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TECHNICAL AND ECONOMIC EVALUATION OF ADVANCED AIR CARGO SYSTEM CONCEPTS

INTRODUCTION

The National Aeronautics and Space Administration has recently inaugurated a series of studies on air cargo systems with three basic objectives: (a) to develop and evaluate advanced transport aircraft design concepts; (b) to obtain from the marketplace the timing and design criteria for future cargo aircraft, and (c) to evaluate the logistics requirements of the U.S. Air Force and determine the feasibility of a joint civil military aircraft design.

Many of the advanced cargo concepts studied by NASA (refs. 1-3) and by NASA contractors (refs. 4-7) have indicated significant benefits in performance and economics over current wide-body freighter aircraft. In order to merit serious consideration for production, however, two prerequisites must be satisfied. First, the new design should offer both cost and operational advantages over current aircraft. Projected operating cost reductions must be large enough to meet the competition from existing aircraft currently in production (ref. 8). The new design should also offer some unique operational characteristics and be designed to serve a particular market requirement. Secondly, there must be a sufficient demand from the marketplace for the new aircraft.

Even in passenger service, the demand response to a change in service level can only be predicted with satisfactory results when small variations in certain parameters are considered. Predicting the demand characteristics of air cargo has totally confounded the forecasters. Growth has been disorderly and has followed no particular pattern. As a result, the cargo market defies analysis on a macro scale, and a measure of success is only achieved when the analyst employs a disaggregate approach in addressing selected market segments.

NASA has therefore defined a series of studies of the air cargo market to evaluate the timing for, and the potential market response to, advanced technology aircraft. The near-term market environment is assumed by some carriers to be service sensitive (ref. 9), perhaps as a consequence of the type of market served by those organizations. Unfortunately, the service offered to air cargo users has recently deteriorated (ref. 10). If the 1990 environment finds an increased use of air transport for planned distribution, then demand would be more price-elastic. Current and planned NASA studies are investigating the degree of elasticity in future air freight markets, since the demand for a new aircraft is most favorable in a price-sensitive environment. Basic freighter design characteristics will also be derived from these efforts. The purpose of this paper is to review the progress of these market studies, to report on NASA and NASA-sponsored studies of advanced freighter concepts and to identify the opportunities for the application of advance technology.

AIR CARGO MARKET STUDIES

The prospects for near-term growth of the air cargo market will probably depend on the resolution of serious institutional issues such as deregulation and revised tariff structures, and on the recovery of the airlines from several years of adverse economic conditions. Under such conditions, advanced technology applied to current or derivative aircraft probably will play a minor role in stimulating near-term market growth. The realistic consideration of the development of a new dedicated freighter before the turn of the century presupposes a successful effort to promote a more orderly growth of air cargo operations. The complex international rate structure, for example, often deters the shipper - particularly when his product is eligible for widely differing air transportation rates which depend on the classification of his product and the destination country (ref. 11). Seasonal peaks and backhaul problems must be resolved and service level offered by the carriers must be stabilized.

The current rates employed by the air cargo carriers attract low density freight which tends to fill up the aircraft well before the weight capacity is reached. The ocean shipping industry, in contrast, has a rate structure which offers incentives for higher density cargo. A thorough reexamination of both domestic and international tariff structures is needed.

Much has been written about the vast opportunities available to an aggressive air cargo airline industry (e.g. ref. 12). Many of the market projections confidently show a sustained growth of air cargo through the turn of the century. Figure 1 is typical of such projections in which the prediction of growth for the current market operation is assumed to be 11 percent per annum. This market environment is characterized by the focus on emergency shipments and highly time-sensitive freight. Many observers of the air cargo scene contend that for growth to reach or exceed an 11 percent rate, new market objectives must be pursued and developed. The new approach must emphasize routine, planned shipments to provide additional growth and to bring stability to the carriers in terms of development of regular, predictable traffic. Additional commodities must be attracted to the air mode such as those illustrated in Figure 1, and new markets would require a revitalized route network. If such a potential for expansion does exist, and several NASA studies are examining the possibilities, the growth could reach the top curve on the figure which represents a 16 percent per annum rate. Most analysts would agree that without a high growth rate, there will be no market for a new dedicated freighter before the turn of the century.

The far-term (circa 1995-2000) prospects for an enhanced air cargo system may generate demand for a new, low cost freighter. If a solution is found for the institutional problems clouding the near-term growth prospects, and if the shipper's basic service requirements can be met, then the far-term market may be expected to be more price elastic than today. A reduction in operating costs brought about through the introduction of a new advanced technology airplane could result in lower rates to the shipper and a concomitant increase in traffic. An approximate comparison of freight yields for domestic operations in 1974 shown in Figure 2 indicates that air rates are substantially higher than those for the competing surface modes (ref. 13). Air freight yields and U.S. domestic rate determinations by the Civil Aeronautics Board are ultimately based on operating costs which are in turn determined by the type of airplane in service. The lower part of Figure 2 depicts average costs for four types of aircraft (ref. 14). Over 65 percent of the all-cargo freighters in service in 1975 were either Boeing 707's or Douglas DC-8-63F's (ref. 15). As advanced wide-body aircraft with larger payload capacity were brought into regular service, operating costs declined. NASA studies of advanced freighter designs, reviewed later in this paper, suggest substantial cost savings over current wide-bodies.

NASA Air Cargo Systems Studies

The charter of the NASA as established by the U.S. Congress dictates that the agency's prime focus on aeronautics shall be in developing research and technology. NASA does not participate in the detailed design and development of new aircraft. The purpose of NASA or NASA-sponsored preliminary design studies of advanced aircraft is primarily to identify and prioritize technology requirements. In planning future research programs, the agency must often be aware of the timing for the probable introduction of a new design into operation. For these reasons, a program has recently been formulated to answer several critical issues related to dedicated freighter development. Questions which focus on these issues are listed in Figure 3.

The first issue relates to the timing for the introduction of the aircraft. The second issue concerns the possible stimulation of market growth with the introduction of a more cost-economical transport vehicle (i.e., definition of the price elasticity of the market). The third issue addresses the possibility of a common civil/military aircraft concept. If the projected military airlift deficiency coincides with the civil need for additional airlift capacity, then there will be a strong motivation for considering a common civil/ military aircraft design. A portion of the production costs could then be absorbed by the military, thereby reducing the purchase price of the airplane to a civil buyer.

Fourth, the NASA studies will hopefully identify design and operational characteristics from the marketplace which will guide the future airplane design teams. Design range and design payload weight and density are just some of the critical inputs required from market evaluation studies. Finally, an overall cost-benefit assessment of an advanced air cargo system will, if the results are favorable, provide incentive for increasing the tempo and scope of preliminary design activities, both within government and industry.

The first of a series of studies to address the issues defined in Figure 3 is now underway. The objectives of the CLASS (Cargo/Logistics Airlift Systems Study) program are shown in Figure 4. This effort will take advantage of previous studies and international experience in past air cargo operations. Developing eligibility characteristics for the 1990 air cargo market is one of the critical aspects of the study, with consideration of the most favorable network characteristics, commodity features, and production, procurement, and marketing requirements of both shipper and consignee.

The evaluation of the sensitivity of modal shares and overall air cargo growth to improved aircraft performance is a major NASA objective. NASA has on-going technology programs reviewed later in this paper which can contribute to reduced aircraft operating costs for both near- and far-term applications. The micro data base to be developed in the CLASS study will not only support these objectives but could also be of universal value to the industry. The contractors are conducting in-depth surveys of over 150 users (shippers and consignees), 24 carriers and 18 airport terminals around the world. Over 1000 mail surveys will contribute to the data base. The CLASS program is scheduled to be completed in April 1978.

Civil-Military Design Commonality

In recent years within the United States, there has been an interest in the possibility of a single airplane design which could effectively serve both the military airlift requirement and the civil market needs (ref. 16). Many observers believe that only through such a joint venture will the civil operators be able to acquire a dedicated freighter design in the twentieth century. The proposal includes the development of a mechanism which would allow the sharing of the production costs. There is even a possibility of shared use of a number of these aircraft, with commercial airplanes and crews being available for call-up in a military emergency.

Preliminary studies have identified some of the design issues which must be dealt with if such a common airplane will ever become a serious consideration. A summary of the design differences between civil and military vehicles is presented in Figure 5, which shows a current wide-body used by the civil carriers and the comparable military transport. The civil vehicle was designed for passenger commonality with two decks, a low wing, moderate floor loading capability, capacity for a maximum container height of about 2.5 meters and upper deck access approximately 5 meters above ground level. The military vehicle, in contrast, is a high wing, single-bay airplane which facilitates the design of a low floor for roll-on, roll-off delivery of motorized vehicles and rapid access to unitized cargo. The military requires a 4.1 meter (13.5 feet) height clearance inside the cargo bay in order to transport critical military equipment. This dimension far exceeds the space available on today's civil wide bodies and is one of the critical inconsistencies that must be faced. Heavy floor support for high density motorized vehicles is another key difference. There are several preliminary design studies which have attempted to optimize the military airplane (refs. 17, 18). These results will help to quantify the design penalties of a common design.

AIRCRAFT DESIGN STUDIES

A brief synopsis of airfreighter design evolution and potential future concepts is presented in Figure 6 for both civil and military applications. Although there were earlier aircraft, the first freighter that transported any volume of cargo is generally agreed to be the Douglas C-47 Skytrain which had its first flight in 1935. The Douglas C-54 Skymaster, which served both civil and military roles, had its first flight in 1942. The Lockheed C-130 Hercules, a current military workhorse, had its first flight in 1954 and the Douglas DC-8 (series 10), in 1958. The Lockheed C-141 first flew in 1963 and the C-5 in 1968. The Boeing 747 was introduced in 1969. In this 34-year period, the gross weights have increased from 0.012 Gg (26,000 lb) for the C-47 to nearly 0.36 Gg (800,000 lb) for the 747 and C-5 aircraft. During this evolution, the direct operating costs have been reduced from approximately 34 cents per Mg-km (20 cents per ton-mile) for the C-54 to about 9.0 cents per Mg-km (5.4 cents per ton-mile) for the B-747 (based on 1973 costs). Part of this cost reduction is attributed to performance gains derived from new technology and part is accomplished through increased vehicle size (ref. 19). Note that the two conceptual designs on the right side of the figure continue the trend towards escalation in gross weight.

Mission and Design Requirements

If a dedicated freighter is a possibility, what are the mission and design requirements for such a vehicle that are different from passenger airplane design criteria? In Figure 7, five of these requirements are proposed. Freight density is a highly sensitive variable in the design process since a higher design density will generally result in a more aerodynamically efficient vehicle. Current freight densities are of the order of 3.0 times the "density" of a passenger when account is made of the main-deck volume utilized on the aircraft for each available seat. Current and future NASA-sponsored market studies will attempt to determine if freight densities are likely to increase with the new commodities attracted by lower air freight rates.

Compatibility with intermodal containers may be another critical requirement. Many authoritative sources (e.g., ref. 14) believe that intermodality with the ground transportation system may be the key to the development of the full potential of the air freight system. The essential element to increased intermodality is, of course, the larger container that can be exchanged between transportation modes. This type of operation perhaps best suits the type of market characterized by routine, high value shipments rather than the market developed around the delivery of emergency and extreme time-sensitive freight.

