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SUMMARY

A future requirements and advanced market evaluation study indicates derivatives of current wide-body aircraft, using 1980 advanced technology, would be economically attractive through 2008, but new dedicated airfreighters incorporating 1990 technology, would offer little or no economic incentive. They would be economically attractive for all payload sizes, however, if RD and T costs could be shared in a joint civil/military arrangement. For the 1994-2008 cargo market, option studies indicate Mach 0.7 propfans would be economically attractive in trip cost, aircraft price and airline ROI. Spanloaders would have an even lower price and higher ROI but would have a relatively high trip cost because of aerodynamic inefficiencies. Dedicated airfreighters using propfans at Mach 0.8 cruise, laminar flow control, or cryofuels, would not provide any great economic benefits. Air cushion landing gear configurations are identified as an option for avoiding runway constraints on airport accommodation of very large airfreighters. For all options, significant technology requirements and/or operational constraints are noted.

INTRODUCTION

Options and configurations considered herein for multirole aircraft address all-cargo vehicles suitable for efficient and economical transport in either civil or military service. An aircraft configuration fully suitable for both civil and military use has yet to be defined despite considerable efforts over the past several decades. Incompatibilities have arisen over conflicting demands: civil cargo requires fast, economical movement of low density pallets or containers in regularly scheduled operations between airports having well equipped cargo terminals, whereas military cargo requires large volume airlift of supplies and equipment (some outsize and/or high density) responding to emergencies and operating between airports not always equipped to handle cargo.

*Numbers in parentheses designate References at end of paper

Cargo versions of passenger transports generally have been satisfactory in meeting civil but not military needs. Aircraft configured for military airlift, however, have not proven to be economically viable for civil use. Toward solving this dilemma, effort has been underway for the last several years to arrive at a common design configuration for an all-new cargo aircraft which not only would be economically attractive to the civil sector but also would be suitable for in meeting all military airlift demands.

The economic attractiveness to the civil sector of any all-new (dedicated) cargo aircraft, whether or not it has military commonality, requires consideration of many factors. To provide insight in this area, review will first be made of a recent 30-year outlook study which examined the future requirements and economics of the civil cargo fleet, and included the economic impact of military participation. Several candidate advanced technology options for dedicated cargo aircraft will then be examined in terms of cargo fleet economics plus other considerations including the potential benefits and constraints of configurations, and technology requirements which need to be addressed.

CIVIL FLEET 30-YEAR OUTLOOK

A recently completed study (1)* for NASA by the Douglas Aircraft Company determined the requirements for the world fleet of civil freighter aircraft that would meet the cargo market demand to the year 2008. Identified in that study were economic constraints on future dedicated cargo aircraft which could profoundly affect the introduction of advanced technology. A description of the study and results pertinent to multirole cargo aircraft options and configurations follows.

OUTLOOK STUDY METHODOLOGY - The cargo aircraft fleet mix operational characteristics and economics, for forecast time periods extending between 1978 and 2008 were determined using an existing Douglas simulation program called FRAME (Future Requirements and Advanced Market Evaluation). The FRAME program outlined in detail on figure 1, accepts a cargo system model and related inputs (e.g. cargo

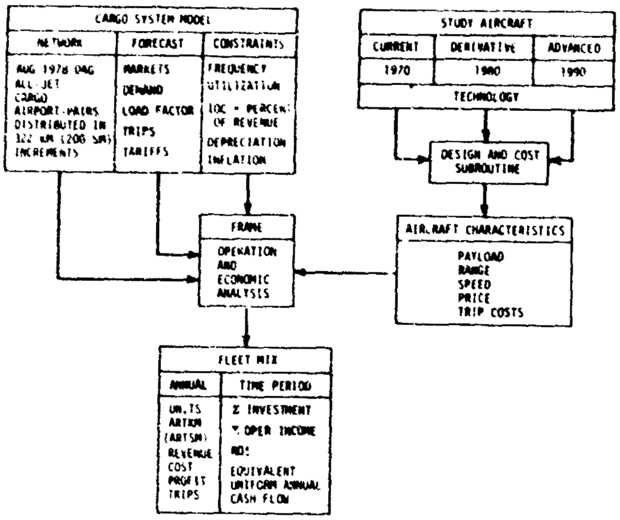

Fig. 1 - Program used in future requirements and market evaluation

market demand growth forecasts) and operational variables (e.g. system network characteristics, constraints). It also accepts aircraft characteristics (e.g. payload, aircraft price). Using this information the program provides annual operational and economic information on the fleet mix of aircraft to satisfy the needs defined by the system model for the time period of concern.

The cargo system model input was developed from a base provided by an historic analysis (from 1967 to 1978) of the air cargo system. For the 431 worldwide airports served by all-cargo operation, city pair data were analyzed to provide a distribution of jet airfreighter type by distance along with the distribution of available throughput capability. Market growth beyond 1978 was based upon forecasts developed during the recent, comprehensive Cargo Logistics Airlift Systems Study (CLASS) (2). It should be noted that account was taken of system-induced growth factors and the changing all-cargo aircraft share of the total market.

Aircraft characteristic inputs to the FRAME program were developed from a base provided by analysis of the the fifteen generic types of jet aircraft currently used for all-cargo operation. Since the types fall into three distinct sizes, averaging the capabilities and characteristics within each size provided three synthesized aircraft to represent current small narrow body, large narrow body, and widebody aircraft, respectively. The capabilities and characteristics of derivative and dedicated future cargo aircraft were also synthesized. The derivative and dedicated aircraft incorporated technology advances expected to be available in 1980 and 1990 respectively. The advances, represented as increments in weight, specific fuel consumption (SFC), lift/drag ratio (L/D), manufacturing cost, and maintenance cost, were estimated to be as follows:

TECHNOLOGY	1980	1990
Structures	-8% Wt -1% Mfgr Cost	-24% Wt. -13.5% Mfgr Cost -2% Maint. Cost
Propulsion	-8% SFC -2% Eng. Wt.	-13% SFC +7% Pro. Cost -5% Maint. Cost +4% Eng. Wt.
Aerodynamics	+4% L/D	+8% L/D +3% L/D
Act. Flt. Contr.	-2.5% Wt.	-5.5% Wt.
Landing Gear	-1% Wt	-1% Wt
Cargo Loading	-	-4% Wt

FLEET MIX AND ECONOMIC OPTIONS - Any number of scenarios, regarding types and timing of new aircraft, can be used in forecasting the future fleet mix. In the Douglas study, the scenario, for the 1978-2008 time period, allowed introduction of advanced technology derivative aircraft in 1984 and of dedicated aircraft in 1994. Thus the fleet mix in 1984 of current-type aircraft was determined, and subsequently competed with new derivative configurations projected to enter the fleet following 1984. The introduction and growth of derivative aircraft, incorporating 1980 technology, were evaluated parametrically to determine effects of aircraft size (from 23 to 181 tonnes) and range (from 3200 to 7000 km). The results defined the 1994 fleet of current and derivative aircraft types to compete with new dedicated freighter aircraft. These new aircraft, utilizing 1990 technology, were evaluated to determine the best dedicated aircraft to meet the market demand. The fleet economics that would result with the preferred mix of the dedicated, derivative and current aircraft were then derived out to the year 2008.

