Design Concepts for Future Cargo Aircraft

R.H. Lange*
Lockheed-Georgia Company, Marietta, Ga.

The design of cargo aircraft for the future is influenced by an ever-increasing number of performance, operational, environmental, and economic requirements. Ingenuity in design concepts and application of advances in technology are required to derive efficient cargo aircraft compatible with these apparently conflicting requirements. This paper presents results of preliminary design studies of advanced technology cargo aircraft, including novel distributed-payload spanloader designs, hydrogen-fueled transports, nuclear-powered transports, and ram-wing vehicles. The data cover airplane gross weights up to approximately 2,000,000 lb and payloads up to 900,000 lb.

I. Introduction

REPRESENTATIVE design requirements of cargo aircraft include increased productivity, rapid cargo loading and unloading, noise abatement, engine emission control, and, more recently, reduced fuel consumption. Ingenuity in design concepts is required to derive efficient cargo aircraft compatible with these apparently conflicting requirements, and also for consideration of alternate fuels. Lockheed has maintained a continuing effort in preliminary design and systems studies of advanced technology aircraft. The application of advanced technology such as supercritical aerodynamics, graphite epoxy composite materials, and active controls show the potential to provide significant improvements in performance and economics of cargo aircraft, and results of these applications are published.[1-4] As the size of transport aircraft has increased, advances in technology have permitted continuing improvements in performance and economics; however, further improvements are likely to be obtained in smaller increments.[5] This latter result has fostered consideration of innovative design approaches as a means of providing larger incremental improvements in performance and economics of large cargo aircraft. This paper presents results of feasibility studies of advanced technology cargo aircraft including conventional, novel distributed-payload spanloader, and ram-wing vehicle designs. These studies cover gross weights of 1.2×10^6 lb and payloads of 6000,000 lb.

Data presented for cargo aircraft utilizing liquid hydrogen as an alternate fuel are obtained from Lockheed studies of hydrogen-fueled, long-range transport aircraft conducted under NASA Contract NAS1-12972.[6] Nuclear powered transport design concepts data presented cover gross weights up to 1.6×10^6 lb, and are part of a broader technology assessment of nuclear aircraft propulsion.[7]

II. Study Formulation

Objectives

General objectives of the feasibility design studies described in this paper are:

1) Investigation of innovative aircraft design concepts to achieve more efficient performance, reduced fuel consumption, and lower direct operating costs.

2) Investigation of alternate fuels and propulsion systems for application to long-range transport aircraft. Specifically, liquid hydrogen is selected as the alternate fuel, and nuclear power is the propulsion system.

Guidelines

The studies contributing to the results reported in this paper are consistent with the following guidelines:

1) In objective no. 1, preceding, all designs are derived for an arbitrarily assumed payload of 600,000 lb and a takeoff gross weight limited to 1.2×10^6 lb. Range capability, cruise speed, and cruise altitude are fallouts, dependent upon the achievement of best performance for the design concept under consideration. Advanced technology applications include supercritical wings, 50-60% utilization of composite materials in the structure, and advanced turbofan or turboprop engines.

2) In objective no. 2, the hydrogen fueled cargo transports technology data base, except for propulsion, is the same as that obtained in the NASA ATT systems studies.[1,2] The data presented herein are for the largest payload, 250,000 lb, and the longest range, 5500 naut miles. The preferred hydrogen fueled transport design concept is compared to a jet A-fueled transport, designed to perform the same mission.

3) The preliminary design of each configuration is conducted only to the extent necessary to determine the technical and economic feasibility of practical transport configurations. It should be emphasized that the design concepts described herein are presented to illustrate the capabilities of a design and do not represent refined and optimized preliminary design efforts. Any of the design concepts can be made to achieve better performance or better efficiency when subjected to a parametric design optimization process.