Many analyses of air freight economics have cited the high costs involved in ground operations (e.g., ref. 20). The design of the airplane must be adapted to the rapid and efficient handling of the cargo unit, whether it be pallet or fully intermodal container. Loading access at truck bed height would greatly facilitate loading of the aircraft, assuming, of course, a single-deck design. Figure 8 shows current loading procedures for the upper and lower decks of a current wide-body freighter. The equipment needed to raise and lower the cargo to the access levels is expensive and time consuming to maintain, store, and operate.

Because of the probability of a relatively low production run of a new freighter aircraft, particularly if the design payload substantially exceeds the Boeing 747-F capacity, there will be a strong motivation for minimizing the acquisition cost of the airplane. The reduction in aircraft price with increased fleet size illustrated in Figure 9 occurs for two reasons. As more aircraft are produced, the fixed nonrecurring costs can be amortized over a greater number of airplanes. Secondly, successive units benefit from "learning-curve" trends in recurring costs which reflect continued improvements in production line techniques. On the right side of Figure 9 is found the direct operating costs and aircraft investment costs for an 80 airplane fleet. (Aircraft investment cost represents the return on investment per airplane required by the operator to attract the capital to finance the fleet purchase (see ref. 6)). For this small fleet, the airplane price-sensitive costs dominate fuel costs (based on current market price for fuel). The trade-off between high performance design features and low-cost design and construction techniques may depend on the fleet size. Furthermore, current and future market studies may indicate a relative insensitivity to speed in air cargo line-haul operations, in contrast to passenger market exigencies. A past study has shown that a modest reduction in design speed simplifies the aerodynamic design and provides acquisition cost savings (ref. 21). A strong motivation exists, therefore, to examine low cost design features.

The fourth item on Figure 7 refers to the potential for civil-military commonality. The potential reduction in acquisition costs possible through cost-sharing in the aircraft development has not yet been fully quantified.

A final requirement is the adaptability of the airplane to a distribution system tailored to serve the cargo market. A foreknowledge of the proposed network to be served in conjunction with predicted market volumes would dictate design stage lengths, payload weights and fleet sizes for a family of freighters to serve future market needs. One such system that has been proposed in the hub-spoke operation. The large aircraft would travel between major world hubs (Figure 10), serving the "wholesale" delivery function.

Smaller, feeder aircraft and/or surface vehicles would deliver cargo to and from the hub center in a "retail" mode. A successful application of this concept exists in the U.S. with the Federal Express Corporation operation (ref. 22). Federal Express offers a small package, overnight delivery service. The system proposed in Figure 10 represents a significant increase in scale over the Federal Express operation, both in package size and in the size of the aircraft operating between hubs.

Incorporation of Advanced Technologies in Transport Aircraft

What are the likely candidates for new or improved cargo aircraft in the future? The montage of Figure 11 presents a variety of aircraft which can incorporate advanced technologies and offer improved economics. Derivative aircraft utilizing extensive parts from existing aircraft would be the earliest opportunity to incorporate changes. Derivative aircraft can obviously be manufactured at a considerably lower capital investment cost than that required for a new design. Two derivatives of a current wide-body are shown which would substantially increase payload capacity. The twin or "catamaran" freighter would require only a new section between the fuselages (ref. 1).

For technology application past 1985, new aircraft designs are shown which can take full advantage of new technologies and thus benefit from higher performance than derivative designs. The fuel-conservative airplane represents an amalgamation of several current studies of new technology application to both passenger and cargo transport developments. These studies are consolidated under the NASA ACEE (Aircraft Energy Efficiency) Program represented in Figure 12. Critical objectives in this program are to develop and demonstrate new technologies so that future aircraft incorporating these advances will be accepted by the manufacturer and carrier communities. Most of the technology applications under study by the three contractors (Boeing, McDonnell-Douglas and Lockheed) are identified in Figure 12.

In the area of aerodynamics and configurations, work is underway on supercritical airfoils, winglets and engine-airframe integration. The supercritical airfoil (ref. 23) was originally developed at NASA's Langley Research Center to increase the drag-rise Mach number by delaying the onset of shock waves at a given wing thickness ratio. More recently, supercritical wing technology has been directed toward improving fuel efficiency at a given flight speed by increasing the thickness ratio, thereby permitting a lower wing sweep and increased aspect ratio. The exact contour of the supercritical airfoils was defined after thousands of hours of wind tunnel tests and the resultant improvement in performance has been conclusively demonstrated in three flight demonstration programs. Winglets are aerodynamically tailored devices located at the wing tips which provide a further reduction of the configuration drag. Research on propulsion-airframe integration is directed towards reducing the interference drag that occurs when engines are integrated with the configuration.

Another effective way of reducing fuel consumption and improving performance is by reducing aircraft weight through the use of advanced composite materials. These composites are lightweight, yet have over twice the strength and stiffness of conventional aircraft materials. As shown in the insert, these materials consist of fibers such as graphite, boron, or nylon embedded in a matrix such as epoxy resin. Common fiberglass is an example of a composite material.

The term "active controls" refers to a system which ties together the aircraft control surfaces, load and motion sensors and an on-board computer. The computer receives the inputs from the sensors and sends signals to the control surfaces to minimize undesirable motion and limit the loads on the aircraft structure. For example, the loads on the structure from transient phenomena such as maneuvers and gusts can be alleviated with active-control systems. When active controls are implemented at the beginning of the design process, substantial reductions in aircraft weight and drag can be achieved. As shown in Figure 12, the use of "black-box" systems to reduce static stability permits reductions in tail size, weight and drag. Ride quality and maneuverability can also be enhanced.

The ACEE program will also support the design of an advanced, more fuel-efficient turbofan engine by supporting component and experimental engine development. Engine component improvement includes specific efforts to diagnose the causes of performance deterioration in current engine designs and to identify component changes to enhance performance and reduce deterioration. Studies will also examine advanced turboprops which offer great savings in fuel efficiency yet can cruise at nearly the same speed as turbofan engines.

Application of laminar flow control to wing and empennage surfaces is being studied. The airflow over the surface of conventional airfoils such as found on today's transports is smooth and layered (laminar) only near the wing leading edge. Just beyond the front portion of the wing, the flow abruptly transitions from a laminar to a turbulent state causing the skin-friction drag to increase dramatically. Aerodynamicists have proven in a flight test program (ref. 24) that if some of this air near the wing surface can be removed, this boundary layer of air can be maintained in a laminar state. Laminar flow control can pay enormous dividends in fuel savings if operational problems can be solved.

The approximate contributions of most of these technologies in improving fuel efficiency are shown in Figure 13. The approximate date of introduction of each technology element is also indicated. While some of these technologies may see early application to derivative aircraft such as shown as shown in Figure 11, other advances must await new aircraft design. Laminar flow control will be the most difficult technology to implement but offers the greatest single advantage for a post-1990 new design. The goal of the program is to offer a 50-percent gain in fuel efficiency by 1995.

One advanced, post-1995 new concept is shown in Figure 11 which incorporates several advanced concepts in an integrated, synergistic design. The "laminar-flow control" aircraft shown has been designed to achieve an aerodynamic efficiency unparalled by previous transport designs. Lift-to-drag ratios of 45 to 50 are projected. This vehicle has extreme range capability and yet maintains a high payload weight fraction. The liquid-hydrogen-fueled design in the lower right corner of Figure 11 is representative of current work within NASA on configurations designed to burn fuels other than petroleum-based products.

New Cargo Aircraft Concepts

As shown in Figure 11, the 1985-1990 time period may spawn a new class of dedicated freighter aircraft. All three major U.S. transport aircraft manufacturers have active preliminary design teams evaluating potential concepts for these advanced freighters. The current contenders for the three companies are shown in Figure 14. All three designs could be available for production by 1990. All three concepts have a single deck to handle the large military cargo and to provide efficient loading. The Boeing design on the upper right has a double-lobe cross section. This design has the capacity to carry 30 equivalent 8x8x20 foot containers arranged in four parallel lanes, which can be simultaneously loaded or off-loaded through a large nose door (ref. 14). The Lockheed concept on the lower part of the figure represents a common military/civil cargo aircraft, which offers a compromise of several design and operational differences between military and civil requirements (ref. 25). A family of such aircraft have been considered by Lockheed reflecting four different design payloads. The Douglas Aircraft Company "Nation Builder" is shown on the upper left. This is a large aircraft (20 percent higher gross weight than the Boeing 747-F) with intercontinental range.

Distributed-load aircraft configurations, which offer great advantages for cargo airlift, have received the most attention in recent NASA studies (ref. 2-7). In this approach, the payload is distributed across the span of the wing of the aircraft. In Figure 15, the bottom sketch shows such a design concept together with a partially-distributed load (twin-body) aircraft and a conventional design. The figure presents the variation of wing bending moment across the semi-span. The moments are normalized with respect to the moment at the wing-body juncture of the conventional, fuselage-loaded aircraft. The figure illustrates the significant reduction in bending moment across the span attributed to either partial (twin-body) or full (spanload) distribution of the payload. On conventional, fuselage-loaded aircraft, the aerodynamic forces are only offset by any wing-mounted engines or fuel in the wing, and the resultant high stresses must be countered by heavier and/or stiffer structural members. Placement of payload in the wing can provide a close match between aerodynamic and intertial loading, thereby minimizing the bending stresses in the wing structure. Reduction in bending stresses results in lighter structural weight as illustrated in Figure 15 where the ratio of empty-to-gross weight decreases from 0.39 to 0.31.

The first series of four design studies produced the configurations found in Figure 16. The study results from the NASA-sponsored contracts to Douglas, Lockheed, and Boeing are reported in references 4, 5, and 6, respectively. A summary of these studies can be found in reference 3. A fourth design was completed within NASA and is shown on the lower right of Figure 16. The design input for all of these efforts specified a 0.27 G(600,000 lb) net payload contained in 8x8 containers. The design process became an exercise in wrapping the most efficient airfoil section around several rows of containers. The Lockheed design team elected to maintain a capability to accept outsized payload (4.1 meters in height) in the fuselage; about 80 percent of the payload is carried in the wing section.

Several important conclusions that pertain to the spanloader concept were drawn from these studies. The number of 8x8 boxes was predetermined by the available volume within the containers and by payload weight and density. A cross-section of the wing shown in Figure 17 illustrates a typical arrangement of container bays and the location of the fuel. With the exception of the Lockheed design, the containers are loaded from the wing tips. The selection of thickness ratio (wing maximum height divided by wing chord) or the number of bays determines the wing span. Thus, for a given number of containers and number of bays, the wing span (tip-to-tip distance) is predetermined. Since wing span is a fundamental determinant of aerodynamic efficiency, the designer is limited in the efficiency of his design by the maximum allowable thickness ratio (currently assumed to be approximately 0.20) and by the specified payload characteristics.

All of the design teams employed wing-tip devices such as winglets to enhance aerodynamic performance. These devices provided a high payoff because the wing of these designs was so highly loaded toward the tips. The total drag of these vehicles was reduced by about 15 percent with the addition of the tip devices.

The studies quantified the structural weight advantage of the spanloader over conventional design. For the Boeing design, for example, the payload-to-empty weight fraction was some 30 percent higher than for an advanced-technology, fuselage-loaded airplane considered in the study. The wings were constant chord without the taper or twist normally built into conventional designs to optimize aerodynamic performance. Any cross-section taken perpendicular to the wing leading-edge would show that each such section is identical to its neighbor (except in the regions where additional supporting structure is needed for engines or struts). As such, there was a significant repetition of parts in the spanloader design which provides a significant reduction in design, tooling, and production costs. The Boeing fuselage-loaded aircraft had about 4 times the number of unique parts as did the spanloader design.

