about 35 percent are possible for a conventionally loaded airplane design with LFC. Gross weight is increased for a configuration with an all-turbulent boundary layer by only about 8 percent. With the large wing area associated with the span-distributed-load design, the ratio of wetted area to wing area approaches 2 compared to 4 or 5 for conventional airplane designs (ref. 24). Thus, the benefits cited for conventionally loaded LFC aircraft can be expected to be even greater when LFC is applied to a span-distributed-load design.

REQUIRED RESEARCH AND TECHNOLOGY

The eventual development of the span-distributed-load airplane requires a systematic development of a technological base in all the aeronautical disciplines. Analytic and experimental analysis of high thickness-ratio airfoils is a prerequisite for the successful application of this concept to a practical aircraft design. Two-dimensional wind-tunnel studies must be accomplished in very high Reynolds number ground facilities to achieve the closest simulation to the anticipated flight environment. Wind-tunnel tests of several configurations representative of the span-load concept can provide a basis for selecting the best configurations and would permit a realistic definition of the aerodynamic benefits of this class of aircraft. Performance characteristics and stability and control data must be generated as part of these studies. Landing and taxi loads pose special problems for span-loaded aircraft and must receive special attention. Acceptable criteria for spanwise cargo distribution, maneuvering loads, control surface response, and gust response need to be determined and the impact of these criteria must be evaluated for distributed-load designs. The characteristics of ACLS on a span-loaded aircraft model should be determined to assess the benefits and problem areas with this type of landing system.

Handling criteria for large, unconventional aircraft require evaluation and study. The low roll-response rates characteristic of large airplanes may introduce serious handling problems requiring specialized control laws and methodology. Direct side force needs to be evaluated as a possible expedient for providing adequate control response in the landing and take-off modes.

Composite-materials technology offers the promise of significant improvements in structural efficiency, provided the necessary technological base is developed to allow these new materials to be used effectively in large aircraft. In the work done to date in composite-materials technology, however, very little attention has been given to the problems of fabricating full-size structural components for large aircraft. A development program should be undertaken to design, fabricate, and test several composite-material structural components representative of very large aircraft components. The results of the program could be used in developing a data base for the design of large composite components. Bonding of composite materials could provide further reduction in structural weight; this possibility requires investigation.

Advances in structures technology are required to develop large, low-cost, and lightly loaded skin panels. Acceptable lower limits on minimum-gage structure could be substantially different from current limits; such limits need definition and evaluation for design impact. The interior structural design of the wing requires imaginative development. A requirement for pressurization places additional demands on the structural design. Although an open interior space is required for cargo loading and for inspection, the structure must simultaneously satisfy the demands of high strength and low weight and cost. These advances in design require analytical and experimental studies.

Developments in avionics are required to support the technological base for the very large aircraft of the future. An optimal integrated guidance and control system depends on advanced applications of digital fly-by-wire techniques and digital computer systems. Advanced pilot displays must be integrated with computerized flight management and control functions to insure safe operations and to increase operational effectiveness. Preliminary flight-deck designs appropriate to these unique aircraft designs should be evaluated.

SUMMARY OF RESULTS

A review and analysis has been made of the span-distributed-load concept and its application to an advanced cargo transport design. The results of the study are as follows:

1. A historical survey indicates that as early as 1930 designers of all-wing aircraft were aware of the benefit of the distributed-load design for long-range, military payloads. Much of this early technological development can be transferred to the contemporary design process.

2. Significant advantages over current wide-body freighters are foreseen for large, distributed-load cargo aircraft in improved payload fraction and productivity and in reduced fuel consumption and operating costs. The capital required for modification of current terminal areas or the construction of new, all-cargo distribution centers to support these aircraft must be figured into future cost-benefit analyses.

3. A preliminary market analysis based on projections of the International Civil Aviation Organization data shows a potential commercial need for about 150 advanced cargo aircraft by 1990. Military sources predict a need for a high productivity airplane to enhance their logistic capability.

4. The span-distributed-load concept is found to be a natural application for laminar-flow control. A much larger percentage of the wetted area of the distributed-load design can be laminarized than can the surface of a conventional design.

5. Critical technological requirements include analytical and experimental development of thick airfoil sections, definition of handling qualities associated with large distributed-load airplanes, application of innovative structural design concepts incorporating large extruded composite members, and development of advanced fly-by-wire and digital computer systems for application to an integrated guidance and control system.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Va. 23665
December 3, 1975

APPENDIX

EQUATIONS FOR FLEET SIZE DETERMINATION

Assume:

Load factor = 65 percent

Block speed = 200 m/sec (385 knots)

Range = 4630 km (2500 n. mi)

$$\text{Block time} = \left(\frac{\text{Range}}{\text{Block speed}}\right) + 0.5 = 6.7\ \text{hr/trip}$$

where the 0.5 factor accounts for ground and air maneuver time and ascent and descent. From reference 25, utilization is given as a function of block time:

$$\text{Utilization} = 4400\ \frac{\text{block hr}}{\text{yr}}$$

Productivity = Block speed × Utilization × Payload (per airplane)

$$\text{Productivity}\left(\frac{\text{Gg-km}}{\text{yr}}\right) = 3.17 \times 10^{6}\ W_P,\ \text{Gg}$$

or

$$\text{Productivity}\left(\frac{\text{ton-n. mi}}{\text{yr}}\right) = 880\ W_P,\ \text{lb}$$

Cargo traffic = Productivity × Load factor × Fleet size

Then

$$\text{Fleet size} = 4.86 \times 10^{-7}\left[\frac{\text{Cargo traffic}\left(\frac{\text{Gg-km}}{\text{yr}}\right)}{W_P(\text{Gg})}\right]$$

or

$$\text{Fleet size} = 1.75 \times 10^{-3}\left[\frac{\text{Cargo traffic(ton-n. mi)}}{W_P(\text{lb})}\right]$$