Use of Current Aircraft - A 30-year outlook for the cargo fleet mix is shown in figure 2 in terms of cumulative units of current, derivative and dedicated aircraft. For the current fleet, the small, narrow body aircraft will be replaced by the large narrow bodies, which in turn will be replaced by the widebody types in the mid-1980's. The number of widebody freighter aircraft will increase from the current 35 to about 95 units by 1985.

Derivative Aircraft - 1980 technology incorporated into derivative aircraft were calculated to provide a 20 percent reduction in trip cost and a 15 percent reduction in the price of an aircraft comparable to current widebodies. Derivative aircraft are shown in figure 2 to have a 150-tonne payload, which would provide the best return on investment (ROI) to the airlines. Reduction in aircraft size to a 91 tonne payload, however, would reduce ROI by only one percent. With regard to aircraft range, development of a short and long range combination of a 150 tonne derivative would be economically preferred, giving a four percent increase in airline ROI and a 20 percent decrease in investment relative to the reference fleet of current aircraft. There would be little economic penalty, however, in developing only a medium range derivative. The number of airfreighters would total 325 by 1995 with 250 being 150-tonne derivative aircraft; however, the current widebodies would remain competitive over progressively decreasing operating ranges. Considering the several designs of widebody aircraft currently in the market, it is quite likely that more than one of the manufacturers will offer future derivatives modified for cargo operations.

Dedicated Aircraft - The study assumed that the dedicated freighter would not be modified for passenger operations. In view of the limited market for such dedicated aircraft, the economic analysis was performed on the basis of a ROI to the manufacturer of 15 percent.

With 1990 technology, the price of a 95-tonne dedicated freighter would be 45 percent less than for a comparable current widebody, when viewed in 1994 dollars. The 150-tonne size shown for the dedicated freighter on figure 2 is not quite optimum with regard to economics but may be more attractive from other considerations (e.g. airport congestion) than would be the 68-tonne size which had the best airline ROI.

The economics of the 68 and 150-tonne aircraft were calculated on the basis of two manufacturers (which will be the more likely situation), as well as for one manufacturer:

PAYLOAD A/C TYPE	68-TONNE DEDICATED		150-TONNE DEDICATED		150-TONNE DERIVATIVE
Number of Aircraft	1253		573		573
Mfgrs.	1	2	1	2	2
ROI, %	25	22	24	21	21
Fleet $, Billions	93	111	101	124	113

For two manufacturers producing a total of 573 150-tonne aircraft to supply the free world civil market demand from 1994 to 2008, airline ROI would be 1 percent less and the total investment would be 13 billion dollars more than for 68 tonne aircraft. Values of ROI are higher than normal. In actual practice, the tariff probably would be reduced (from that assumed in the study) to stimulate the market while still providing the airline a reasonable ROI. For example, an average annual tariff reduction of 1.6 per cent would reduce airline ROI from 21 to 15 percent and produce a potential 2 percent additional annual growth in market demand.

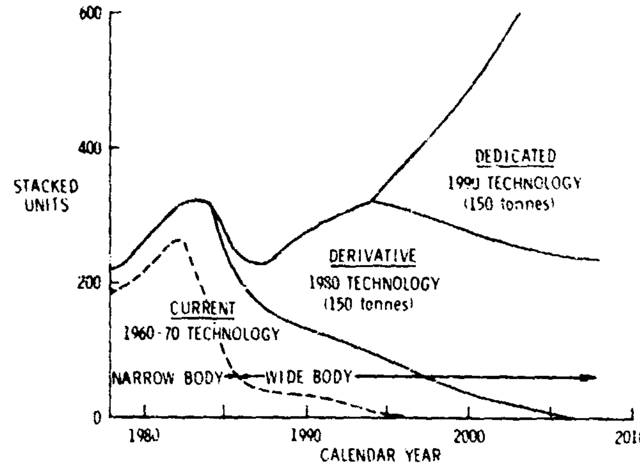

Fig. 2 - 30-year outlook for large fleet mix

Of particular interest is the economics for the 150 tonne derivative aircraft if used to meet the 1994-2008 market demand. About 250 derivative aircraft were presumed to have been built before 1994. Comparison with the dedicated aircraft indicates the derivative aircraft fleet would cost 11 billion dollars less and provide the identical ROI to the airline despite being heavier, and having inferior aerodynamics and a greater specific fuel consumption. Analysis indicates that the significantly lower aircraft price for the derivative aircraft negates the economic benefits of the 1990 technology in the dedicated aircraft. Clearly, manufacturers would be reluctant to initiate development of a new dedicated freighter to be operational in the mid 1990's unless there is some additional stimulus, possibly from the civil passenger or military airlift sectors.

MILITARY PARTICIPATION - The study analyzed program subsidy as a possible approach to stimulating the development and introduction of an advanced dedicated airfreighter. Subsidy, which could take various forms, in this instance consisted of military participation in a dedicated cargo aircraft development and production program.

The analysis postulated that military participation would occur in a single program directed at the development of an advanced long-range type vehicle; that two manufacturer's would address the 1994-2008 market, but only one would produce the military units; that the military would provide one-half of the required research, development and test funding and would subsequently purchase aircraft equal to 25 percent of the U.S. domestic and international fleet buys; and that manufacturers return on investment would be 15 percent. It was further postulated that military requirements would impose no penalties (e.g. payload, performance) on the aircraft.