The structural weight savings and part commonality benefits contribute to the economic viability of the spanloader design concept. On the other hand, for the design payload specified in the first series of studies represented in Figure 16, the aerodynamic performance of the study design was inferior to that of an advanced-technology, fuselage-loaded airplane (lift-to-drag ratio = 16.6 and 21.9, respectively).

Advanced Freighter Evaluation

An economic evaluation of several advanced design concepts is presented in Figure 18. The direct operating costs of the advanced designs have been normalized by the cost for a current wide-body freighter. The data symbols represent a specific configuration design with the trends established from parametric studies. The unswept Boeing spanloader is found to be only marginally superior to the advanced transport of conventional design (fuselage-loaded), which is assumed to have the same level of technology in its design. Note that at least a 30 percent savings in direct operating costs is projected for advanced, fuselage-loaded design over the current operational wide-body freighters. These savings are primarily achieved through the introduction of the advanced technology features currently being studied in the NASA ACEE program.

A rule of thumb criteria proposed in reference 8 states that approximately a 25 percent improvement in the DOC of existing cargo systems is necessary to attract the attention and support of those who underwrite new aircraft development programs. It would appear from Figure 18 that we have satisfied that criteria. However, a word of caution is in order concerning the interpretation of the economic comparison between current and future designs portrayed in this figure. This comparison is based on 1975 costs and operations. Since the advanced design will not be placed into operation before at least 1985, that ten year time interval will have a significant impact on the success of the competition of a new design with current production aircraft. By 1985, a significant number of units of the wide-body design first introduced in 1969 will have rolled off the production line. The manufacturers unit costs in 1985 will be far down the learning curve of recurring costs (Figure 9); and in all likelihood, the nonrecurring costs will have been fully amortized by that time. Another factor mitigating against new aircraft production is the adverse impact of inflation on all cost factors. In the analysis presented in reference 8, even with a 25 percent DOC improvement assumed for a large, advanced technology freighter, a large production quantity has to be assumed just to achieve a DOC equal to that of additional units of the smaller, less productive, conventional technology freighter. Both significant operating costs benefits plus new operational capability may be required before a new airplane can be seriously considered. The prospects for market vitality and growth must also be far more optimistic than that of today's environment.

As design payload of the spanloader is increased, the span-to-chord ratio of the wing (aspect ratio) increases, enhancing aerodynamic performance. Sweeping the wing allowed the speed of the design shown in Figure 18 to be increased by 25 percent which improves productivity and further reduces operating costs. The cost data shown for the swept wing spanloader is obtained from the most recent study completed by The Boeing Company on NASA contract (ref. 6). Although the design payload of 0.54 Gg (1.2 million pounds) was perhaps excessive, this size represents an optimum design based on the parametric analysis done in the study. Beyond this payload weight, the cost would begin to increase because of rapid escalation in airplane cost resulting from the small number of very large airplanes sufficient to handle the assumed annual freight traffic.

The costs for the conventional design also show a minimum and then begin to rise with increased payload as a result of the square-cube law (ref. 26). This law states that for similar structures of varying scale, the load increases as the cube of the linear dimensions, whereas the cross-sectional areas of the members which resist the load increase as the square of the linear dimensions. Thus the stress in the structure tends to increase as the linear dimension. The structural weight of an aircraft must then increase as the linear dimension, or, alternatively, the designer must incorporate advanced technologies such as new materials with higher strength-to-weight capabilities.

A second alternative in bypassing the square-cube law is to employ a different configuration concept. One such approach is the partial or complete distribution of the useful load within the wing, thereby providing substantial relief of the loads generated on the wing of a conventional transport. The twin-body thus offers a minimum cost at a payload well above that for the conventional design, and the full-distributed load concept offers a minimum cost at a design payload weight over three times the design payload for minimum cost of the advanced, conventional design. According to the results presented in Figure 18, the designer and potential buyer of a new aircraft must resolve the following question: Would the market prefer a larger fleet of the more conventional advanced design, or would the system prefer a fewer number of the very large aircraft with substantial savings in operating costs, but with reduced operational flexibility associated with the small fleet size? The operating scenario implied by the latter choice suggests the implementation of the hub-spoke concept of Figure 10. Hopefully, the results of the ongoing market studies reviewed earlier in this paper will shed light on this issue.

The size of the swept-wing spanloader designed by Boeing can be compared to a Boeing 747 in the photograph in Figure 19. The wing span is 2.6 times that of the 747, and the gross takeoff weight and payload weight ratios of the two vehicles are 3.5 and 5.4, respectively. The payload-to-gross-weight ratio of the spanloader is 0.49 compared to 0.32 for the 747-F. The spanloader has four bays capable of accepting 104 8x8x20 foot containers. The technical problems that must be resolved include the areas of aeroelastic effects, handling qualities and high speed aerodynami This spanloader concept employs graphite/epoxy honeycomb sandwich construction and, because of inherent longitudinal instability, relies on a computer-controlled "black box" to provide adequate stability characteristics. Active controls are needed to minimize the loads imposed on the structure from transient phenomena such as gusts and airplane maneuvers. Since the concept incorporates technologies envisioned for 1990, the incorporation of active controls and composite materials for both secondary and primary structure is considered reasonable.

CONCLUDING REMARKS

Results from past market studies suggest that a significant stimulation of growth must occur over the next ten to fifteen years to generate sufficient demand for an advanced technology airplane before the turn of the century. NASA studies are in progress to evaluate the future market characteristics and to determine the possible timing for a new design. Improved utilization of the current air cargo system is apparently the key to near-term growth. The influence of technology on far-term growth will depend in large part on stabilizing the demand and on service level offered.

NASA preliminary design studies have indicated significant potential gains in aircraft efficiency and operational economics for future freighter concepts. Research and technology advances from on-going programs will be available for application to current, derivative, and new aircraft. Critical design criteria that will govern the design methodology for a new dedicated freighter airplane must be obtained from the marketplace once the demand and the timing for the aircraft can be reasonably established. NASA studies have already identified some of these criteria and further efforts are planned to define the unique cargo aircraft design features.

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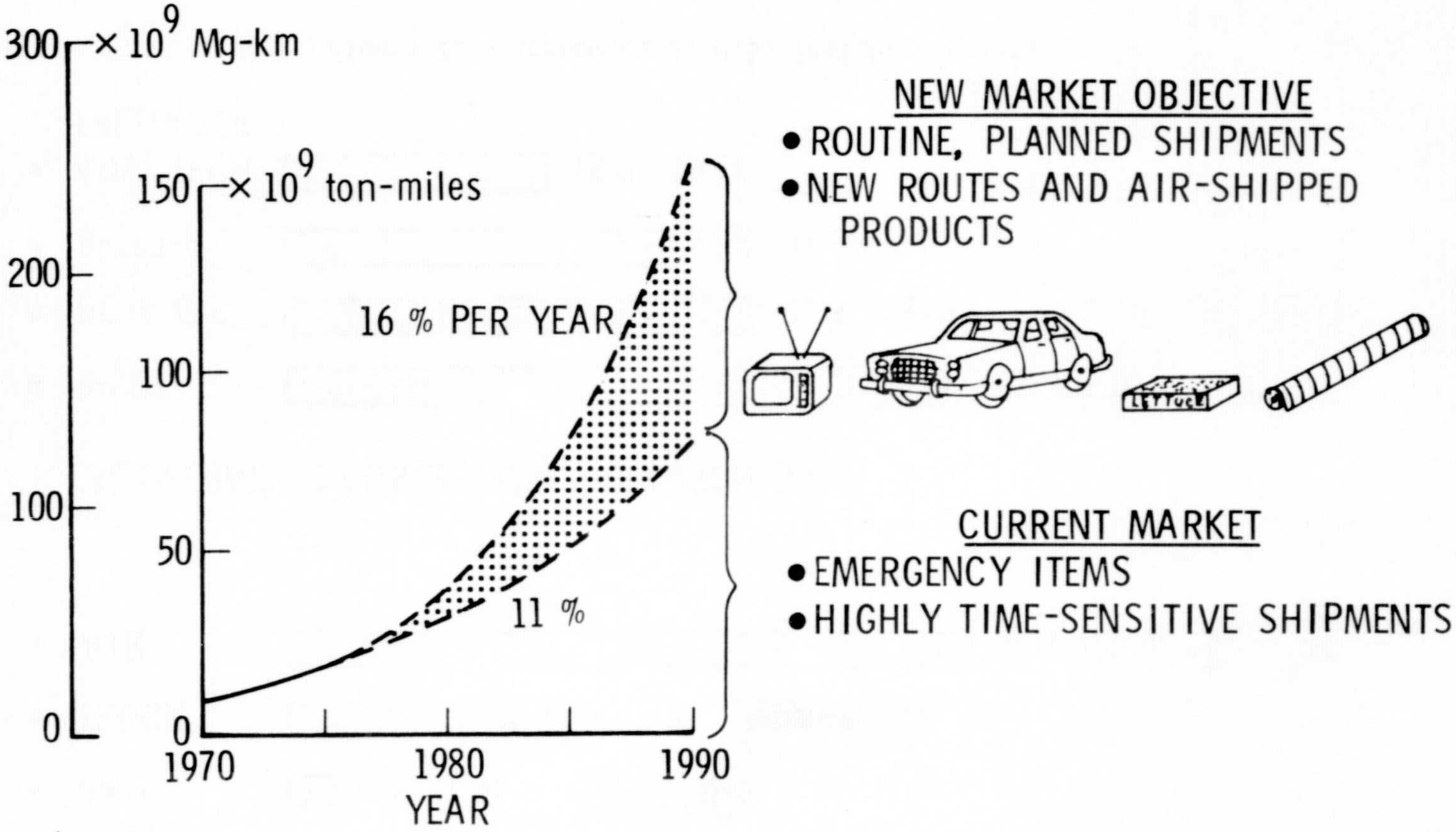


Figure 1. - Growth opportunities in air cargo.