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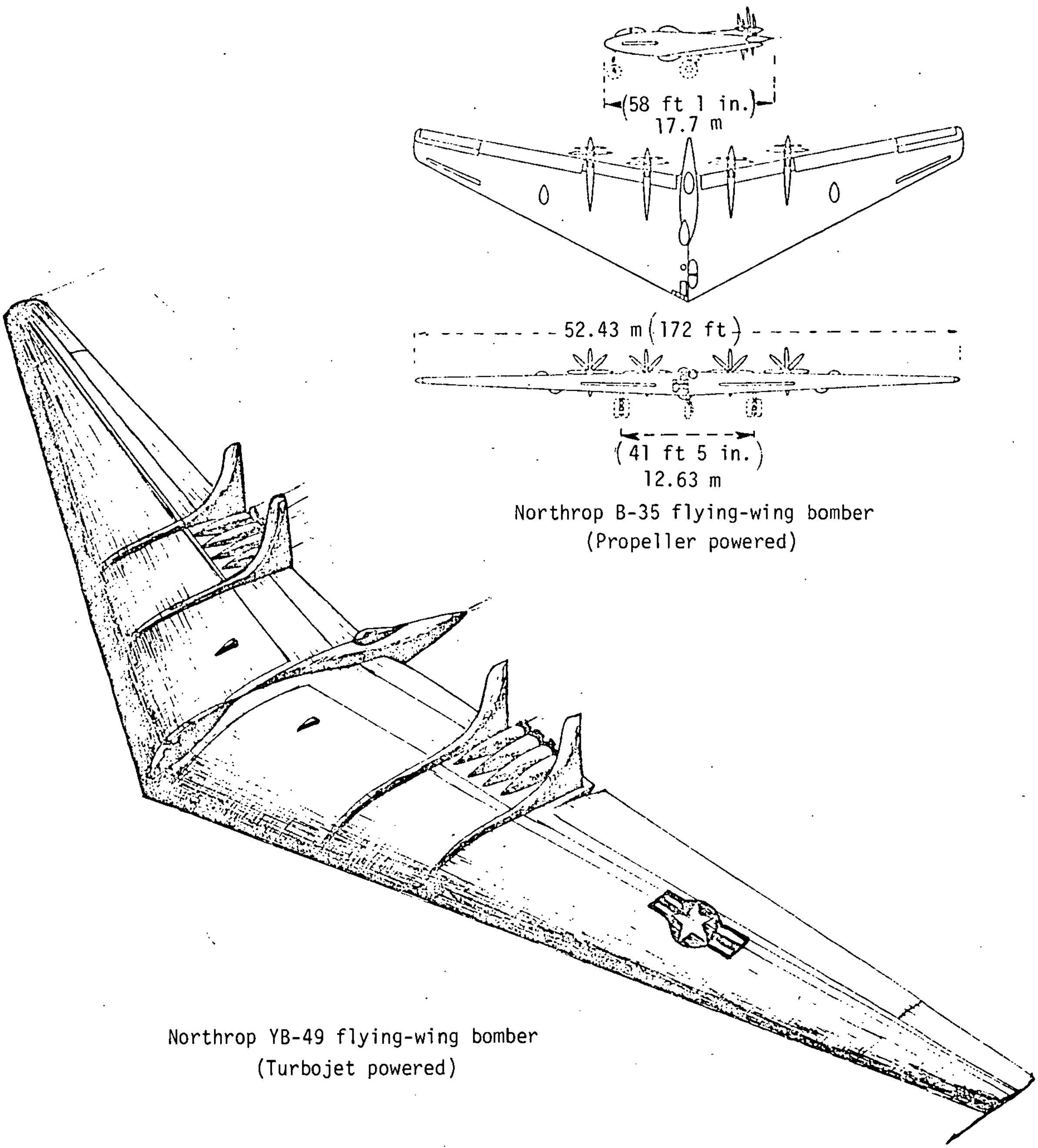
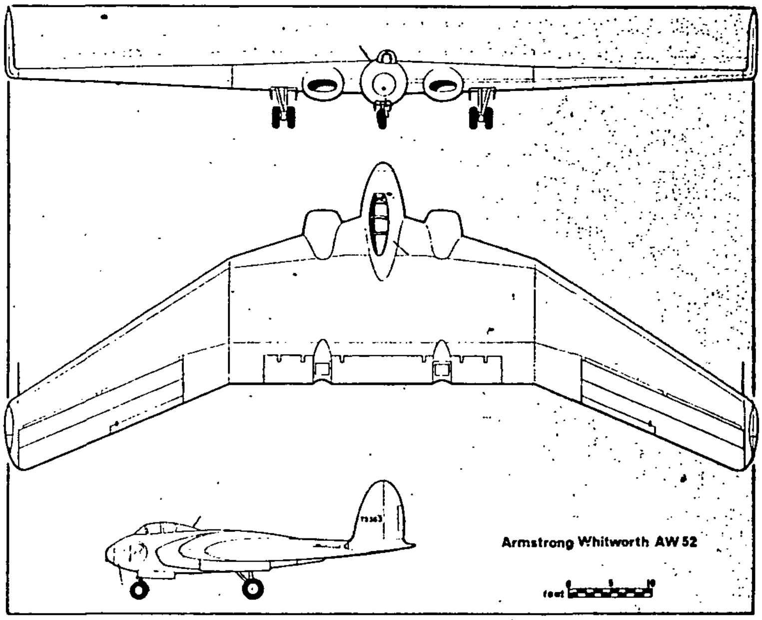


(a) Northrop bombers.

Figure 1.- Early flying-wing aircraft.



(b) Armstrong Whitworth AW 52.

	AW 52	B-35	YB-49
Span	27.4 m (90 ft)	52.4 m (172 ft)	Same as B-35
Length	11.3 m (37 ft)	16.1 m (53 ft)	
Wing area	122 m^2 (1314 ft^2)	372 m^2 (4000 ft^2)	
Gross weight	15.5 Mg (34 150 lb)	94.8 Mg (209 000 lb)	
Power plant	2 Rolls-Royce Nene turbojet engines	4 P&W Wasps with 4, 8-blade pusher props (Contrarotating)	8 Allison TG-180 turbojets

(c) Comparison of characteristics.

Figure 1.- Concluded.

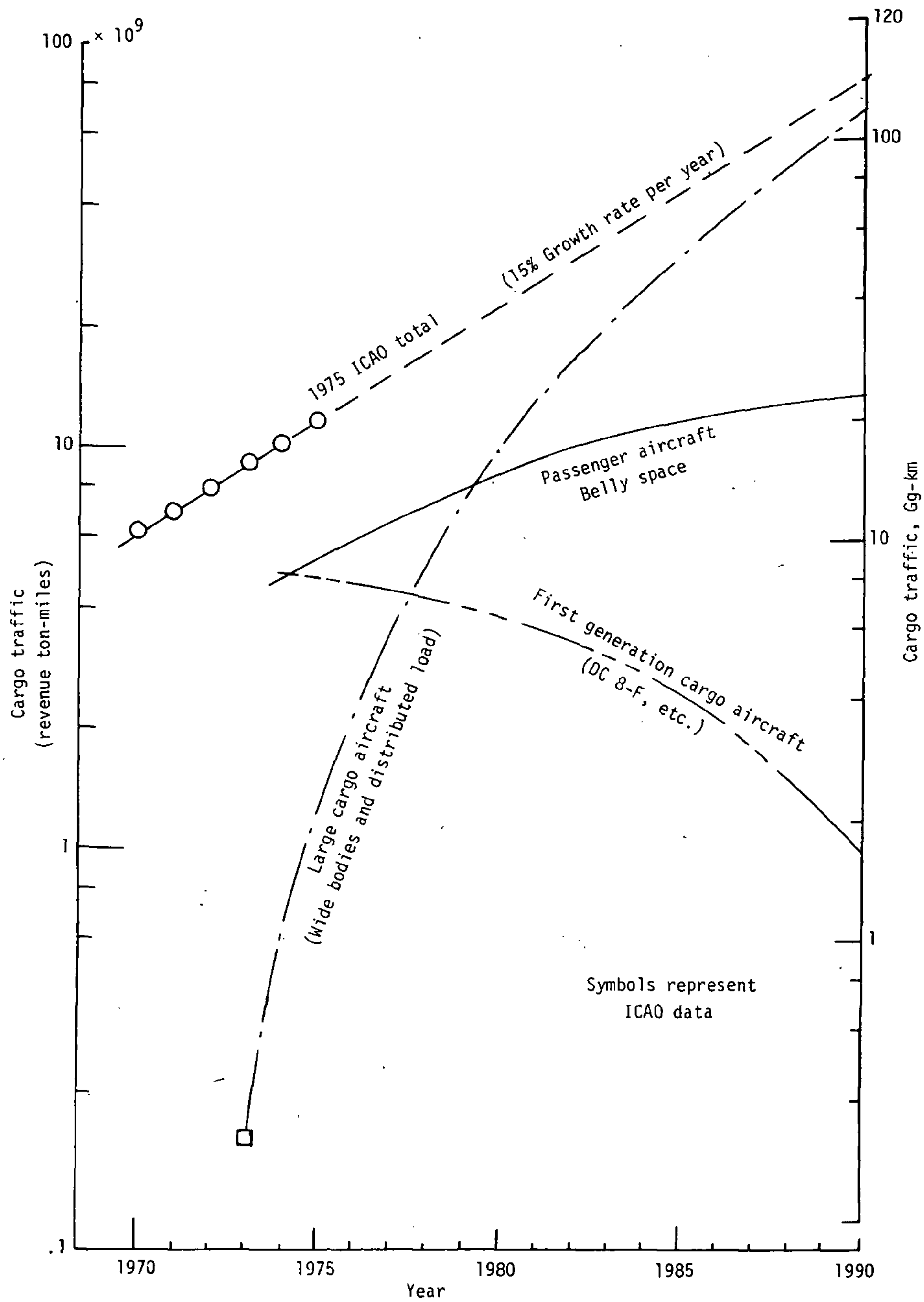


Figure 2.- World air cargo market projection (ICAO states, excluding USSR and China).