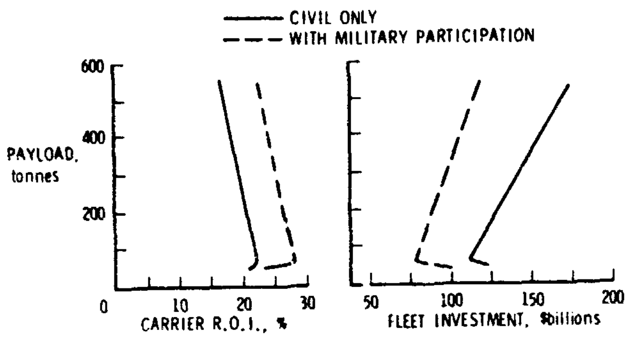

Fig. 3 - Economic impact of military participation

Figure 3 presents the effects of military participation on carrier ROI and fleet investment for various aircraft payloads. Military participation would make a dramatic improvement in the economic attractiveness of dedicated freighter aircraft. ROI would be increased by about 5.5 percent and fleet investment would be reduced by about 30 percent. Very large payload aircraft would become economically feasible. Latitude in the economics might even be sufficient to allow a slight degradation in weight and/or performance due to addition of aircraft features to better accommodate military payloads.

TECHNOLOGY OPTIONS AND CONFIGURATIONS

The civil fleet 30-year outlook has been examined regarding conventionally configured derivative and dedicated aircraft which incorporate advanced technology. Somewhat less conventional configurations and technology options also are candidates for use in multirole cargo design. Several such options will be discussed and evaluated from both economic and non-economic considerations.

LAMINAR FLOW CONTROL - Laminar flow-control (LFC) is a technology for reducing airplane drag by maintaining laminar boundary layers. The drag of a fully laminarized airfoil is almost ten times smaller than that of a modern turbulent flow airfoil. Potentially, LFC could be applied to any surface exposed to the airstream (e.g. wing, fuselage, empennage). Laminarization is accomplished by sucking a small amount of the external boundary layer through the skin. An LFC system thus requires a perforated or slotted skin on a rather sophisticated structure incorporating internal ducting, and a compressor to expel the sucked air.

Example Configuration - The 30-year outlook study examined the application of LFC to a conventionally configured, turbofan powered airfreighter of 150-tonne payload capacity designed to cruise at a Mach number of 0.85. Suction was applied over the forward 85 percent chord of the wing upper surface in combination with a 15-percent trailing edge flap. Using information from their USAF-sponsored New Strategic Airlift Concepts (NSAC) study (3), the incremental changes in aircraft parameters from a reference 150-tonne dedicated conventional airfreighter were estimated by Douglas to be:

Structural Weight:	+6.5%
Engine Weight:	+2%
Lift/Drag-cruise:	+22%
C_L at Takeoff:	-13%
Specific Fuel Consumption:	+2%
Wing Area:	+8%
Aircraft Manufacturing Cost:	+4%
Aircraft Maintenance Cost:	+10%

The absence of high-lift leading and trailing edge devices resulted in a decreased takeoff lift coefficient. The increase in specific fuel consumption and engine weight were due to the power units required for the structural system.

Economic Analysis - The economic study of the example LFC aircraft was carried out on the same basis as for the long range (7000 km) dedicated aircraft produced by two manufacturers, (without military participation) and addressed the civil market demand from 1994 to 2008. Fuel price was assumed as $1.81 in 1994, increasing 9 percent per year through 2008. Results of the economics study were as follows:

Aircraft:	Reference	LFC
Trip Cost at Design Range per tonne of payload	$513	$460
Aircraft Price per tonne of payload, $'s 1994	$975,000	$1,049,000
Airline ROI, percent	21.0	20.7
Fleet Investment billions	124	130

The results indicate use of LFC would reduce trip cost by ten percent, increase aircraft price by 6.5 percent, reduce ROI by 0.3 percent and increase fleet investment by 4.5 percent.

Economic Update - The above results may be somewhat pessimistic as the changes cited were based on the state of the art as it appeared to Douglas in October 1978 during their ongoing LFC studies carried out as part of the NASA Aircraft Energy Efficiency (ACEE) program. Continuation of these extensive studies in LFC technology and system concepts has reduced uncertainties in several areas. In a recent Douglas analysis under the ACEE program, 85-percent chord, upper surface LFC was applied to a 300-passenger (31-tonne payload) transport aircraft design having a range of 9250 km, a cruise Mach number of 0.80 and utilizing technology compatible with a 1990-1995 operational time period. Incremental changes from a baseline reference design were estimated and the values for selected parameters are listed below together with those of the 1978 example configuration:

Aircraft Config:	1978 Example	1979 ACEE
Structural Weight	+6.5%	
		+2.5%
Engine Weight	+2%	
Lift/Drag	+22%	+27%
Wing Area	+8%	+11%
Airc. Mfgrg. Cost	+4%	+2.1%
Airc. Maint. Cost	+10%	+3.4%

While direct one-to-one comparisons are not possible because of different aircraft design conditions, improvements are evident in the economically critical areas of weight, manufacturing cost and maintenance cost.

Possible Constraints - The achievement of LFC is significantly influenced by aircraft configuration and operations. As the Reynolds number increases, laminarization becomes increasingly difficult to achieve and surface smoothness constraints become more severe. Wing sweep also increases the difficulty, because of destabilizing pressure gradients arising from unstable cross flow produced within the boundary layer. Disturbances from engine noise must also be minimized.

From an operational standpoint, contamination of LFC surfaces must be either avoided or controlled to maintain laminarization. Insect spatter, debris and ice can roughen the surface and also clog the pores or slots in the surface. While contamination control (e.g. spray nozzles) must be incorporated for protecting and cleaning the surface, maintaining LFC would be more difficult during operations where insects, dust, or debris are present in quantity, and during cruise through rain or ice crystal clouds.

From the foregoing discussion, fully applying LFC would be more difficult for aircraft having either highly swept or very long chord wings, or for those required to operate from unprepared airstrips (e.g. military supply of forward bases). Conversely a potentially attractive LFC airplane would be one that has a high aspect ratio, short chord wing and operates over a long range at high altitude. Such an airplane concept, shown in figure 4, has been evolved over a period of many years by Dr. Werner Pfenninger, who is well known for his work on LFC. The wing is braced with struts (laminarized) to achieve a very high aspect ratio (16.3 for this particular configuration). Engines are strategically located to reduce noise disturbances to the boundary layer. More details about this concept and its characteristics can be obtained from (4).