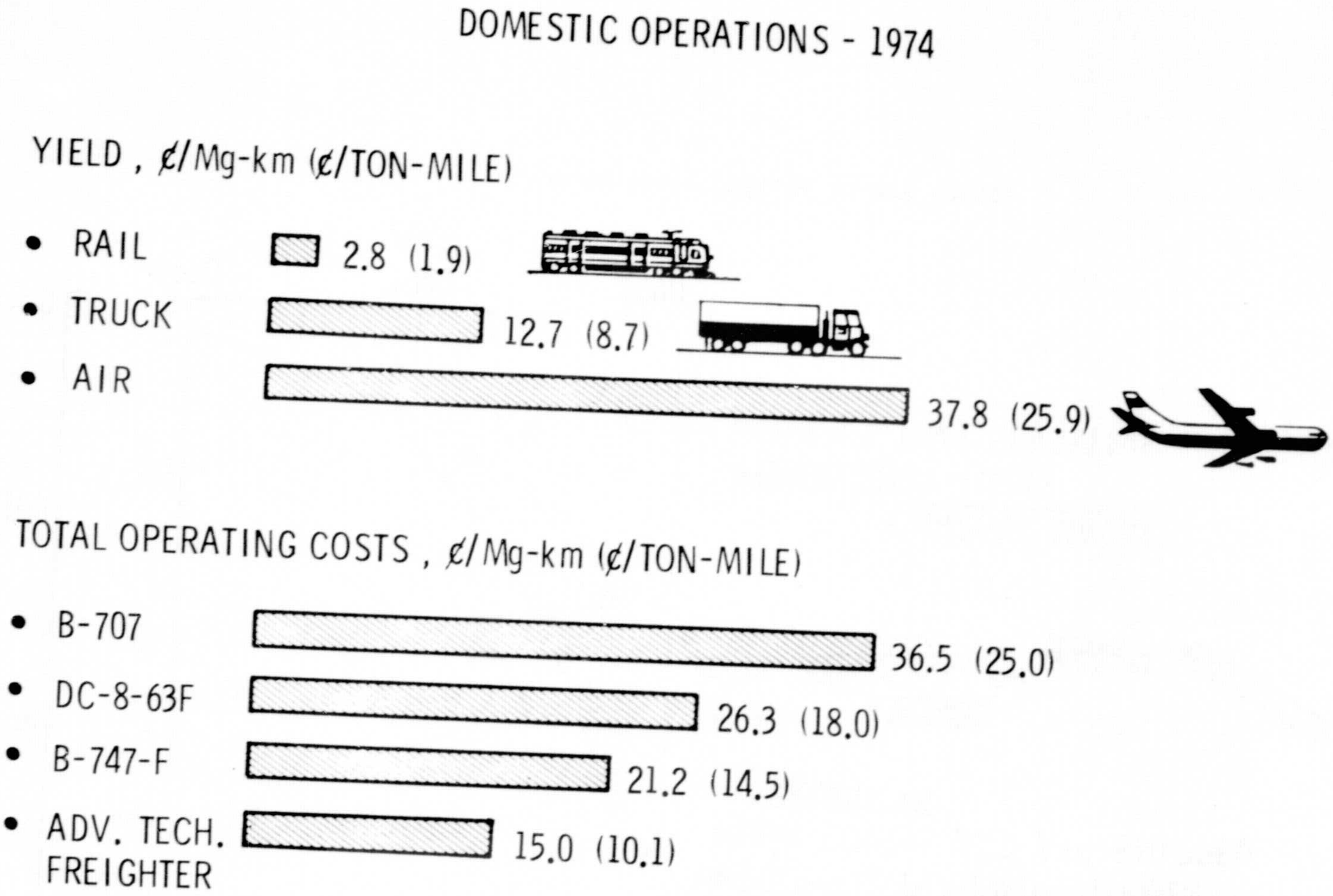


Figure 2. - Economics of U.S. freight carriers.

- WILL THE MARKET SUPPORT THE DEVELOPMENT OF A NEW DEDICATED FREIGHTER BEFORE THE TURN OF THE CENTURY?
- CAN ADDITIONAL AIR MODE GROWTH BE PROMOTED THROUGH THE INTRODUCTION OF AN ADVANCED TECHNOLOGY AIRPLANE?
- WHAT ARE THE CRITICAL TECHNOLOGY REQUIREMENTS?
- WHAT ARE THE OPERATIONAL AND ECONOMIC ADVANTAGES AND DISADVANTAGES OF A COMMON CIVIL/MILITARY AIRCRAFT?
- WHAT DESIGN CRITERIA AND OPERATIONAL CHARACTERISTICS CAN BE DERIVED FROM THE MARKETPLACE?
- WHAT IS THE OVERALL COST AND BENEFIT TO THE NATION FOR AN ADVANCED, INTERMODAL AIR CARGO SYSTEM?

Figure 3.- Issues to be addressed in NASA precursor program

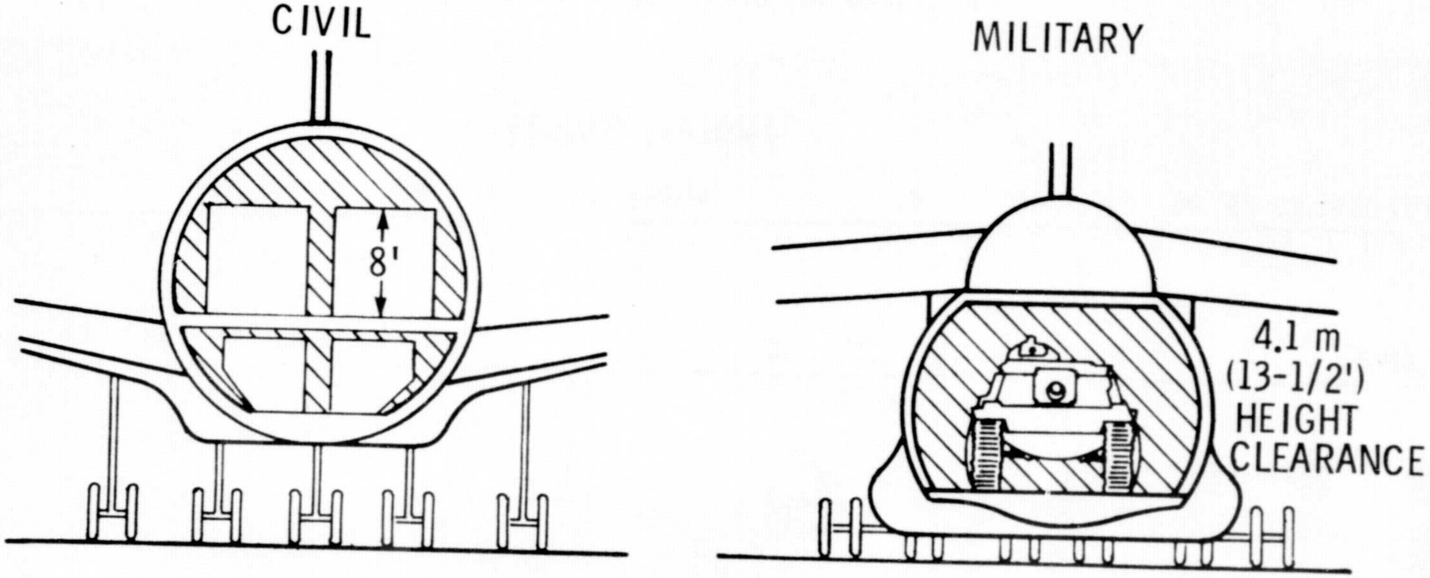
U.S., US-INTERNATIONAL, AND FOREIGN TRADE ANALYSIS

OBJECTIVES

- EVALUATE CURRENT AIR CARGO ENVIRONMENT
- DEVELOP COMMODITY AND NETWORK CHARACTERISTICS AND USER REQUIREMENTS LEADING TO HIGH ELIGIBILITY FOR AIR TRANSPORT
- ASSESS INSTITUTIONAL ISSUES (RATES, DEREGULATION, CURFEWS, ETC.)
- DEVELOP MICRO DATA BASE
- ANALYZE 1990 MARKET POTENTIAL FOR AIR CARGO
- DETERMINE SENSITIVITY OF AIR FREIGHT MODAL SHARES TO IMPROVED AIRCRAFT PERFORMANCE

Figure 4. - Cargo/Logistics Airlift Systems Study (CLASS).

KEY DIFFERENCES IN CURRENT DESIGNS



- LOW WING, HIGH FLOOR (PASSENGER COMMONALITY)
- 8 × 8 AND LD CONTAINERS
- MODERATE FLOOR LOADING
- FIELD LENGTH = 3.7 km (12 000 ft)

- HIGH WING, LOW FLOOR (TRUCK BED LOADING)
- OUTSIZE CARGO
- HEAVY FLOOR SUPPORT
- SHORT FIELD CAPABILITY

Figure 5. - Civil-military design commonality.

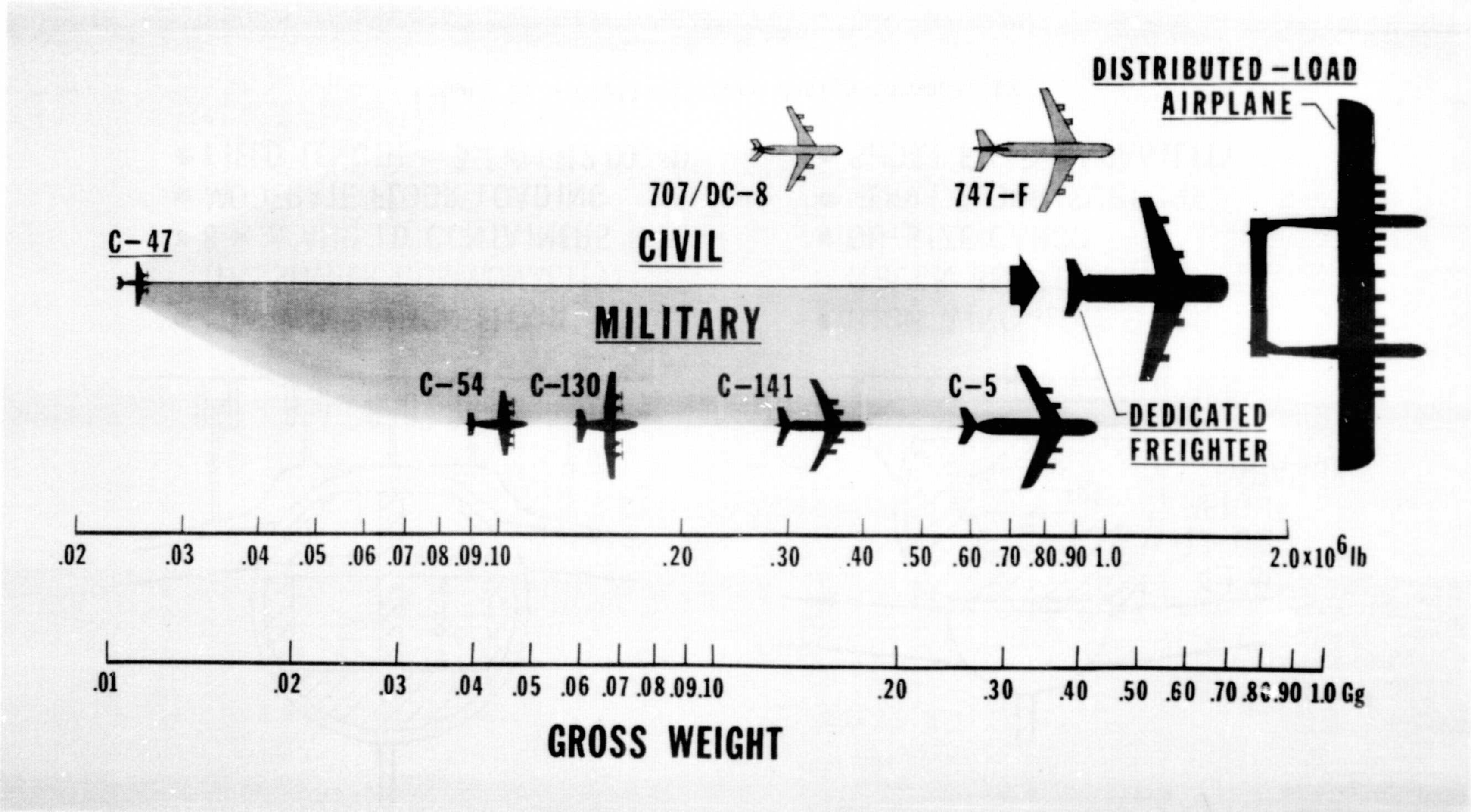
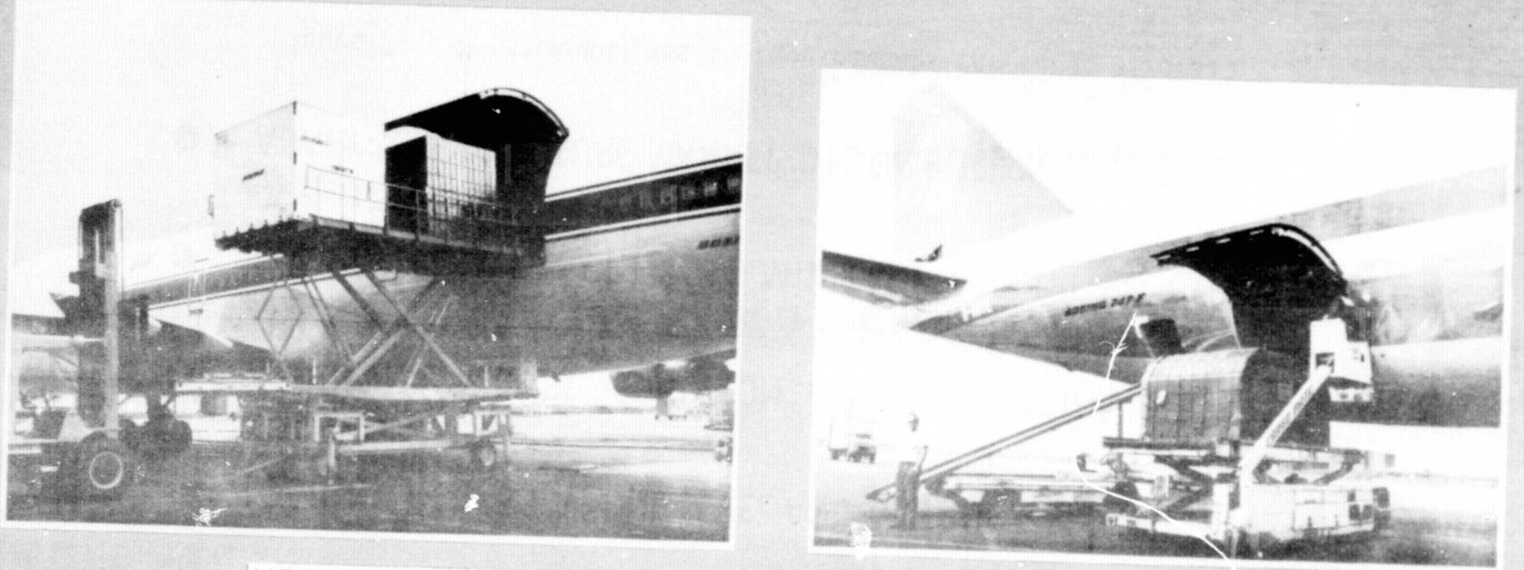