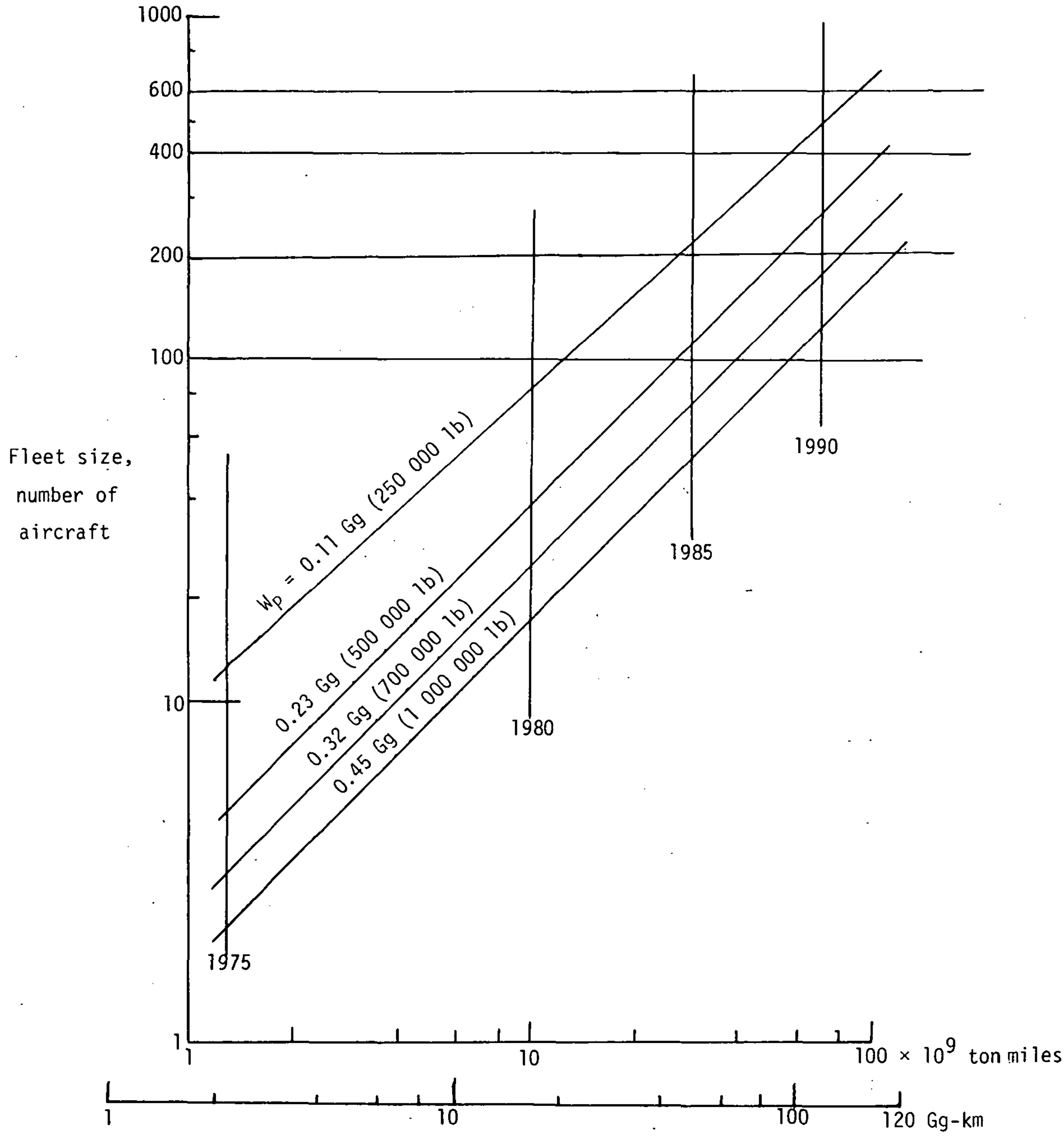


Figure 3.- Estimated fleet size of large aircraft; R = 4630 km (2500 n. mi).

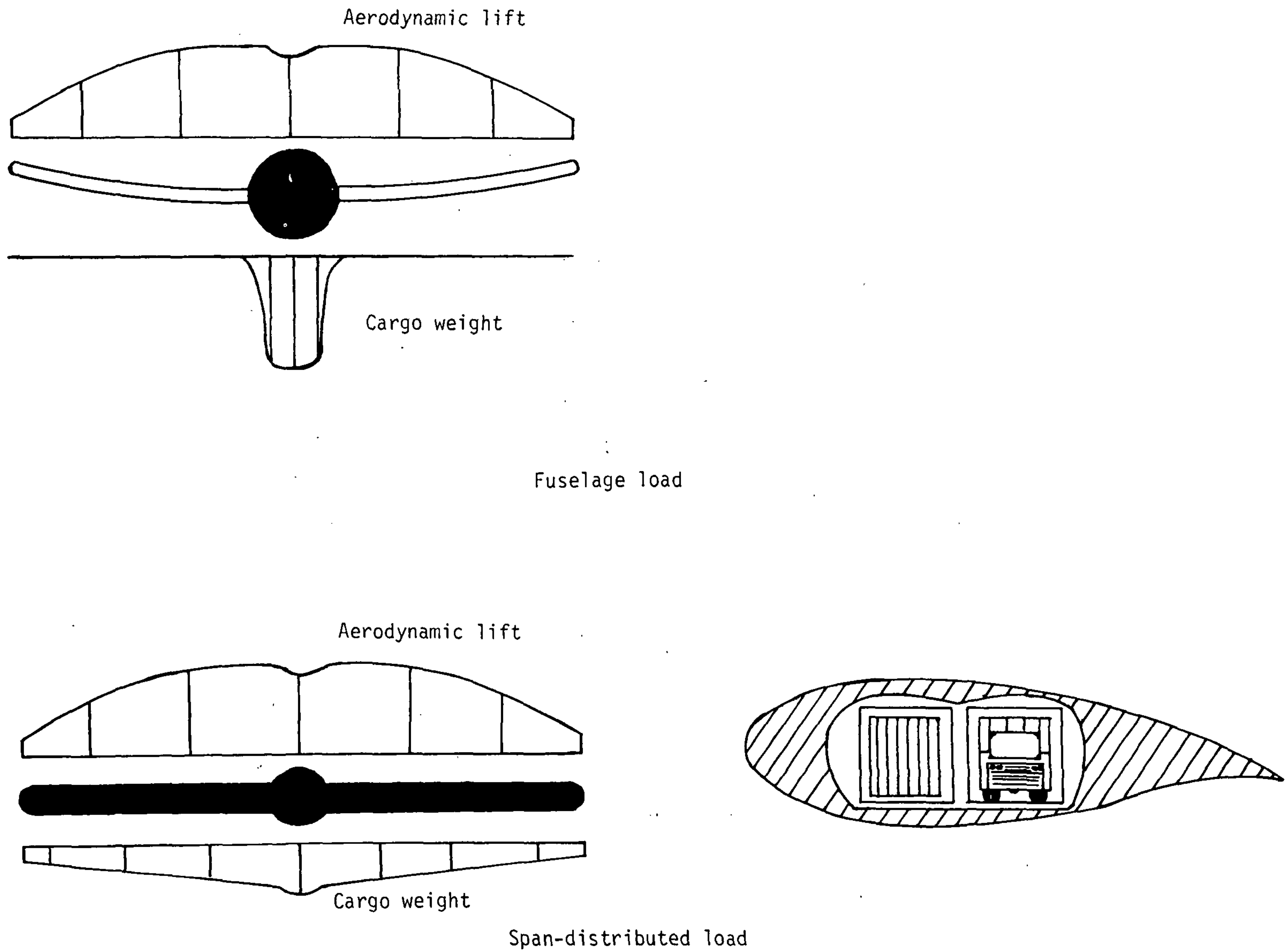


Figure 4.- Payload distribution methods.