III. Preliminary Design

Future Air Cargo System Requirements

At the present time, there are no established requirements for the next generation all-air cargo transport system. The Department of Transportation (DOT) has predicted that the U.S. domestic cargo demand will double in the next 20 years.[8] The air cargo share of this increase, however, is unknown at present, and is dependent upon ecological, political, and physical environments.[9] Recently, the Military Airlift Command (MAC) released its "Military Concept of the C-XX," which establishes characteristics of a large all-cargo civil transport that would facilitate its use in the Civil Reserve Air Fleet (CRAF) to augment military airlift during periods of national crisis. The DOT/Industry Intermodal Air Cargo Test (INTACT) effort is a joint government/industry program that will demonstrate the movement of over-the-road trailers and marine-type containers directly from ocean and motor freight carriers to a C-5 aircraft for air transport over a selected route system. This demonstration will provide data for surface and air modes on interface problems of

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*Manager, Transport Design Department. Associate Fellow AIAA.

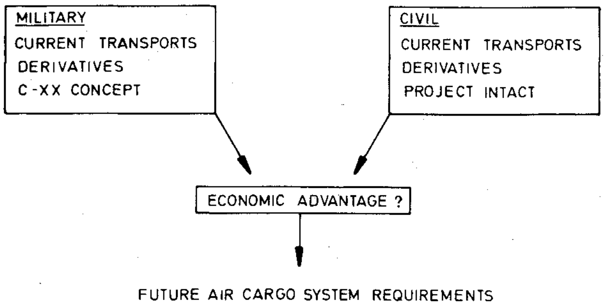

Fig. 1 Evolution of future air cargo system requirements.

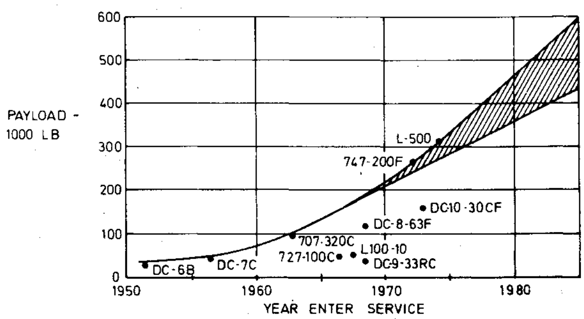

Fig. 2 Cargo payload growth vs year.

equipment and handling techniques for containerized cargo. The synthesis of these and other on-going activities contributing to the definition of a firm set of requirements of the all-cargo transport of the future is a very complex procedure. A highly simplistic representation of this synthesis is presented INTACT on the civil side are shown as part of the acproject INTACT on the civil side are shown as part of the activities underway in the evolution of the future cargo transport requirements. As shown in Fig. 1, however, these activities must pass through a filter showing an economic advantage before the requirements of a future air cargo system can be established.

Because of the lack of a set of firm system requirements, assumptions are made for the payload and other performance characteristics for the design concepts discussed in this paper. In particular, the 600,000-lb payload is arbitrarily selected for consistency with a normal growth rate during the next decade for cargo aircraft, and with the projected air cargo demand. Cargo payload growth shown in Fig. 2 is reproduced from a documented by the Aerospace Industries Association.[10]

Comparison of Design Concepts

Design concepts for the advanced cargo aircraft include conventional swept-wing-type, a delta wing-body configuration, a swept-wing spanloader configuration,[11] an unswept wing spanloader configuration, and a ram-wing configuration. All configurations were designed to an arbitrarily selected payload of 600,000 lb and a takeoff gross weight of 1.2×10^6 lb. Range capability, cruise speed, and cruise altitude are fallouts dependent upon achievement of best performance for the design concept in each case. Applications of advanced technology for each design concept are summarized in Table 1.