Figure 6. - Air freighter evolution.

- DESIGN FOR PROJECTED FREIGHT DENSITY
- COMPATIBILITY WITH INTERMODAL CONTAINERS
- LOADING ACCESS AT ONE LEVEL AND AT TRUCK BED HEIGHT
- ACQUISITION COST REDUCTION (LOW PRODUCTION RUN)
- COMPATIBLE WITH CRITICAL MILITARY AIRLIFT REQUIREMENTS
- ADAPTABLE TO FUTURE MARKET DISTRIBUTION NETWORK

Figure 7. - Mission and design requirements for cargo aircraft.



UPPER DECK

LOWER DECK

Figure 8. - Current wide-body loading.

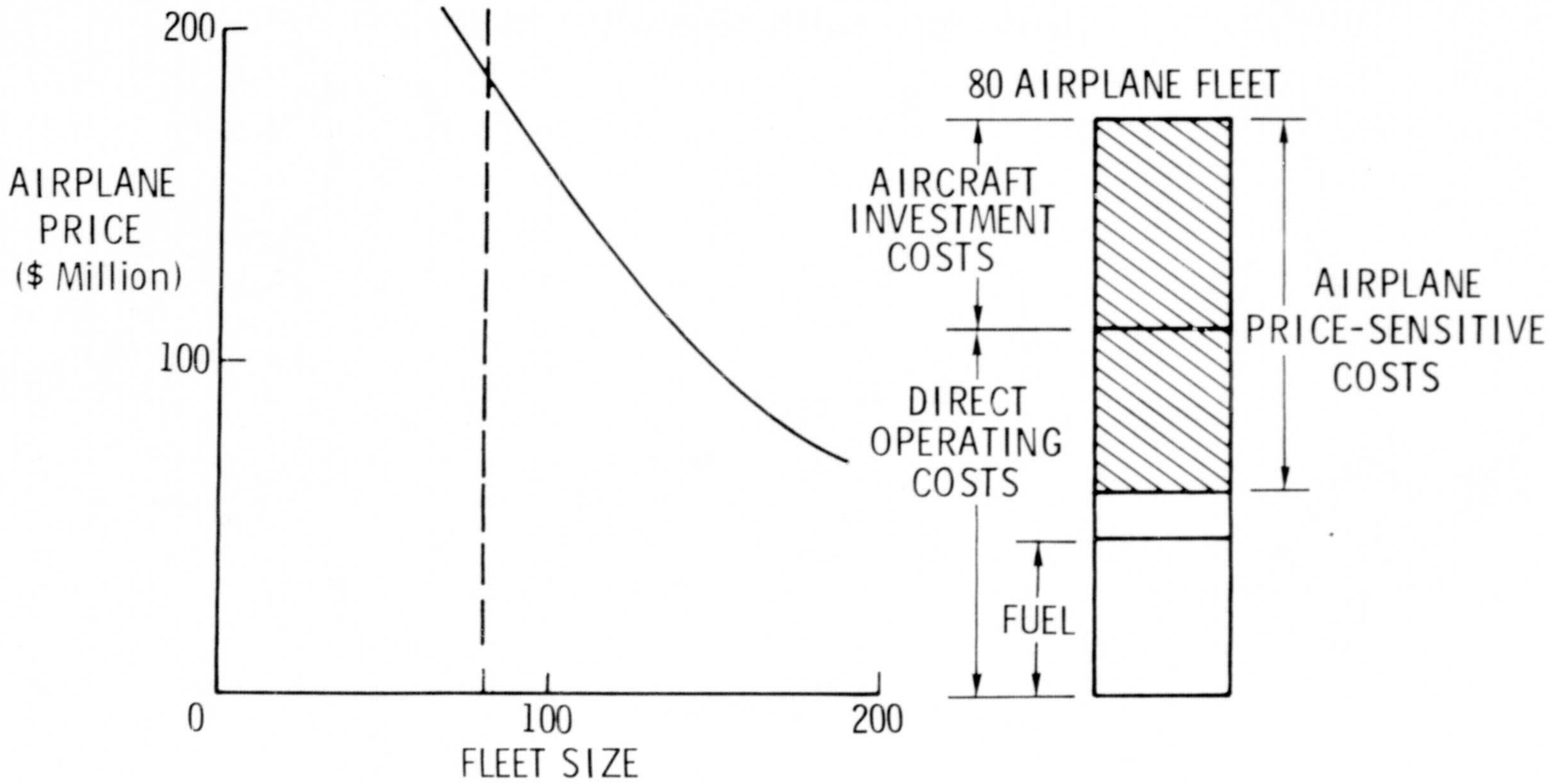


Figure 9. - Impact of airplane acquisition cost.

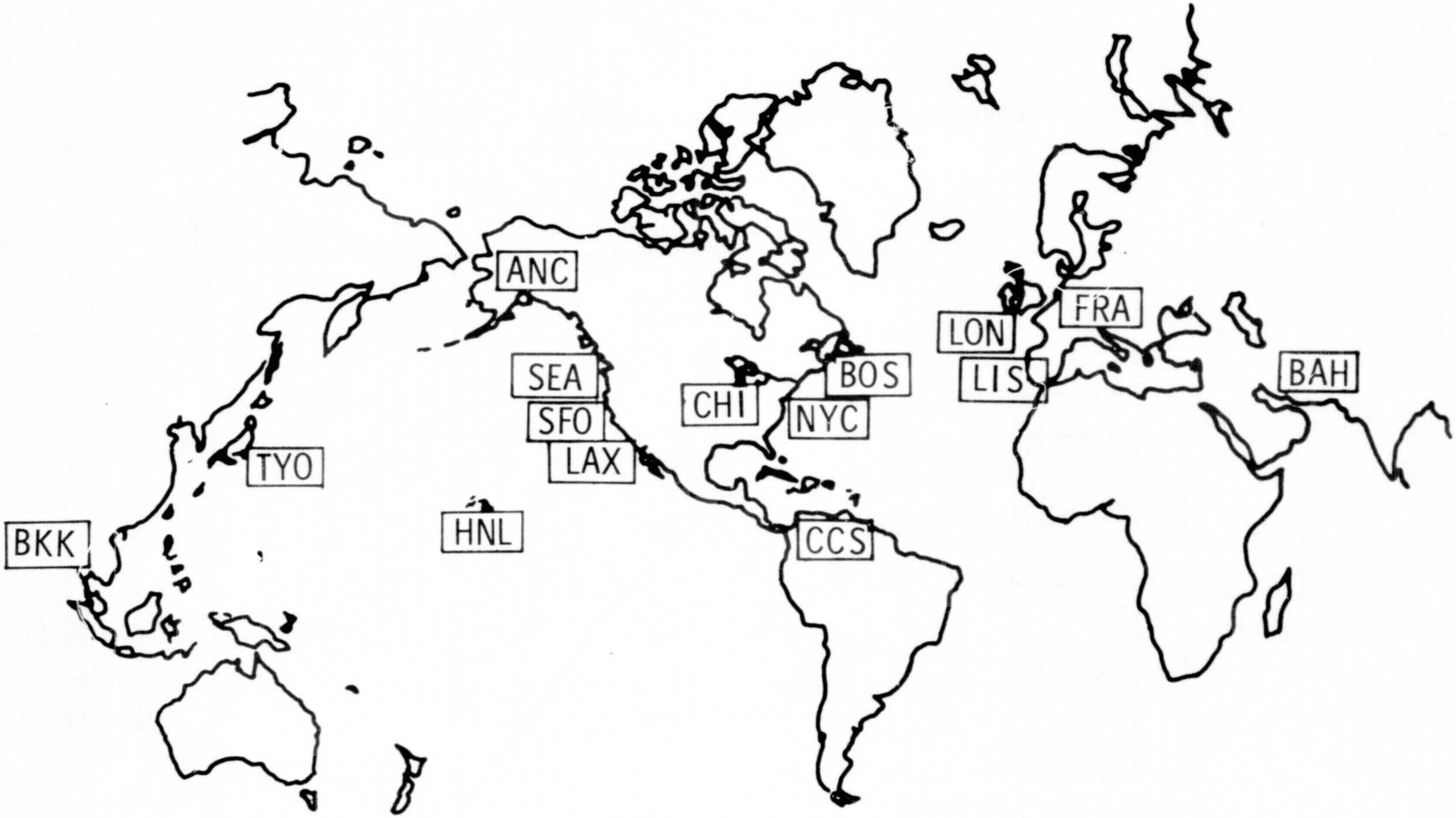


Figure 10. - Airfreight hub-and-spoke concept.