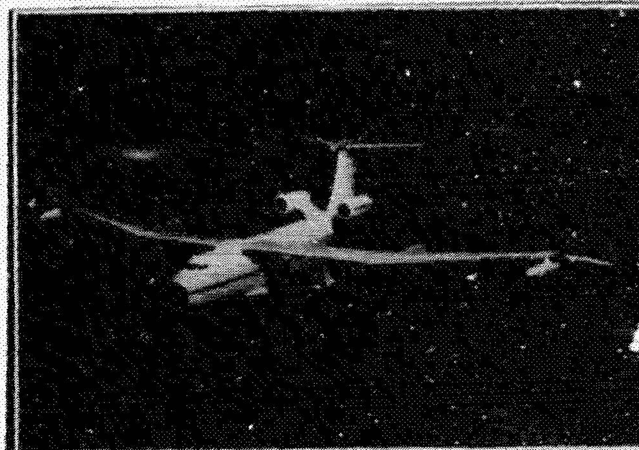

Fig. 4 - Long range aircraft concept utilizing laminar flow control

Technology Status and Requirements - Significant technology has recently been generated for designing practical configurations for LFC aircraft. For example, ACEE-sponsored studies indicate use of LFC on only the wing upper surface will achieve nearly all of the aerodynamic benefits as laminarizing both surfaces while making possible: effective installation of a leading edge Krueger flap to provide both high lift and protection of the LFC surface from insect strikes during terminal area operations, reduced maintenance (e.g. no fuel leakage into LFC panel, less foreign object damage), lower LFC weight penalty; and easier access to subsystems in the wing. Experiments have also indicated that environmental contamination, which decreases the porosity of LFC surfaces, can be removed effectively by in situ steam cleaning with no cumulative degradation of porosity.

Many technology gaps remain which need to be filled. In aerodynamics, information is needed to define appropriate LFC configurations, including airfoil shape, for various wing planforms and range of Reynolds numbers. In powerplants, methodology is needed to define locations and configurations which will not adversely affect laminarization. More research is required in materials, structures and structural fabrication of the LFC surfaces, and in the environmental systems and suction system. Flight test experience is needed for LFC systems and surface cleaning systems. Once solutions to the various problem areas are obtained on an individual basis, an all-new LFC wing with integrated subsystems needs to be built, installed on an aircraft, flight tested and then put into long term service to obtain operational data under real-world conditions.

ADVANCED PROPELLERS - Increasing problems in fuel prices and supply have stimulated reexamination of propellers - not the 1950's version, but a new, highly-loaded, turboprop (propfan) shown in figure 5 which uses advanced blade structure and aerodynamics technology for efficient, high speed operation. Based on analysis verified by wind tunnel studies (5), the propulsive efficiency of the isolated (uninstalled) propfan shows about a 20 percent improvement at Mach 0.8 and a 35 percent improvement at Mach 0.7, when compared to a high bypass ratio turbofan.

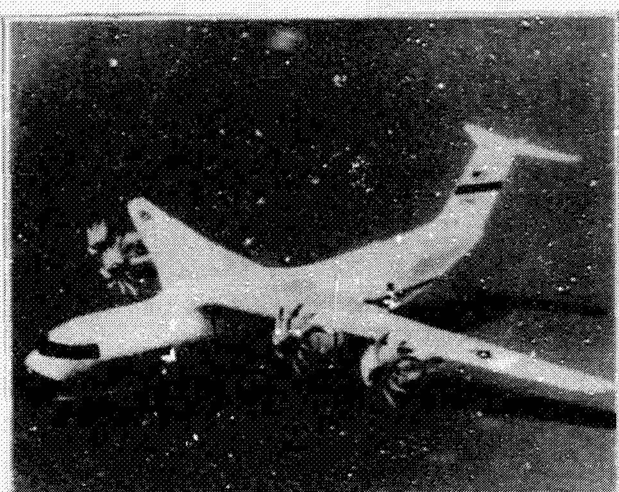

Fig. 5 - Advanced propfans applied to airfreighter

Example Configurations - The 30-year outlook study examined application of propfans to two conventionally configured airfreighters of of 150-tonne payload capacity designed to cruise at Mach numbers of 0.7 and 0.8 respectively. Based on information from the USAF-NSAC study (3), the incremental changes in aircraft parameters from a reference 150-tonne dedicated, conventionally-configured, Mach 0.85 airfreighter were estimated by Douglas to be:

Design M.	0.7	0.8
Structural Wt.	-26%	-4%
Propul. Wt.	+103%	+112%
Nacelle Wt.	-11%	-7%
Spec. Fuel Cons.	-30%	-20%
Lift/Drag-cruise	-6%	-10%
Wing Area	-14%	-10%
Propul. Cost	+29%	+29%

Propulsion weight and propulsion manufacturing costs include the engines, gear boxes and propellers. While the propfan has adv ntages over the reference aircraft in the areas of structural weight and specific fuel consumption particularly for the Mach 0.7 configuration, penalties are incurred due to reduced lift-to-drag ratio and increased propulsive system weight and cost.

Economic Analysis - The economic study of the Mach 0.7 and 0.8 propfan aircraft, carried out on the same basis as for the long range (7000 km) dedicated aircraft produced by two manufacturers and addressing the civil market demand from 1994 to 2008, provided the following results:

Aircraft:	Dedicated M 0.85	Propfan M 0.7	Propfan M 0.8
Trip Cost at Design Range per tonne of payload	$510	$467	$523
Aircraft Price per tonne of payload, $'s 1994	$986,000	$795,000	$1,000,000
Airline Return on Investment	21%	22.1%	19.7%

The design cruise Mach number is a powerful factor in propfan aircraft economics. Compared to the reference aircraft, both aircraft price and airline ROI are significantly better for the Mach 0.7 aircraft but slightly worse for the Mach 0.8 propfan aircraft. A key parameter is specific fuel consumption, with the 10 percent extra saving in SFC at the lower Mach number being critically important to the economic viability of propfans.

Possible Contraints - The results of the above analysis indicate that economic considerations could well limit the cruise speed of propfans to values below those of current transports, which cruise at 0.8 to 0.85 Mach number. The airways are now keyed to the higher speed and the entrance of a M = 0.7 aircraft on prime routes may result in some difficulties. The advent of more sophisticated 4-D air traffic control should, however, ease the problem of safely and efficiently integrating mixed-speed traffic.