With one exception, all design concepts have supercritical wings, high utilization of advanced filamentary composites in the structure, and advanced turbofan engines with FAR 36-10

Table 1 Advanced technology applications

DESIGN CONCEPT	AERODYNAMICS TECHNOLOGY	MATERIALS TECHNOLOGY	PROPULSION TECHNOLOGY
Conventional	Supercritical	60% Composites	Adv. Turbofan
Delta Wing	Supercritical	50% Composites	Adv. Turbofan
Swept Spanloader	Supercritical	60% Composites	Adv. Turbofan
Ram Wing	Conventional	50% Composites	Turbo Prop (Regen.)
Unswept Spanloader	Supercritical	60% Composites	Adv. Turbofan

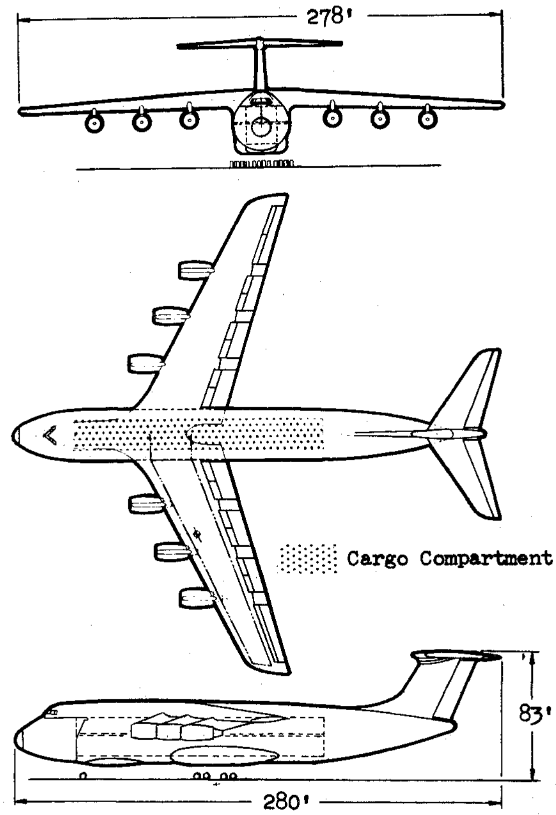

Fig. 3 General arrangement – conventional design: $M=0.80$, wing area = 9990 ft.^{2}

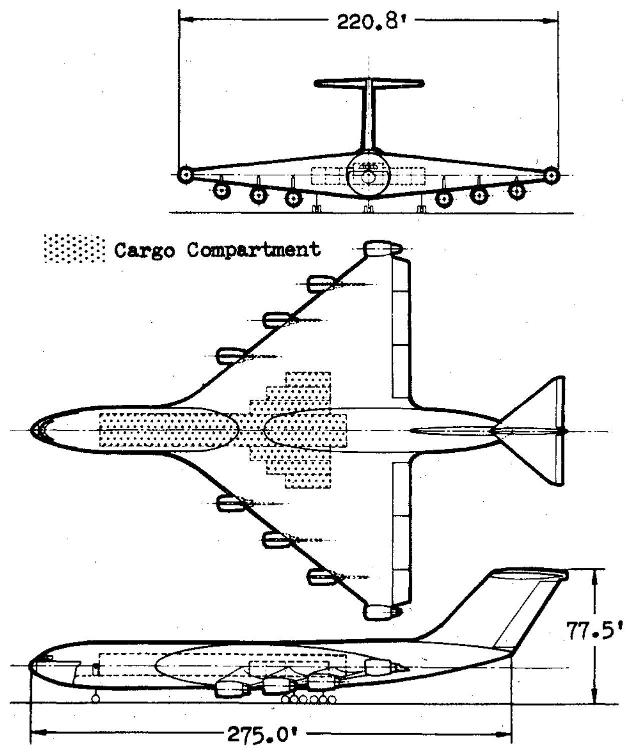

Fig. 4 General arrangement – delta wing design: $M=0.87$, wing area = 16,250 ft^2.

EPNdB noise and low emissions consistent with the NASA ATT systems studies.[1] The one exception is the ram-wing configuration, which utilizes conventional technology wing sections and current turboprop engines. It is not felt that the performance characteristics of this design are substantially affected by the technology, primarily because of the unusual configuration and its cruise flight mode at extremely low altitudes. All aircraft can accommodate outsize vehicles as well as containerized cargo.