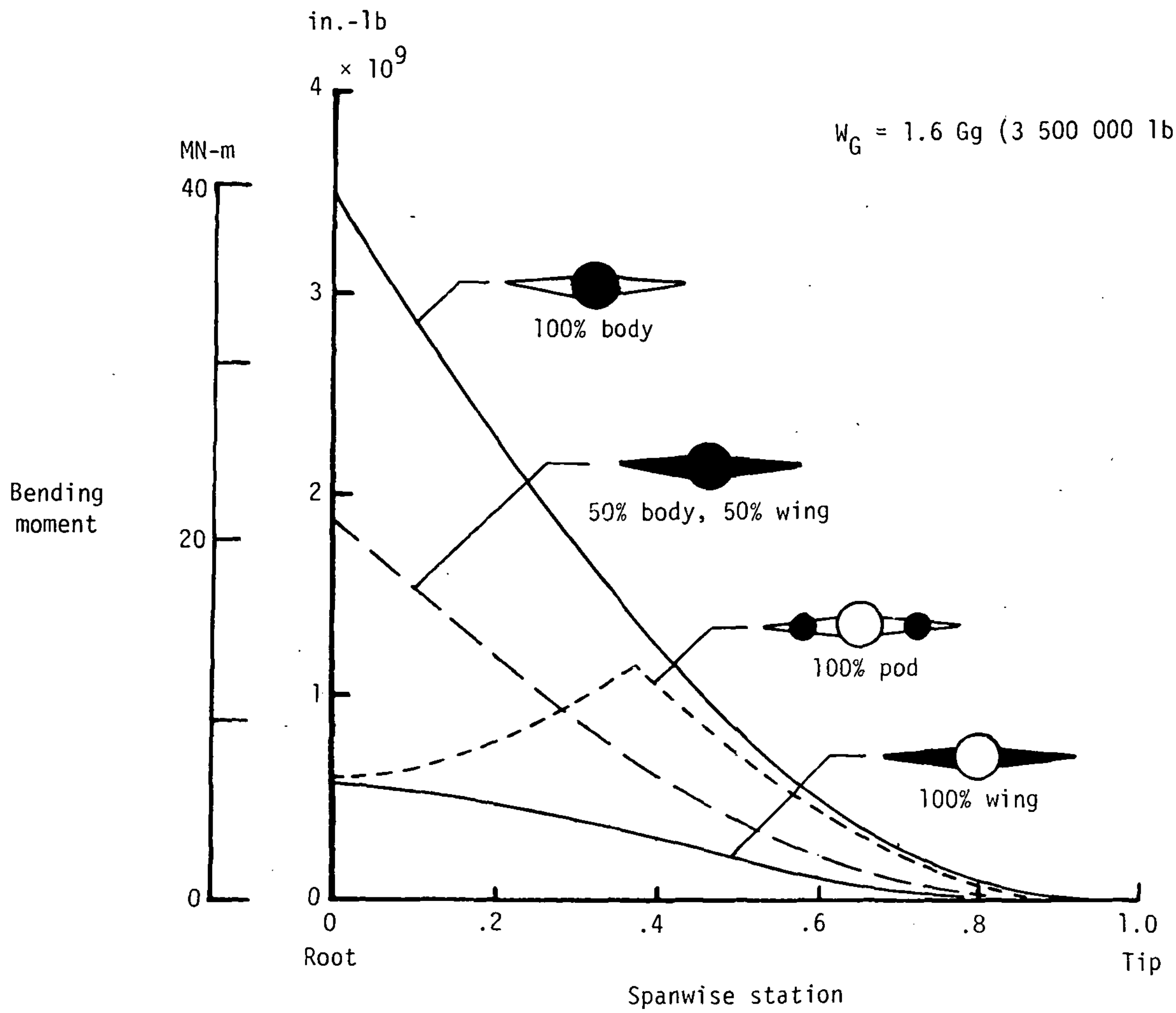


Figure 5.- Payload distribution effects (from ref. 18).

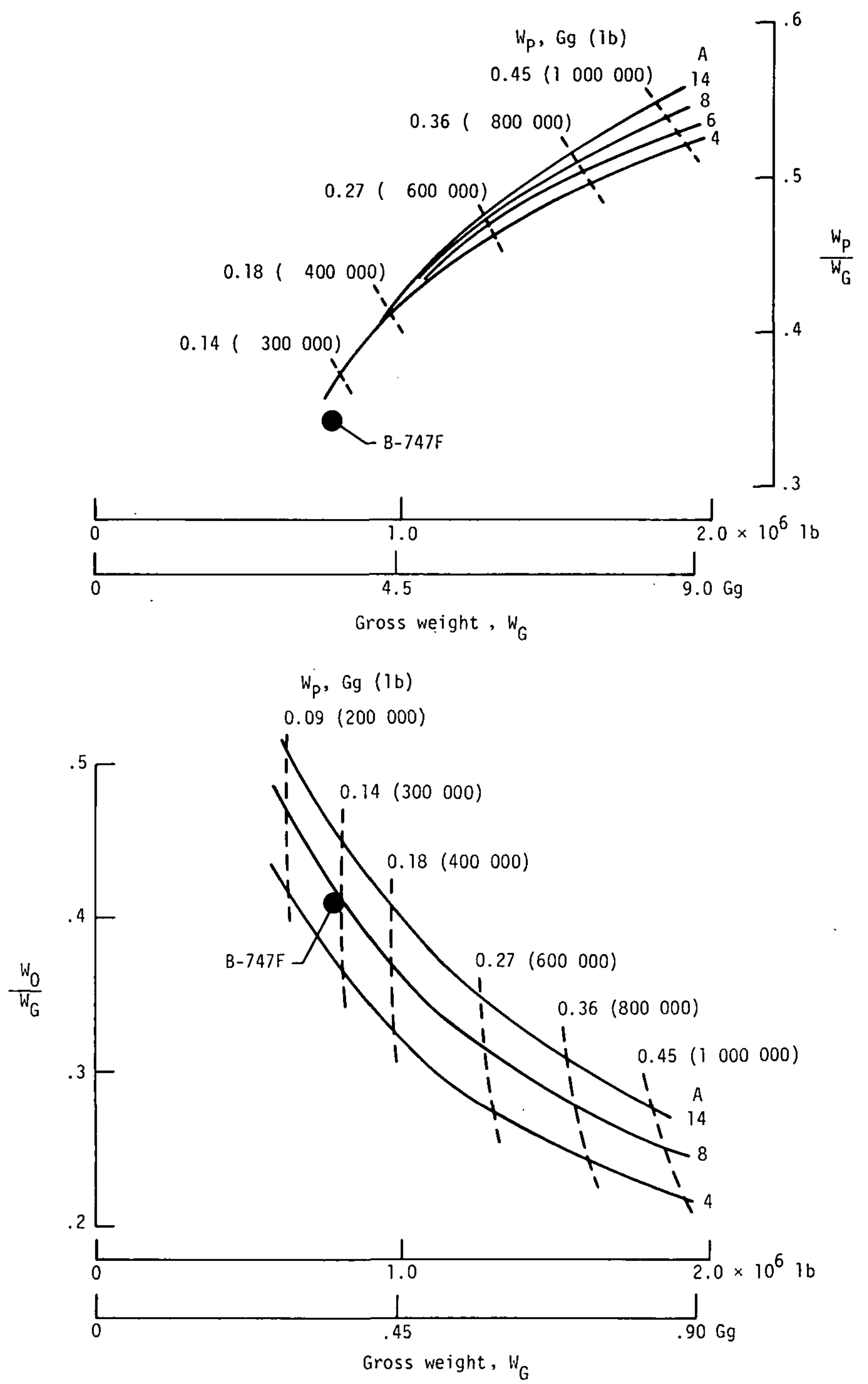


Figure 6.- Payload and empty-weight fractions for distributed-load aircraft (from ref. 10).