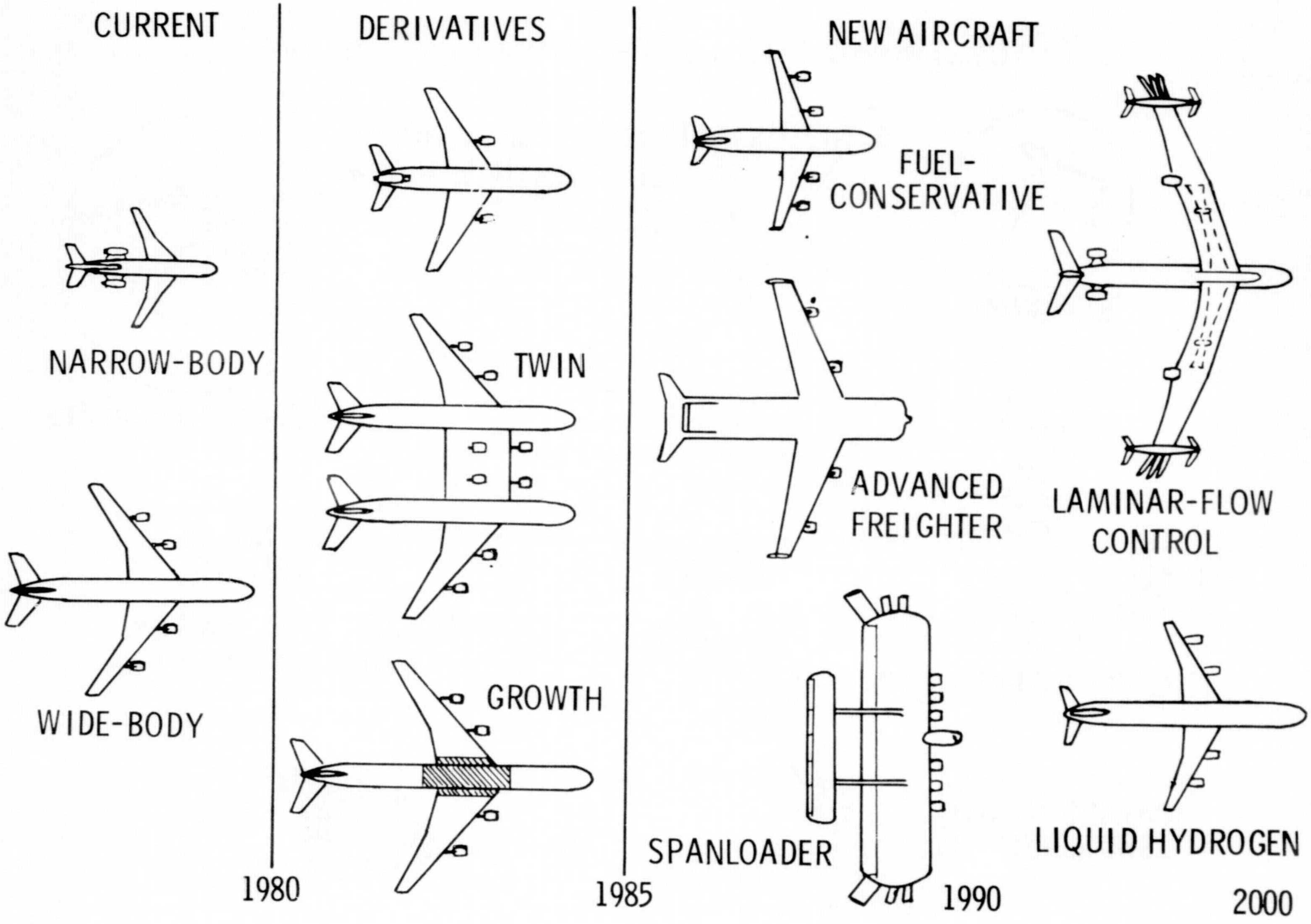


Figure 11. - Subsonic transport aircraft.

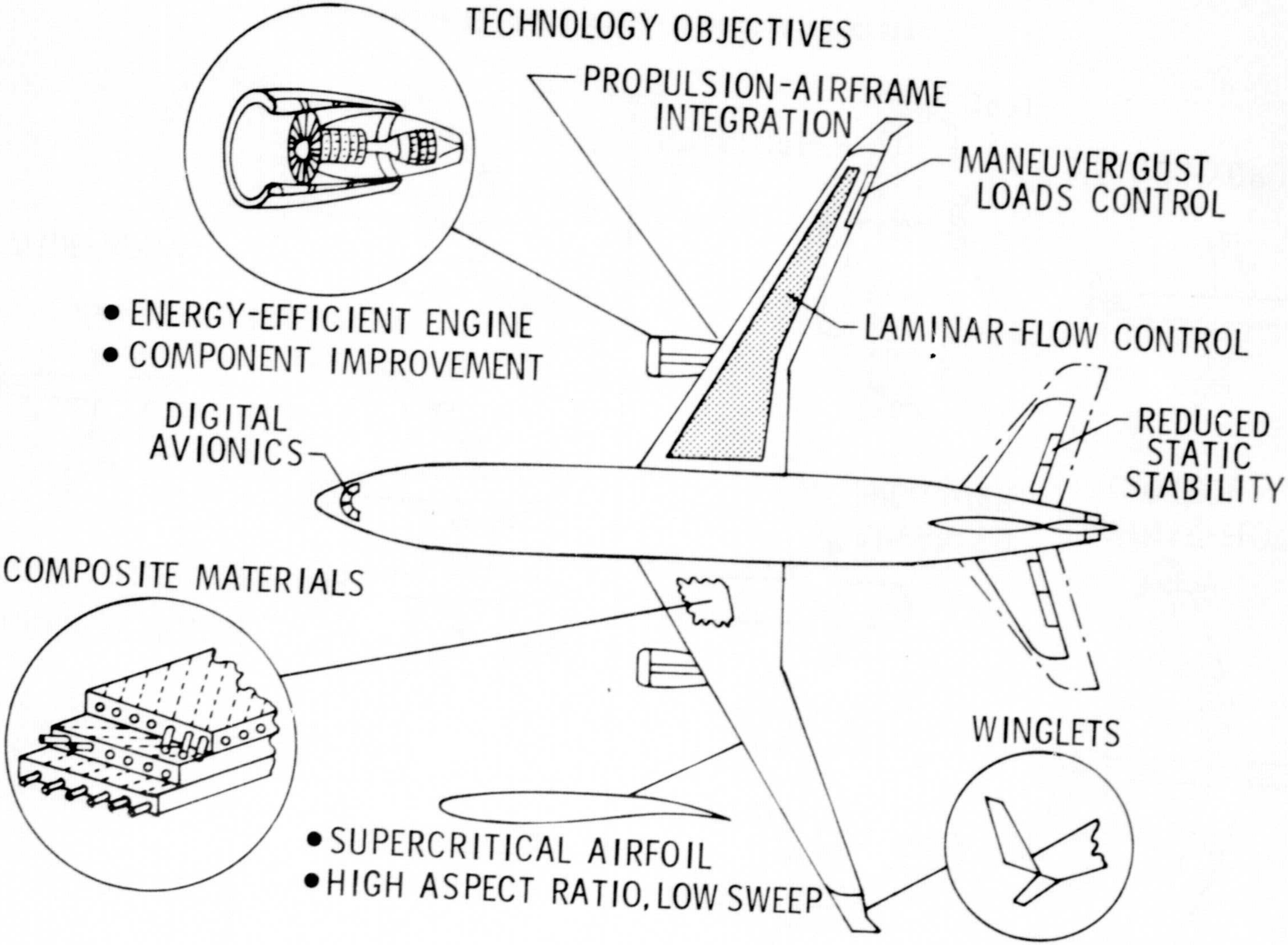


Figure 12. - NASA Aircraft Energy Efficiency Program (ACEE).

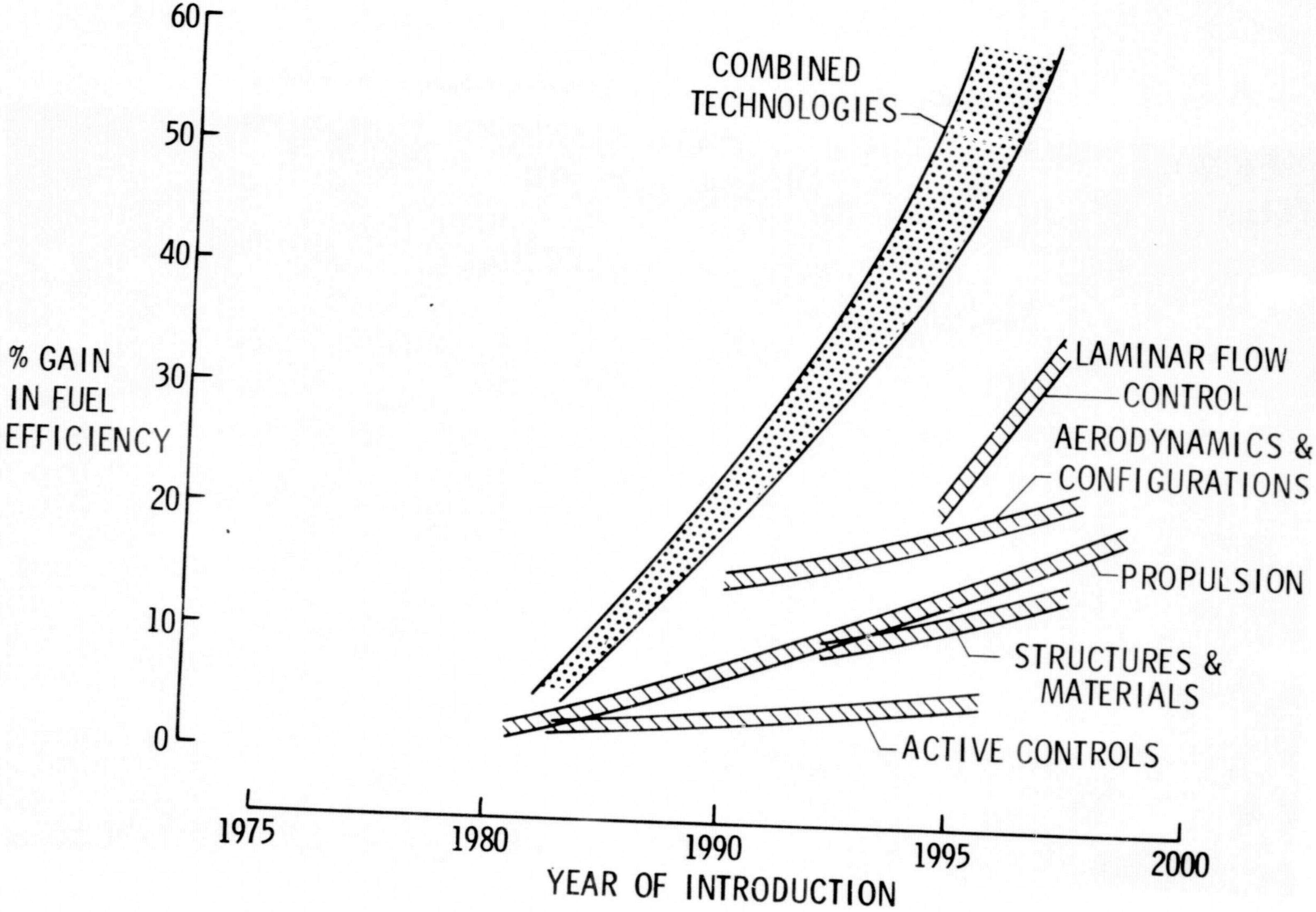


Figure 13. - Fuel efficiency benefits from ACEE technologies.