The general arrangment of the conventional design given in Fig. 3 features a 25° swept high wing, T-tail empennage, and six wing-mounted turbofan engines. The cargo compartment is configured for four rows of 8×8-ft cargo containers, and a nose visor opening is provided for cargo loading in the fuselage. The cargo compartment is shaded on this and all subsequent general arrangement drawings in this section.

The delta wing design, Fig. 4, is swept 53°, has a 16% thick wing, 8-wing mounted engines, and features a fuselage and T-tail empennage. A nose visor opening is provided for cargo loading in the fuselage and wings. The fuselage is required for outsize vehicles and cargo containers.

The spanloader design shown in Fig. 5 has 40° sweepback of the 20% thick wing in order to achieve $M=0.75$ cruise speed. Two rows of 8×8-ft cargo containers, located inside and extending for the entire wing span, dictate the required wing thickness ratio. Loading doors are placed at the two wing tips and at the front and rear of the center body. The six turbofan engines are mounted on top of the wing. A three-element air-cushion landing system is supported by the center and outer bodies and allows the aircraft to be operated from unprepared terrain and water.

The ram-wing design shown in Fig. 6 has a rectangular planform with aspect ratio of 2.0 and 15% thick wing sections. This vehicle operates on dynamic lift similar to an airplane, but normally cruises over the surface at very low clearances. Propulsion is supplied by 6 conventional turboprop engines. Two additional engines of the same type

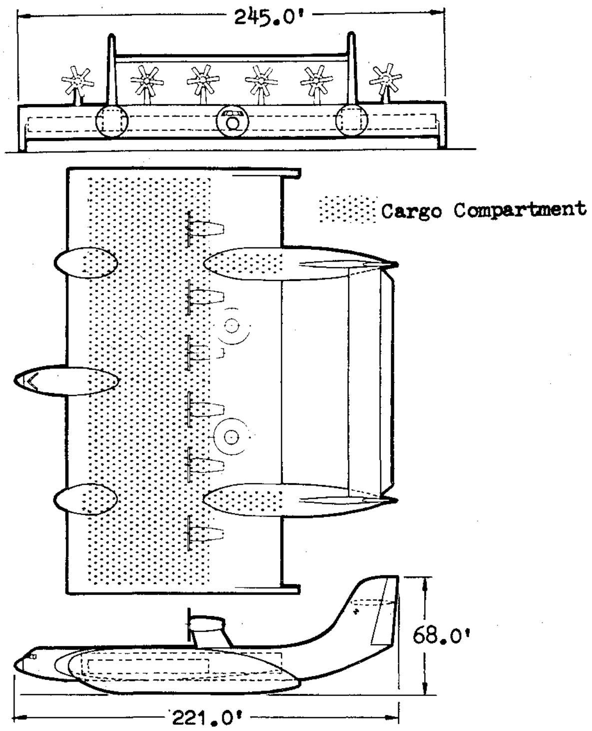

Fig. 6 General arrangement – ram wing design: $M=0.17$, wing area = 30,000 ft^2.