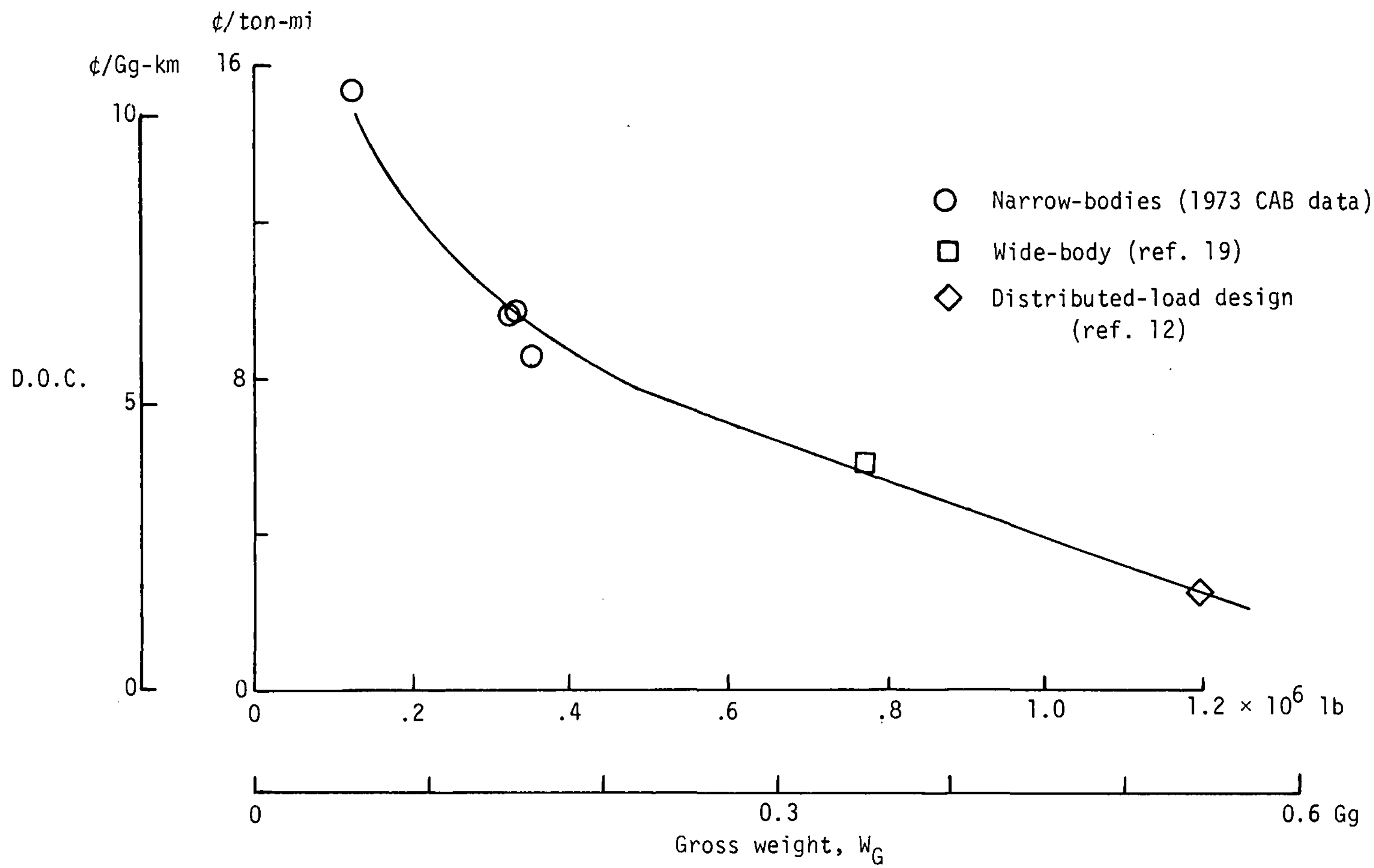
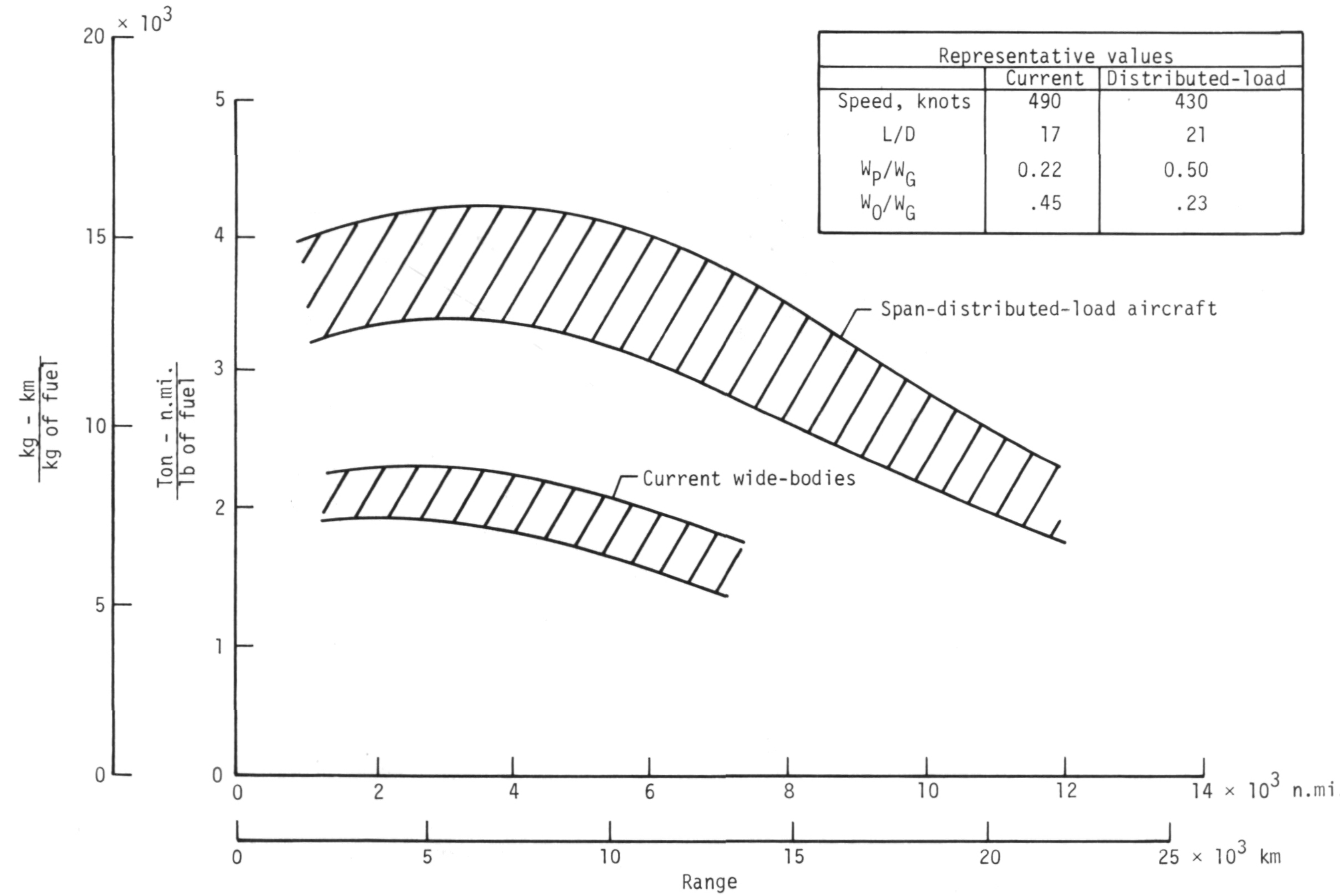


Figure 7.- Effect of size on direct operating costs of all-cargo aircraft. Load factor, 60 percent.