A second constraint may be an upper limit in size of the propulsion system units, at least for the foreseeable future. While large, long-lived, low maintenance aircraft gas turbines exist the same cannot be said for similar-size speed reducers required between the high rotational speed turbine and the relatively slow rotational speed propeller. In fact, an almost order of magnitude increase in unit size would be needed. Also the largest speed reducer units presently in use (about 5000 norsepower) are not particularly trouble-free as compared to turbofan engines. The Douglas economic analysis presumed that no additional maintenance cost would be incurred for propfan aircraft. This presumption may have been overly optimistic. For large aircraft, an alternate to large propfans would be the use of a number of smaller units;

however prior experience has convinced the airlines that significant advantages exist in minimizing the number of powerplants on an aircraft.

Technology Status and Requirements - The technology generated to date for the advanced propfans has centered primarily on improving the propulsive efficiency of the isolated powerplant in efforts first by Hamilton Standard inhouse activity, and more recently by both contract and inhouse studies under the NASA ACEE program. Parametric effects on number of blades, blade geometry (e.g. shape and sweep) and rotational speed, have been investigated both analytically and in model tests. The results show that high propulsive efficiency can be achieved. Effort has also been directed at near-field acoustics because of high noise levels found for some of the configurations where the blade tip speed exceeded the speed of sound. The near-field noise environment is more of a problem for passenger operations than for hauling cargo. It does, however need to be at levels acceptable both to the flight crew and to the aircraft structure (i.e. avoidance of acoustic fatigue).

Several major technology gaps need to be filled. One area concerns the aerodynamic integration of the propulsive system with the airframe without significantly degrading either the airframe aerodynamics or the propulsive performance. For wing installations, the twist imparted to the flow by the propeller subjects the wing to a nonuniform flow field, with the local flow varying both spanwise and chordwise. This nonuniformity, coupled with the presence of the nacelle body, operations at flight speeds approaching the critical drag rise Mach number for the isolated wing, and the use of supercritical airfoils sensitive to variations in flow uniformity, results in a very complex task of maintaining aerodynamic efficiency. Airframe aerodynamic interference on propulsive performance is significantly affected by powerplant location. For example, locating the propeller immediately behind the wing subjects the blades to a non-uniform, cyclic loading which both degrades blade performance and introduces structural dynamic and fatigue problems.

The previous example points out a second area of concern which is the technology required to provide a blade structure adequate for low maintenance, long-term use. The advanced turboprops have low aspect ratio blades which are very n and will likely have a considerable amount of leading edge sweep. The resultant structural shape is less than ideal for the high disk loadings and oscillatory loads which will be experienced.

A third concern is the technology required to design and fabricate the large speed reducers (gear boxes) required between the gas turbine and the propeller. The largest size, flight-worthy speed reducers presently available (about 5000 horsepower) would be suitable for four-engine advanced cargo aircraft no larger than about 25-tonne payload capability. In addition, the maintenance of these units has been significant. While new developments have occurred in gearing technology and materials, production of a satisfactory 20-25,000 horsepower speed reducer system would be a major achievement and require generation of considerable new technology.

CRYOFUELS - Growing concern about crude oil resources and prices prompts examination of aircraft configured to use alternate fuels. NASA studies of various fuels has narrowed the field to three principal candidates: synthetic aviation kerosene liquid hydrogen and liquid methane (6). A recent assessment has been made of the viability of these three fuels from the standpoint of cost, capital requirements, and energy resource utilization, as influenced by fuel production, transmission, airport storage and distribution facilities, and use in aircraft (7). All three fuels were judged viable but synthetic kerosene was judged to be the most attractive alternate fuel at least for some decades to come. Current technology makes possible its production with the most efficient use of coal or oil shale as feedstock and at the lowest price. Since it can be produced with properties essentially identical to present Jet-A fuel, no modifications would be required of aircraft or airports.

For hydrogen and methane, advanced production processes have been identified which, when fully developed, could result in savings of 10 to 20 percent over synthetic kerosene in energy resource utilization. In the event that electricity becomes relatively inexpensive, hydrogen could be produced by electrolysis of water. Examination of cryofuel aircraft options is therefore deemed appropriate for long-range planning considerations.

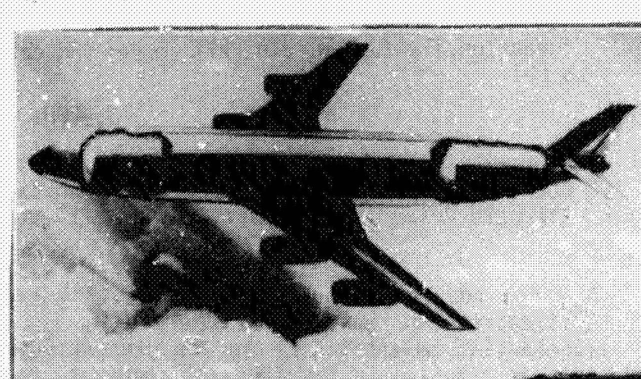

Fig. 6 - Cryofuel transport aircraft concept with fuselage tanks

Example Configurations - Studies, carried out for NASA by the Lockheed-California Company, have defined in detail for both liquid hydrogen (LH_2) and liquid methane (LCH_4), fuel systems appropriate for transport aircraft, plus preferred configurations of the aircraft. The studies, determined that the aircraft should be configured to locate the low density cryofuels within the fuselage both fore and aft of the passenger compartment, as illustrated in figure 6. The performance of a variety of range - payload combinations were investigated with up to 18000 km in range and up to 600 passengers. The performance data derived in the early studies for LH_2 aircraft have been refined for comparison with LCH_4 aircraft and will be reported shortly. For 10,200 - km range, 400-passenger combinations designed to cruise at Mach 0.85, incremental changes in aircraft parameters from a reference, conventionally-fueled transport were calculated by Lockheed to be:

Aircraft:	LH_2	LCH_4
Gross Weight	-25%	-1.0%
Oper. Empty Wt.	0	+10.5%
Specific Fuel Cons:	-66.3%	-18.0%
Lift/Drag, -Cruise:	-8.8%	-1.6%
Wing Area:	-35.3%	-4.5%
Fuselage Length:	+9.5%	+2.2%

The cryofueled aircraft are characterized by heavier fuselages, and lower lift/drag ratios because of the increase in fuselage size relative to the wing. However these disadvantages tend to be nullified by the much lower values of SFC for the cryofuels as a result of their greater available energy content per unit of fuel mass. In the case of LH_2, the decrease in fuel required because of the greatly reduced SFC was sufficient to reduce wing area dramatically and completely offset the weight penalty. For LCH_4, there was only a partial offset.