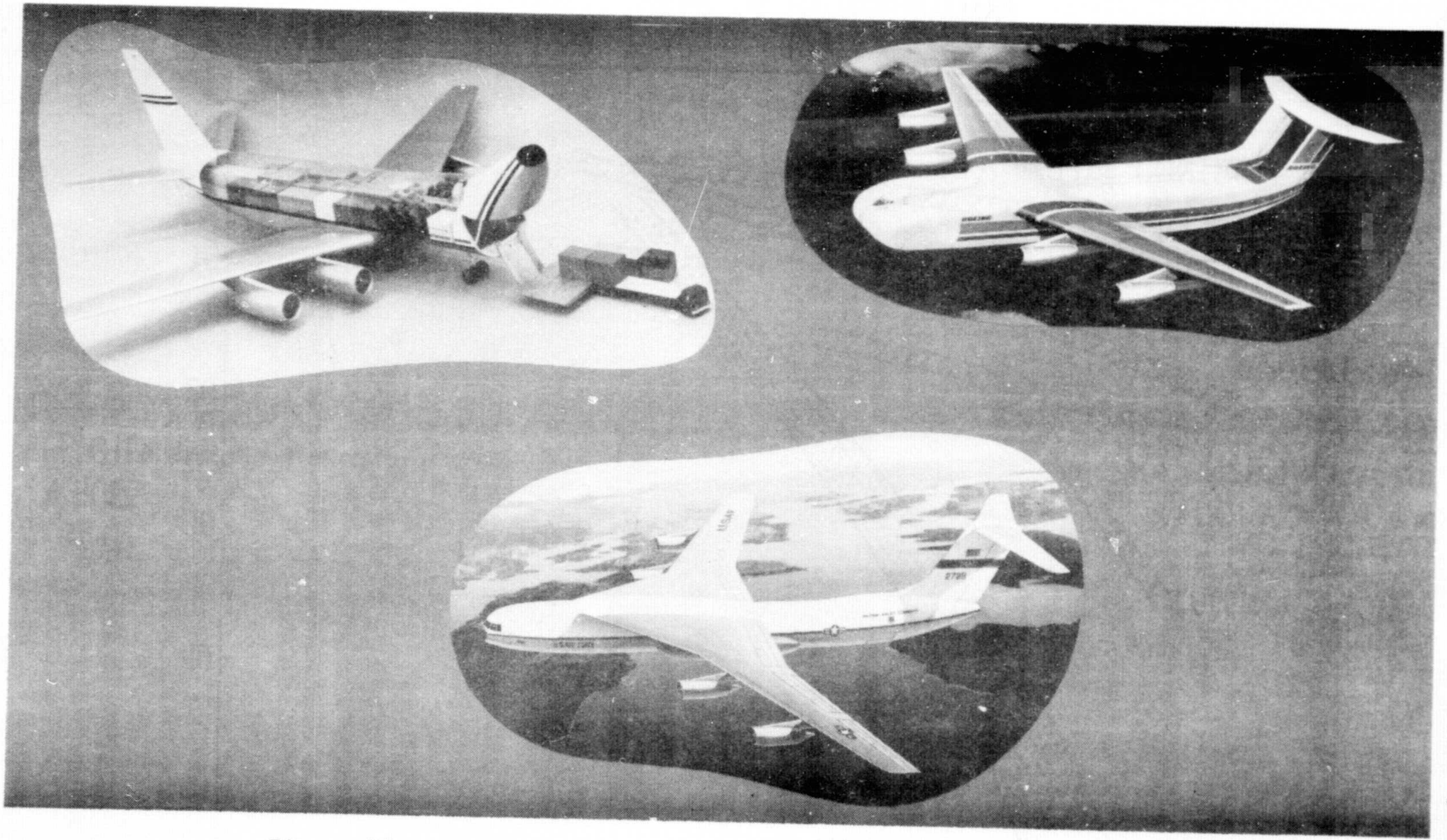


Figure 14. - Industry concepts for 1985 technology freighters.

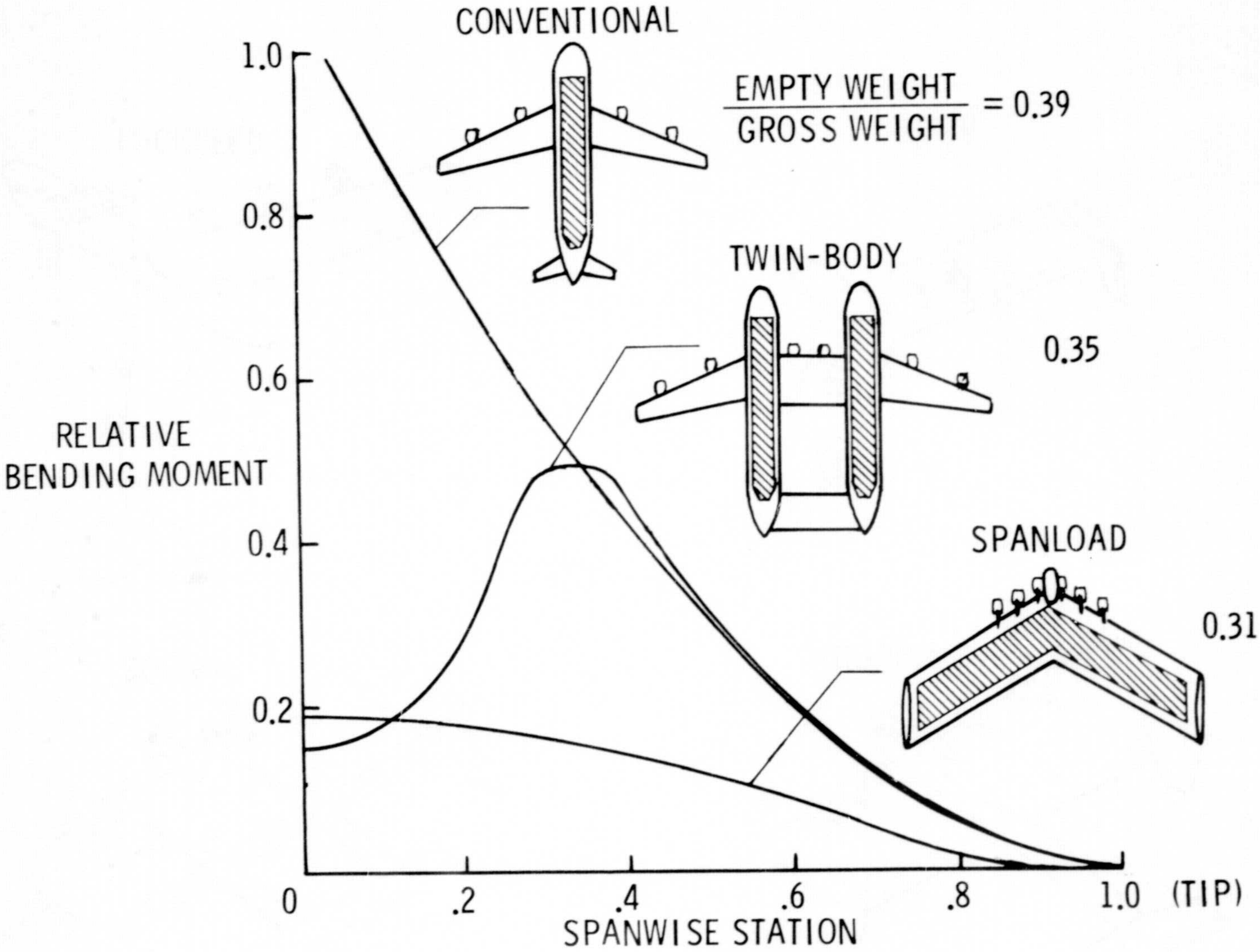
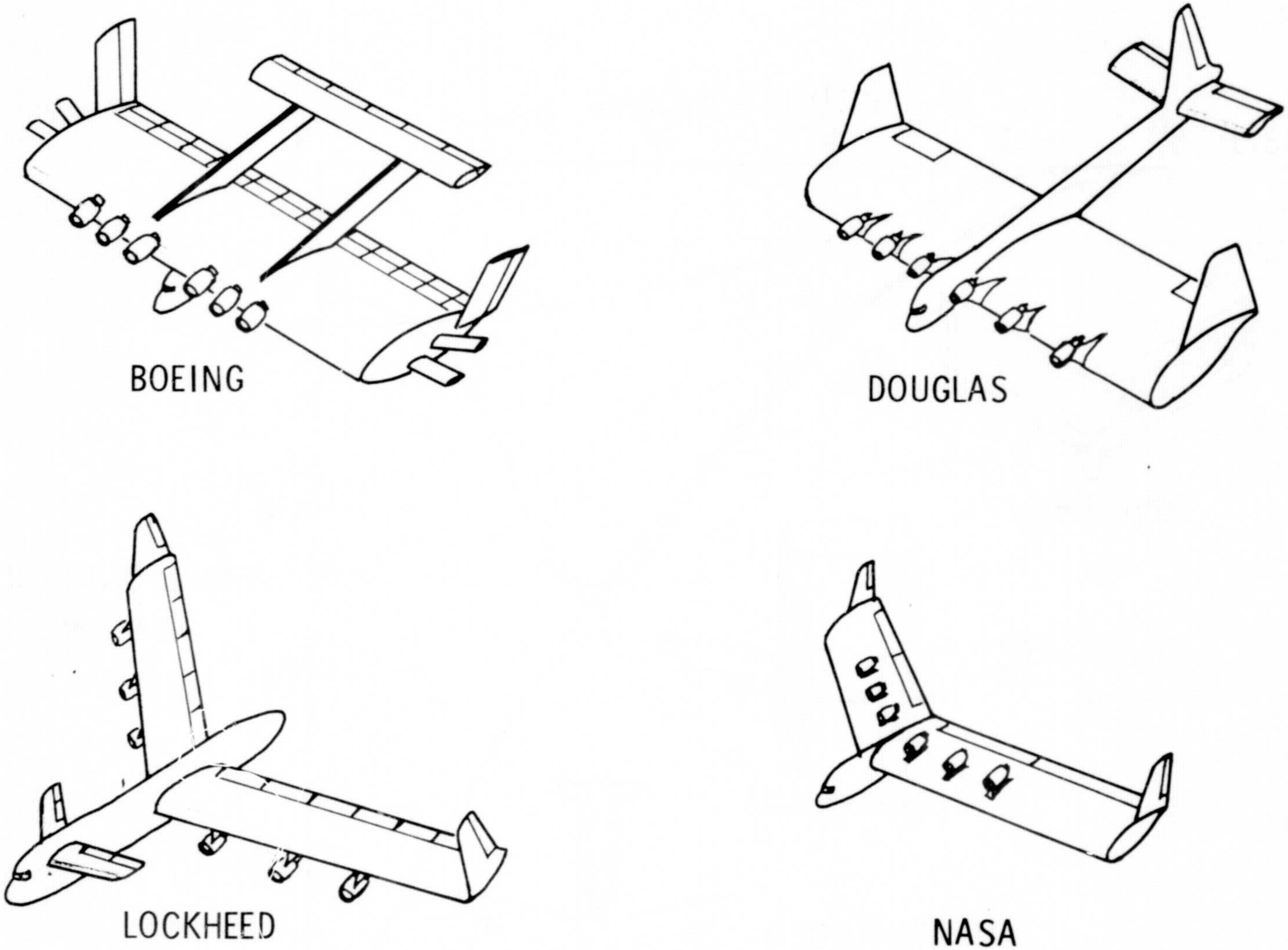