	Representative values	
	Current	Distributed-load
Speed, knots	490	430
L/D	17	21
W_P/W_G	0.22	0.50
W_O/W_G	.45	.23

Figure 8.- Fuel efficiency comparison.

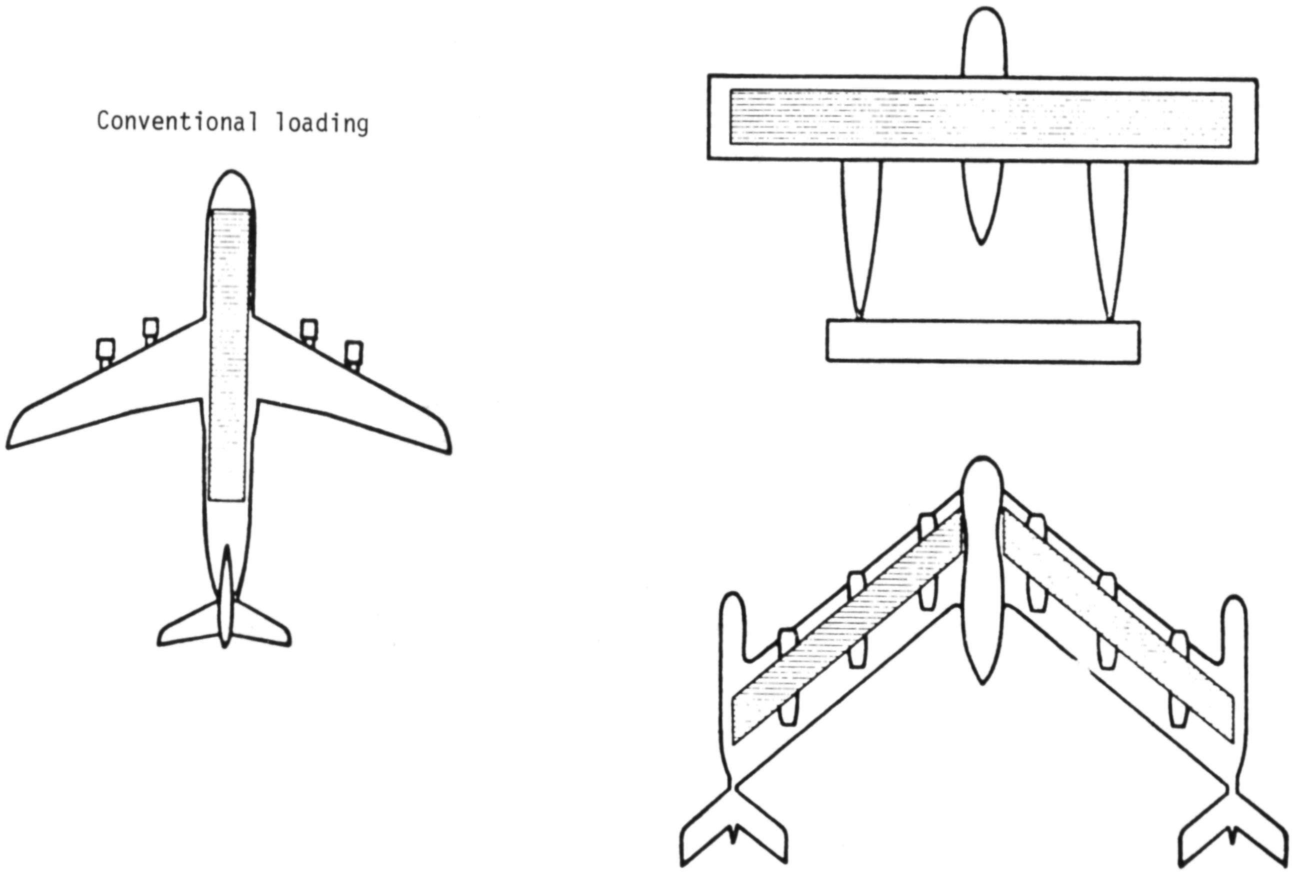


Figure 9.- Load distributions for cargo aircraft.

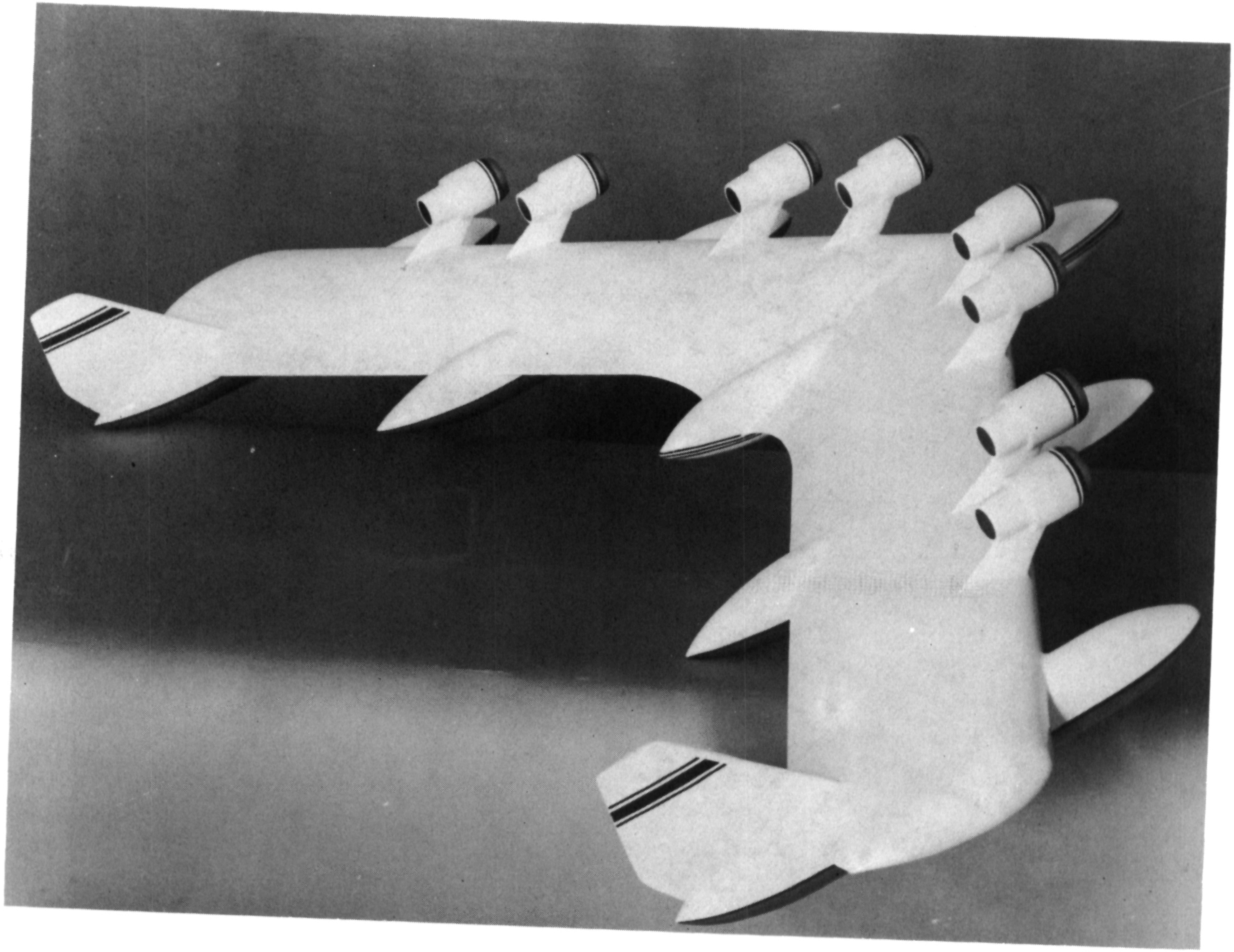


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Figure 10.- Swept-wing distributed-load airplane.