Configuration Economics - While no economic analysis of the type carried out for LFC and propfan was made, values of energy utilization, DOC and aircraft price were calculated. Changes in these values from those of the conventionally-fueled aircraft were indicated to be:

	LH_2	LCH_4
Energy Utilization	-13.2%	-1.2%
DOC	-1.2%	-6.3%
Aircraft Price	+0.7%	+10.0%

A large advantage is shown for LH_2 in energy utilization but not in DOC where LCH_4 has a substantial advantage due to its present lower cost as a fuel. In terms of ROI, however, this advantage of LCH_4 would be diluted by the significantly higher price of the aircraft.

Possible Constraints - Location of the fuel tanks in the fore and aft sections of the fuselage would rule out nose or tail loading for cargo aircraft. Sideloading, while in use today, constrains the handling of outsize cargo, such as heavy military equipment. Since nose or tail loading of cargo has not been a requirement of NASA cryofueled aircraft configuration studies to date, identification of viable configurations in future efforts should not be ruled out.

A second constraint in the use of cryofuels is the requirement for a substantial investment at the airport for special equipment to liquify the fuel. This must be done at the airport since it is economically impractical to transport cryofuels over long distances. Studies carried out for NASA indicate, for servicing an aircraft fleet equal to that handled by the Chicago O'Hare Airport, the capital requirements (in 1980 dollars) for airport liquifier and storage facilities would be about 1120 and 600 million dollars for hydrogen and methane respectively. Thus when cryofuels are introduced, financial considerations will very likely limit the number of airports which are equipped to handle the fuel. Such a limitation would constrain the system network and decrease flexibility for airlift during emergencies.

Technology Status and Requirements - Both of the cryofuels are considered to be good fuels for use in existing engines with few technical problems. LH_2 has been used as the propellant for a number of space vehicles and was flight demonstrated in an aircraft in the 1950's by the NASA Lewis Research Center. Methane is the principle constituent of natural gas, which also has been used to fuel engines, particularly stationary power plants. There are, however, opportunities for increasing the performance of the LH_2-fueled engines by taking advantages of the cooling capacity and combustion characteristics of LH_2. Problems center on the handling of the fuels as cryogens since they have to be stored in insulated tanks and then pumped through lines and valves at temperatures of 20K for LH_2 and 111K for LCH_4. Problems are more serious for LH_2 than for LCH_4, since it has a substantially lower temperature and viscosity.

Two prime technology deficient areas concern the fuel pump and the cryoinsulation for the fuel tanks and lines. The pump problem lies with very high pump speeds (50,000 to 80,000 rpm), and ineffectiveness of LH_2 as a lubricant. In spacecraft, LH_2 pumps have design lives in the order of ten hours, while most aircraft equipment entering airline service should have a minimal life expectancy of at least 1000 hours with good reliability. Prior experience indicates severe problems with ball bearings in LH_2 pumps and suggests use of other bearings types such as compliant foil bearings, now under study for NASA by the Garrett Corporation.

The insulation problem centers on the need for a light weight reliable insulator which does not degrade and has a long life. Investigation of a number of insulation systems narrowed the field of contenders to closed cell foams and to vacuum jacketing, with only small differences between them in insulating quality. Because vacuum systems can be unforgiving if the vacuum is lost, the use of closed-cell foams is considered to be a more reliable approach. Permeation of air into foams poses complications, since at LH_2 temperatures, selective liquification of the air components can occur, add mass to the system, and decrease structural integrity of the foams. Insulation can also be subjected to thermal and load cycling (i.e. vibrations). R and D studies are presently being carried out on foam insulations under NASA contract.

Once components have been developed for the entire cryofuel propulsion system, a need exists for aircraft to be outfitted with the system, flight tested to identify and correct any unanticipated problems, and then placed in demonstration service to establish long-term performance characteristics and develop user confidence.

Another technology requirement needing attention concerns the safety aspects associated with the use of cryofuels in each of three areas: fuel spills occuring at the airport; system failures onboard the aircraft, and post-crash aircraft fires. In fuel spills, which can release great quantities of stored cryogenic fuel, detailed knowledge is required of the physical behavior of the fuel following its release. More is known about LCH_4, since it is essentially liquefied natural gas (LNG) used throughout the world. Following a spill it is known to form a non-buoyant cloud, but the characteristics and behavior of the cloud as it spreads and mixes with the air require better definition. For LH_2, little is known concerning large-scale post-spill behavior, not even about buoyance, although there is some qualitative evidence of neutral buoyancy of the vapor cloud existing for some period of time. NASA effort has recently been initiated to define the hazards associated with large ground-base spills of LH_2.

Uncertainties arise regarding the safety of cryogenically fueled aircraft. Potential problems are associated with fuel lines, valves and other equipment necessarily located within the fuselage, extending the length of the passenger compartment, and operating at cryotemperatures. Little is known about the long-term operational problems and reliability of such configurations. For post-crash fires, the degree of hazards is critically dependent on the time-history of combustion and associated physical properties of the products of combustion which critically depend on the likelihood, manner and severity of fuel system rupture. The post-crash behavior of transport aircraft fuselages is not considered to be defined in sufficient detail, backed by accident statistics, to carry out meaningful hazard analyses. The NASA Lewis Research Center is initiating studies to address the cryofuel hazards associated with both system failures onboard the aircraft and post-crash aircraft fires.

DISTRIBUTED LOAD CONFIGURATIONS - As aircraft increase in size, the available volume within the wing increases more rapidly than the volume required for fuel and payload. This trend arises because wing area must grow in proportion to gross weight (for landing and takeoff considerations) and wing volume increases as the three-halves power of wing area. Above some certain size therefore, the wing volume alone is sufficient for fuel and payload and no fuselage is required. Carrying the payload distributed along the wing span, rather than concentrated in the fuselage, also reduces wing bending moments because weight is largely balanced by local lift. While the cruise equilibrium condition is only one of many structural design conditions, studies have shown substantial weight savings for very large airplanes loaded in this fashion.

Large payload-in-the-wing airplanes, called distributed load freighters (DLF) have been studied by NASA for about five years, both inhouse and under contract. Examination of a number of DLF configurations indicates the desirability of having the wing swept back and untapered, and the critical dependence of configuration geometry on payload height, as it determines the wing thickness. Tradeoffs can be made between airfoil thickness ratio and wing aspect ratio in optimizing a DLF design to accommodate a given number of cargo containers. For DLFs carrying standardized containers having a height of 2.5 to 2.7 m and a density of 100 to 160 kg/m^3, advantages over conventional aircraft are evident only for very large payloads, usually greater than 300 tonnes. Configuring DLFs with external cargo pods may also be necessary for special situations (e.g. outsize payloads).