Figure 15.- Advantages of distributed loading for aircraft design



BOEING

DOUGLAS

LOCKHEED

NASA

Figure 16.- Span-distributed load, cargo aircraft concepts

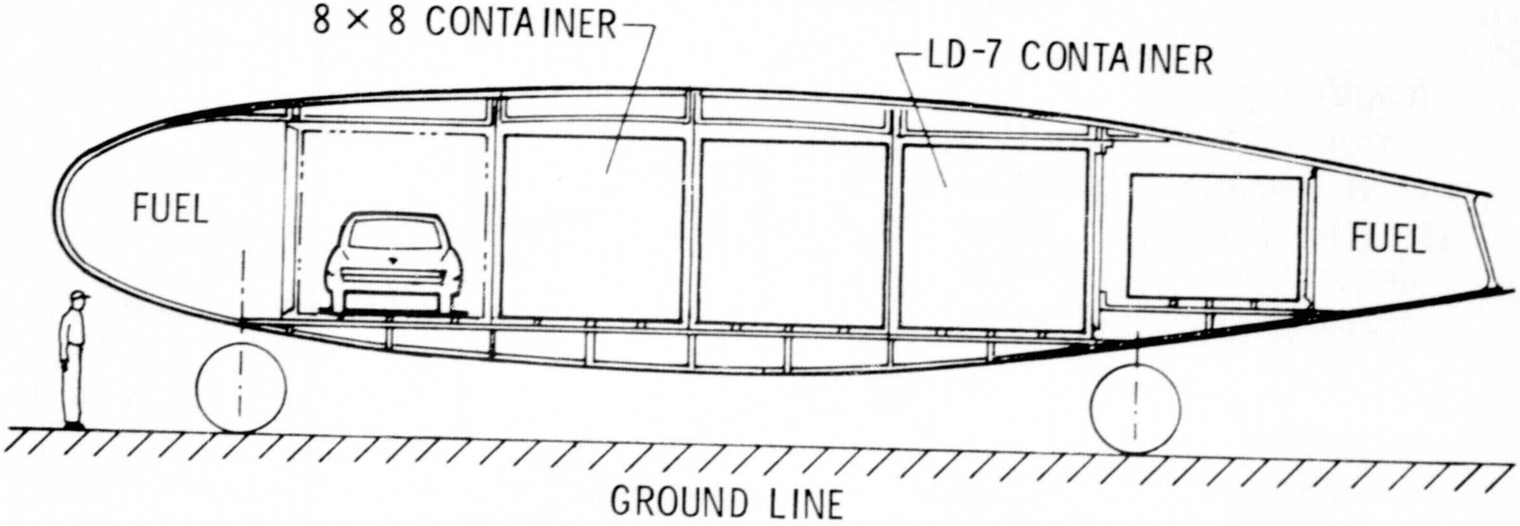


Figure 17. - Wing cross-section of distributed-load freighter.

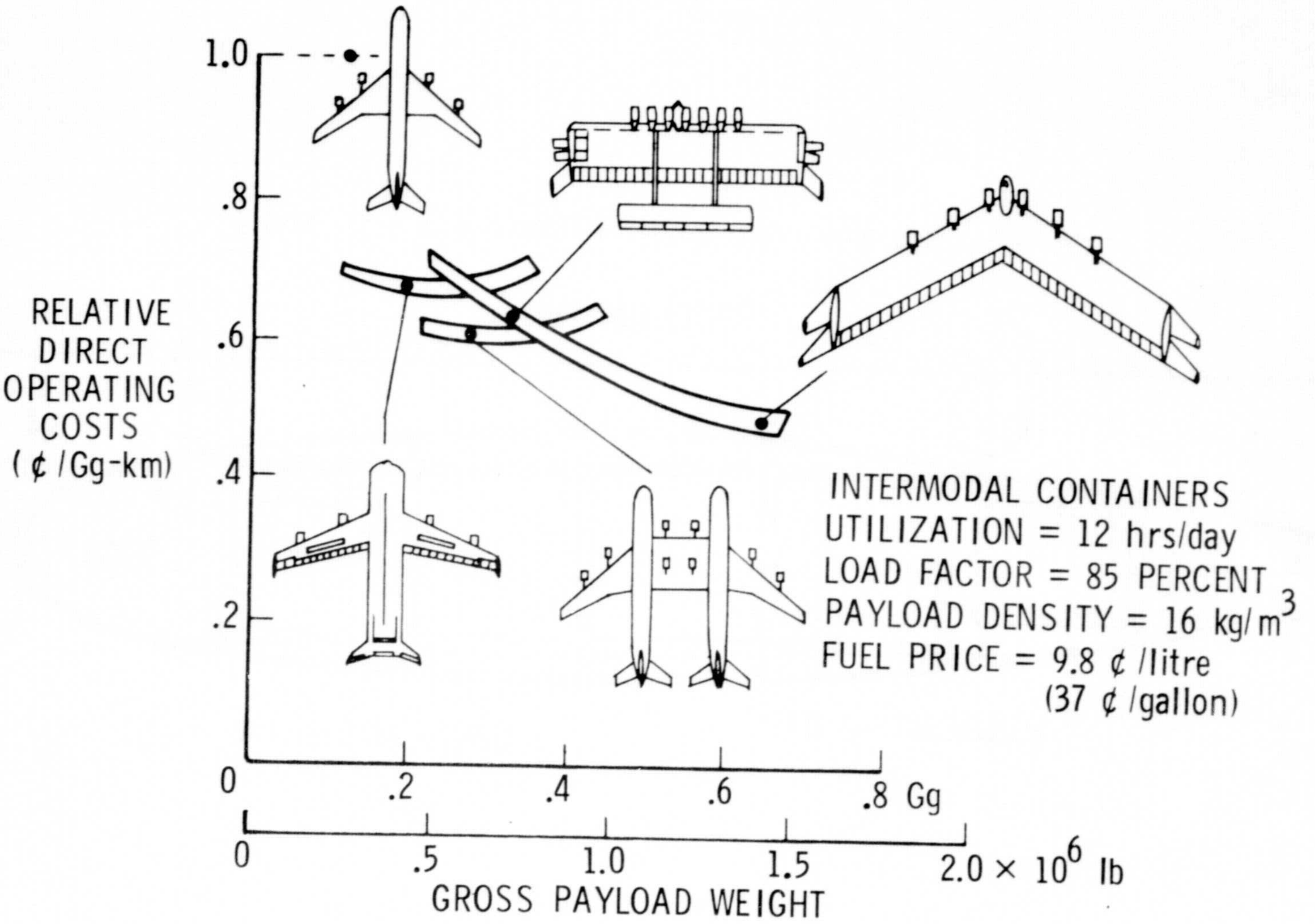


Figure 18. - Economic evaluation of advanced design concepts.

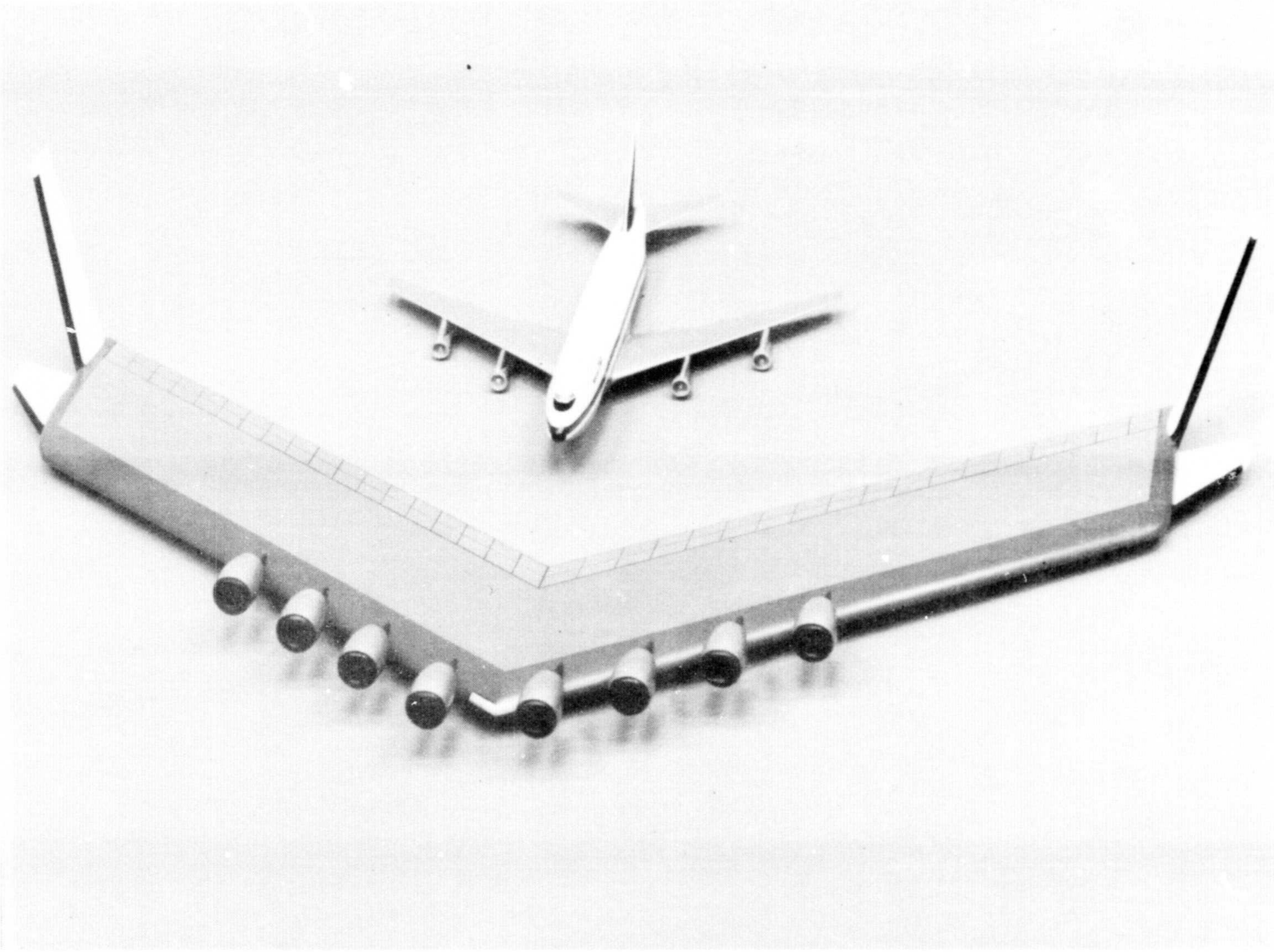


Figure 19. - Comparison of swept-wing spanloader and Boeing 747-F.

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16. Abstract

This paper describes the current air cargo environment and shows the relevance of advanced technology aircraft in enhancing the efficiency of the 1990 air cargo system. Improved utilization of the current system and implementation of regulatory reform are apparently keys to near-term growth. The influence of technology on far-term growth will depend in large part on stabilizing the demand and the establishment of a more substantial minimum level of service.

NASA preliminary design studies are shown to indicate significant potential gains in aircraft efficiency and operational economics for future freighter concepts. Required research and technology elements are outlined to develop a better base for evaluating advanced design concepts. Current studies of the market operation are reviewed which will develop design criteria for a future dedicated cargo transport. Unique design features desirable in an all-freighter design are reviewed.

NASA-sponsored studies of large, distributed-load freighters are reviewed and these designs are compared to current wide-body aircraft. These concepts vary in gross takeoff weight from 0.5 Gg (1 x 10^6 lbs.) to 1.5 Gg (3 x 10^6 lbs.) and are found to exhibit economic advantages over conventional design concepts. However, such large vehicles are not adaptable to today's air transportation system.

17. Key Words (Suggested by Author(s))
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