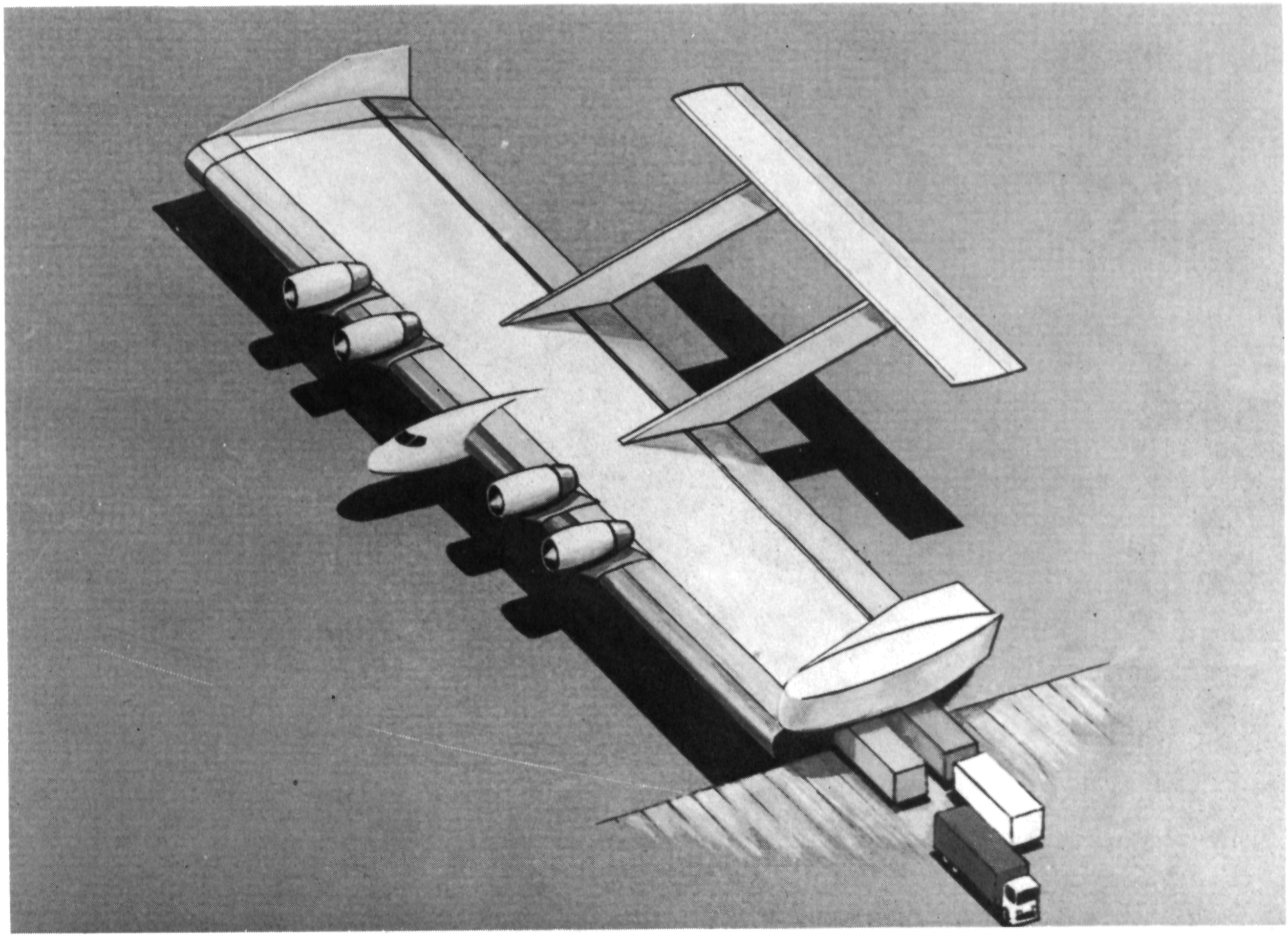

Figure 11.- Unswept distributed-load airplane.

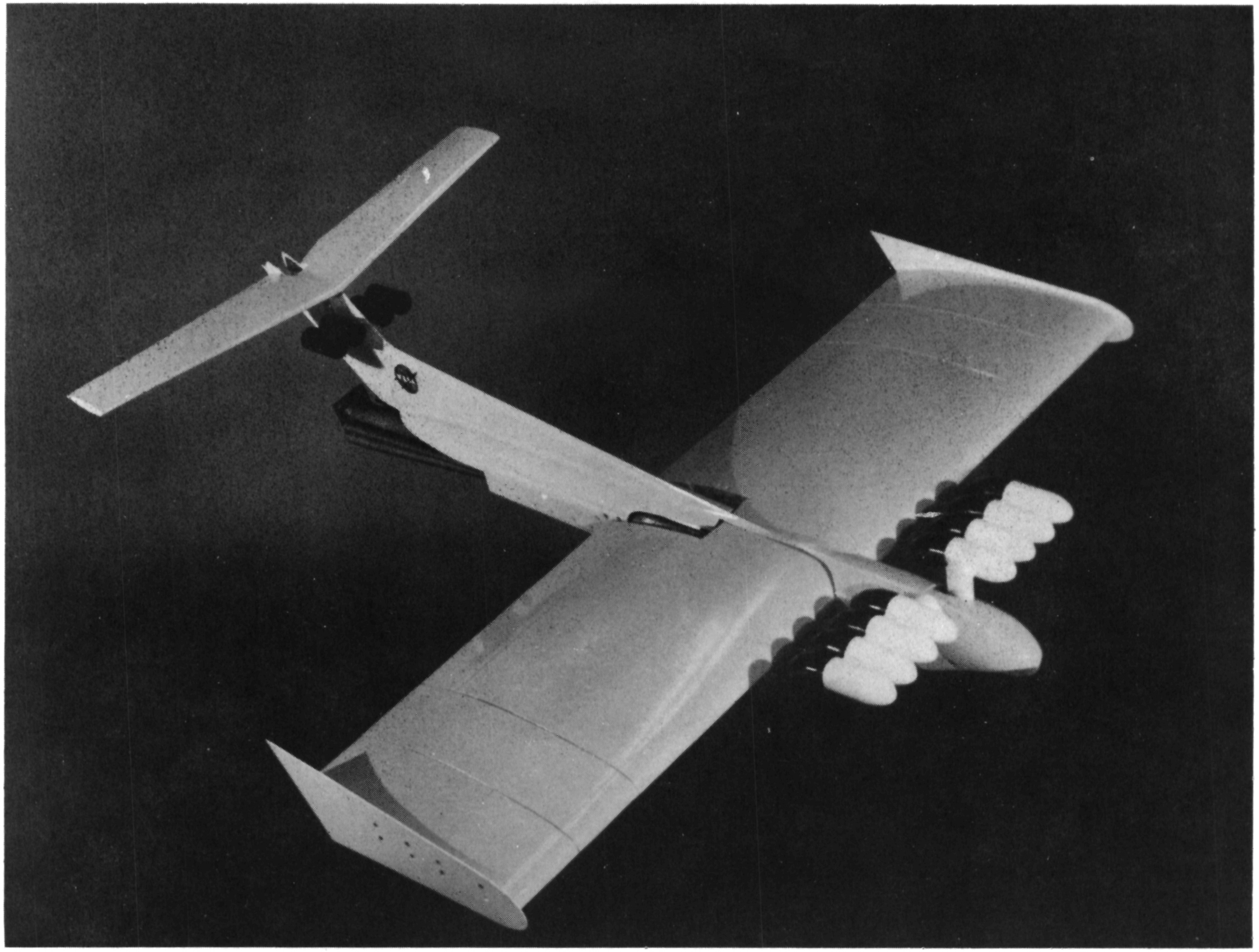

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Figure 12.- Water-based surface effect vehicle.