Example Configuration - The 30-year outlook study examined a DLF of 236-tonne payload capability, designed to cruise at Mach 0.75 and equipped with a center pod to accommodate outsize cargo. This configuration, while not optimum for demonstrating DLF to maximum advantage, had been defined in detail by Douglas in their USAF-sponsored NSA study (3). The incremental changes in aircraft parameters from a reference 236-tonne dedicated conventional airfreighter, designed to cruise at Mach 0.85, were estimated by Douglas to be:

Pylon/Nacelle Weight:	-17%
Structural Weight:	-43%
Lift/Drag-cruise	-13%
Specific Fuel Consumption:	-4%
Wing Area:	+10%
Aircraft Mfgrg. Cost:	-15%

The significant decrease in lift-drag ratio results from the low effective aspect ratio

(5.9) of the wing with winglets which was configured to accommodate two spanwise rows of containers. Decrease in structural weight was very large despite the increased wing area and the cargo pod.

Example analysis - The economic study of the example DLF aircraft was carried out on the same basis as for the long range (7000 km) dedicated aircraft produced by two manufacturers (without military participation) and addressed the civil market demand from 1994 to 2008. Results of the economic study were as follows:

Aircraft	Reference	DLF
Trip Cost at Design Range per tonne of payload	$504	$555
Aircraft Price per tonne of payload, $'s 1994	1,130,000	713,000
Airline ROI, percent	19.7	23.0

The results indicate a significant benefit in airline ROI for the distributed load freighter, which directly results from its 35 percent savings in aircraft price, since trip cost per ton of payload was about ten percent greater. Despite being a non-optimum span-distributed-load configuration, the example DLF aircraft would provide the highest ROI to the airline and the lowest required fleet investment of any of the configurations analyzed in the economic study.

Possible Constraints - Distributed load freighters are attractive primarily for very large payloads (for reasons cited in earlier discussion) which could constrain practical applications for some types of cargo service. The constraint of viable DLF size is not well defined as it depends on a number of factors. One such factor is payload density which dictates the payload volume to be accommodated in the wing (and pods, if required). Another factor is payload geometry, particularly the vertical dimension which influences wing thickness. As an example, the optimum DLF configuration for carrying high-density bulk cargo (e.g. kerosene) would be substantially different than the optimum configuration for carrying 2.5 by 2.5 by 6.3 m containers having the same total mass, but one-fifth the density of kerosene. The wing for the bulk cargo would have a higher aspect ratio and be considerably thinner, with a resultant significantly higher lift-drag ratio.

Another DLF constraint is the need for extra-wide runways and taxiways. Lightening the wing structure to take advantage of reduced bending moments during cruise necessarily requires distribution of the landing gear across a goodly portion of the wing span. Wide landing gear treads pose potential conflict with airports in the United States and abroad. For future airports, Group 4, FAA standards specify 67 m for the maximum allowable wing span, and landing gear treads not to exceed 15.2 m. Distributed load freighters would be definitely restricted in fleet operations without substantial changes in airport and/or landing gear configurations.

Technology Status and Requirements

Distributed load configurations per se do not involve the implementation or exploitation of a specific advanced technology option (e.g. laminar flow control, propfans). Various problem areas have been identified, however, where technology requirements exist. Improvement in DLF aerodynamic efficiency is one such area. The wing airfoil sections necessarily need to be thick, possibly greater than 20 percent of the wing chord. For such thicknesses, advanced airfoil shapes which provide good aerodynamic efficiency at relatively high subsonic cruise Mach numbers, such as the NASA supercritical series for thinner sections, have not yet been developed. Use of untapered wings of low aspect ratio in DLF configurations will be accompanied by high induced aerodynamic drag unless appropriate aerodynamic devices, exemplified by the fins conceptually shown on the wing tips of the DLF configuration in figure 7, can be devised to increase the effective aerodynamic aspect ratio.

Achievement of adequate flight control, particularly near the ground, is another problem of very large span vehicles anticipated to be particularly troublesome for DLF configurations because of the high mass moment of inertia around the roll axis. Technology is needed not only for design of systems to counteract specific dynamic inputs such as from gusts but also for definition of the disturbing inputs themselves.

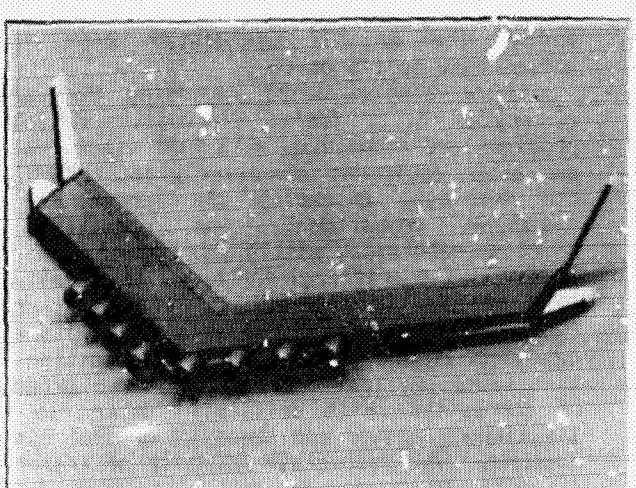

Fig. 7 - Very large distributed-load freighter concept

Because a DLF is very close to the ground during landing and takeoff, the propulsion system units cannot be located under the wing on pylons, but must be located in non-standard locations above the wing or even buried within the wing. Advanced technology is required for efficient integration of the propulsion system in such locations.

A final requirement is the technology needed to design an acceptable and reliable DLF landing system. In one contract study for NASA of a very large DLF having a span of 153 meters and a gross weight of 1,361,000 kg, shown in figure 7, use of clusters of conventional type landing gear was found to require some 80 wheels spaced across a span of 122 m. All sorts of problems can be envisioned with use and maintenance of such a system. Several candidate DLF landing system concepts have been identified but not yet developed.

MULTIBODY CONFIGURATIONS - Studies of fully span-distributed-load, all-wing cargo aircraft, such as just described, have shown savings in weight and aircraft price for very large payloads but not for payloads of the order of 100 tonnes or less, where conventional design aircraft appear to be superior. Preliminary studies indicate that there may be an intermediate range of payloads where a semi span distributed-load configuration may be attractive. The multibody aircraft, shown in figure 8, is an example of such a configuration.