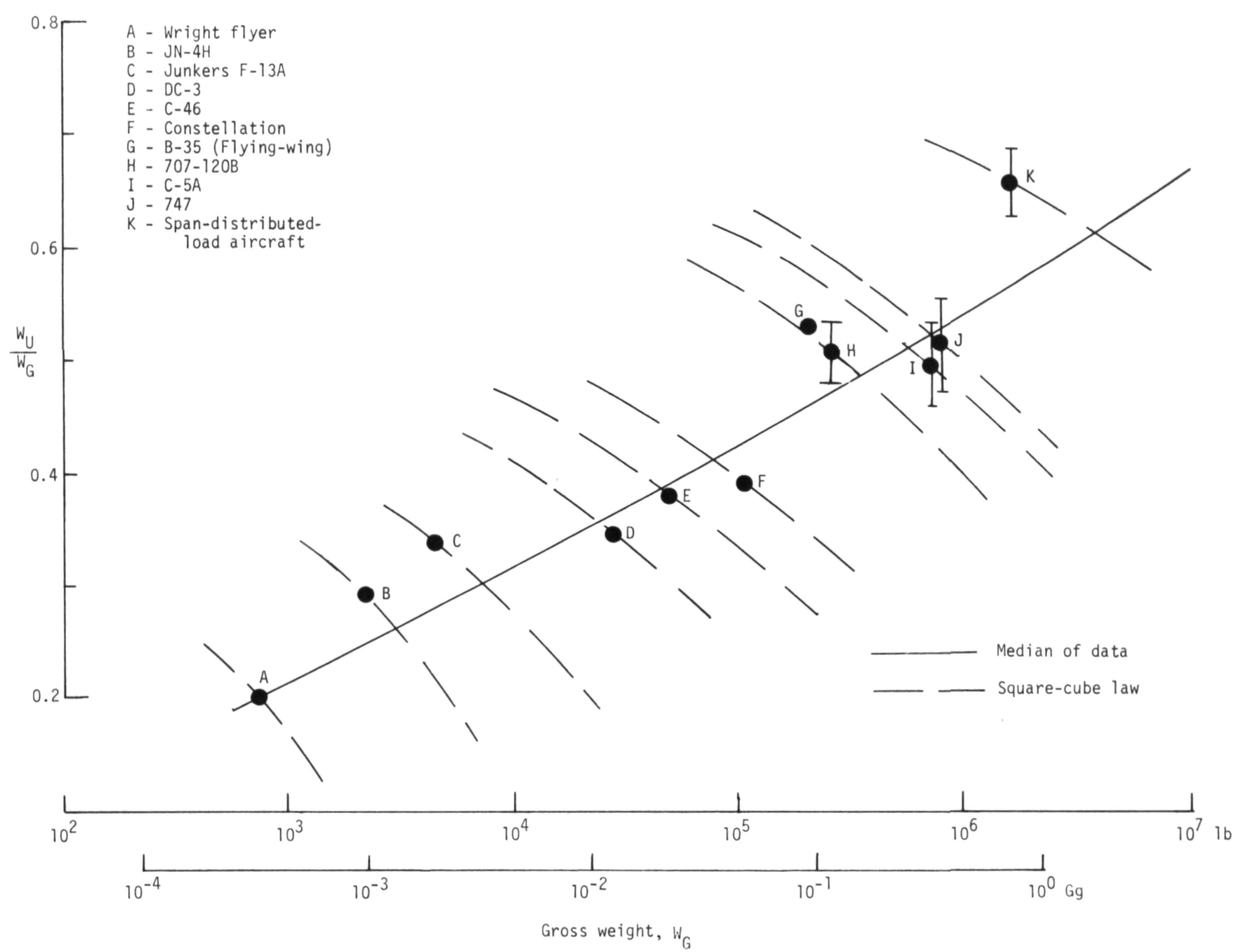

Figure 13.- Useful load fraction. Historical and square-cube law extrapolation (ref. 19).

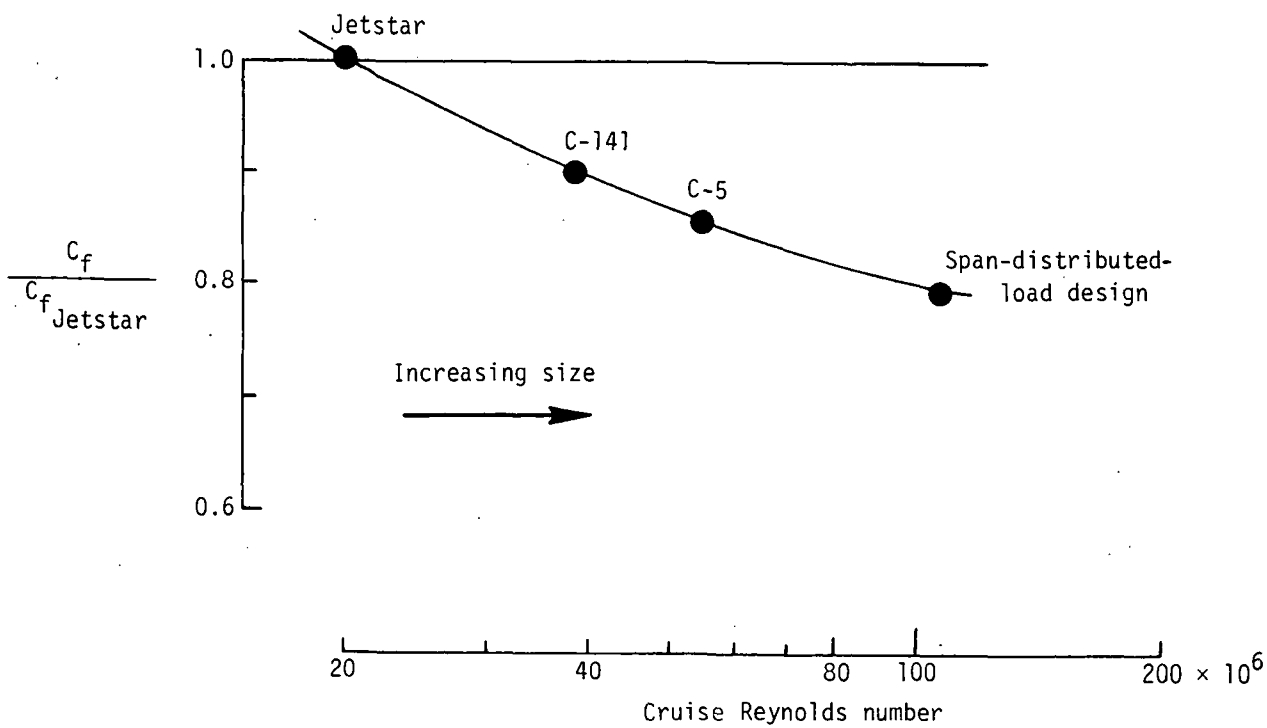

Figure 14.- Decrease in skin friction with size (ref. 20).

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