Fig. 8 - Multibody airfreighter concept

Configuration and Characteristics - Multibodies show promise in several areas. Reductions in wing root bending moment should provide savings in structural weight and cost. Part commonality, to reduce manufacturing cost, can also be achieved in the bodies (fuselages), wing sections, tail, and aircraft systems. Preliminary design studies have even indicated the feasibility of pairing fuselages from existing cargo aircraft designs to provide inexpensive multibodies. In the USAF-sponsored New Strategic Airlift Concepts study by the Boeing Company (8), a multibody configuration was competed against seven other configurations. The multibody aircraft, designed to carry a 182-tonne payload at Mach 0.76 over a range of 8500 km, was found to be the best configuration in productivity and life cycle costs.

Many technical unknowns exist concerning how best to configure this type of aircraft (e.g. number of bodies). Basic questions arise as to the aircraft's aerodynamic performance throughout the ground-air flight cycle, stability and control behavior, structural characteristics, and arrangement of support system. Moreover, experimental data on multibody cargo aircraft configurations are minimal, giving rise to numerous uncertainties in selection and use of design procedures.

A NASA-sponsored study is presently underway by the Lockheed-Georgia Company to determine the technical and economic feasibility of multibody aircraft configurations. Parametric effects will be determined for factors such as wing thickness, sweep back angle, aspect ratio, wing loading, payload weight, body cross section and engine location for both two and three-body arrangements. Characteristics for selected two and three-body configurations will be compared with reference conventional aircraft. The study will also identify any likely operational constraints and technology requirements which must be satisfied to bring the concept to fruition.

AIR CUSHION LANDING GEAR - Most a[illegible] today have sized their runways, taxiwa[illegible] apron/gate areas to be capable of [illegible]n[illegible]ing aircraft up to the size of the Boeing 747, and it will be difficult to make changes to accommodate significantly larger aircraft. Much larger airfreighters will be desirable, however, as pointed out in the economics discussion pertaining to the civil cargo fleet 30-year outlook. The Air Cushion Landing Gear (ACLG) is one new aircraft technology that, if developed to its conceivable full potential, could substantially reduce the problems of accommodating very large aircraft during landing, taxi, and takeoff maneuver. The ACLG can distribute the aircraft landing and taxi loads over the runway and taxiway as well as diffuse loads into the aircraft structure. Runway thickness and width would not be critical and the ACLG aircraft could even take off and land on unprepared surfaces. Large ACLG aircraft would, therefore, be capable not only of emergency operations from battle damaged runways or nearby open areas but also of routine operations from protected waters and improved sites having no paved runways.

Configuration and Technology - Air Cushion Landing Gear, (ACLG), invented by Mr. T. D. Earl who presently is with Bell Aerospace Textron, was first fitted to a light (1120 kg) amphibian in 1967 and flight tested sucessfully on both land and water. In a subsequent research and technology development program sponsored by the USAF and the Canadian Government, a similar retrofit was carried out for a medium (18,600 kg) cargo transport and 57 takeoffs and landings were made. The results of these studies plus analyses and laboratory experiments have generally identified ACLG capabilities, configuration constraints, and problem areas. In a recent study effort for NASA, Bell Aerospace Textron considered a series of aircraft ACLG applications to determine the most attractive, analyze potential benefits and define and prioritize technology requirements (9).

In the applications study, eight aircraft configurations including five transports were selected. They ranged in size from a small general aviation amphibian to a large multi-mission aircraft. A new integrated ACLG aircraft arrangement, illustrated in figure 9, was employed for the five transport concepts. The ACLG configuration differs from the prior retrofitted ACLG designs by having increased cushion area, and a wider track. An inherent feature of this design is a low height cargo deck with kneeling capability for easy on-off loading.

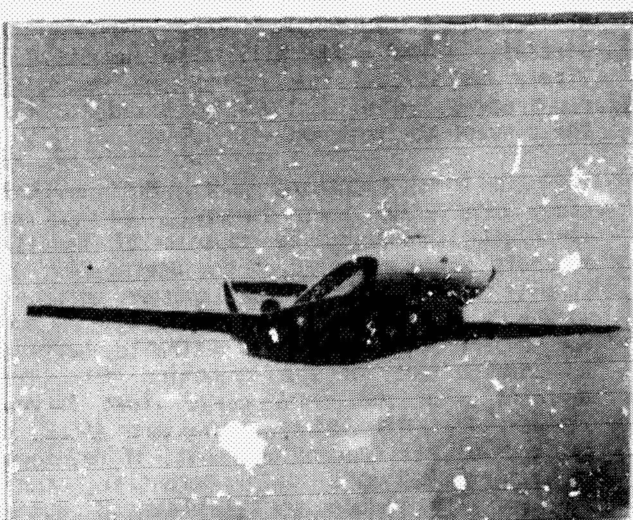

Fig. 9 - Air cushion landing gear airfreighter concept

Technology requirements were identified in eleven areas, with four commanding near-term development priorities. These four include: trunk material life development, cushion braking development, trunk flutter suppression and flight effects. While little ACLG effort is presently underway, an R and D effort to provide the technology required to design a large ACLG airfreighter was estimated to require 10 to 15 years if carried out at a moderate pace.

Additional information on technology requirements and readiness was recently identified and evaluated (10), not only for ACLG airfreighters, but also for a variety of other configurations including those discussed earlier.

CONCLUDING REMARKS

The civil cargo fleet 30-year outlook analysis pointed out the importance of fleet economics. Incorporation of 1980 technology into stretched derivatives of present-day wide-body cargo airplanes would be economically sound through reduction in aircraft price and trip cost and increase in return on investment to the airline, and would be viable for several decades to come. New dedicated airfreighters, incorporating 1990 technology, would offer little or no economic incentive when competed against derivative aircraft, even though they could be lighter, and have improved fuel consumption characteristics. The economic attractiveness of dedicated airfreighters could be dramatically improved by military cost sharing in the research, development, and test phase, and even very large payload aircraft would become economically feasible.

Examination of several advanced techology options and configurations identified propfan airfreighters, designed to cruise at Mach 0.7, to be economically attractive with regard to trip cost, aircraft price, and return on investment. Span-distributed-load airfreighters had the lowest price and the highest ROI but suffered from a relatively high trip cost due to aerodynamic inefficiencies. Use of laminar flow control for airfreighters would not provide great benefits from economic considerations. For all of the options, significant technology requirements and/or operational constraints were noted. Use of air cushion landing gear configurations was identified as an attractive approach for avoiding the constraint of runway limitations on accommodating very large airfreighters.

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