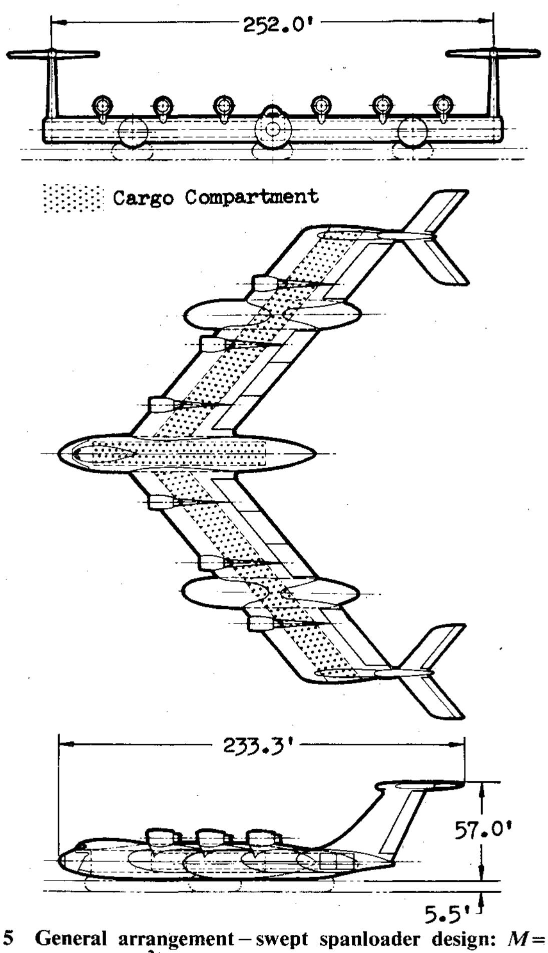

Fig. 5 General arrangement – swept spanloader design: $M=0.75$, wing area = 14,000 ft^2.

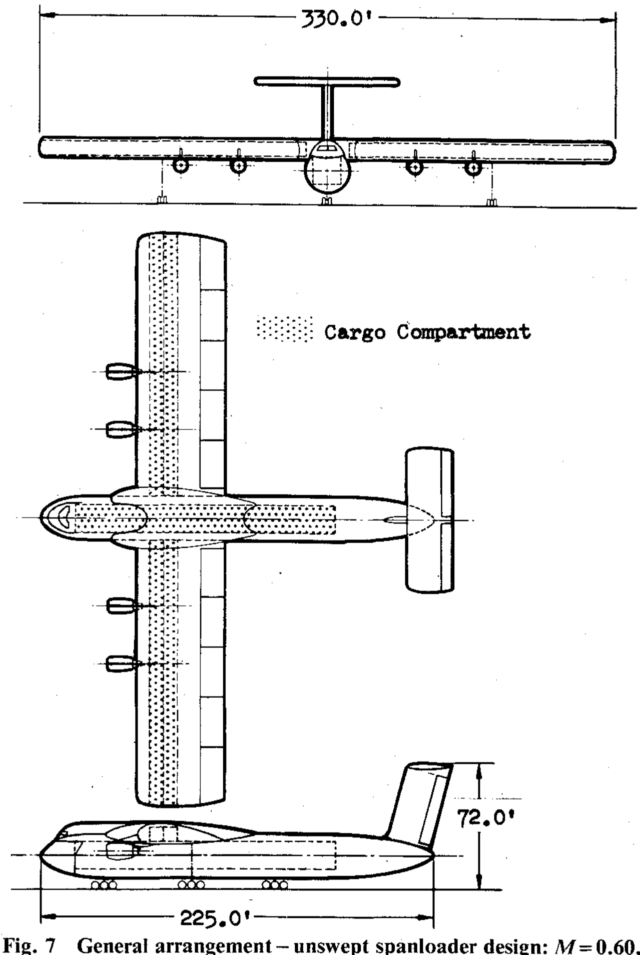

Fig. 7 General arrangement – unswept spanloader design: $M=0.60$, wing area = 16,500 ft^2.

Table 2 Configuration characteristics

TAKE-OFF GROSS WT = 1,200,000 LBS			PAYLOAD = 600,000 LBS		
PARAMETER	DESIGN CONCEPT				
	Conventional	Delta Wing	Swept Spanloader	Ram Wing	Unswept Spanloader
Cruise Mach Number	0.80	0.87	0.75	0.17	0.60
Operating Weight - Lbs	440,500	316,000	279,000	301,000	280,000
Fuel - Lbs	159,500	284,000	321,000	299,000	320,000
Aspect Ratio	7.50	2.7	6.1	2.0	6.3
Cruise Altitude - Ft	37,000	35,000	35,000	12	25,000
Cruise L/D	17.4	14.0	19.9	30.0	20.2
Thrust per Engine - Lbs	56,700	54,000	52,500	4,500 HP	55,000
Number of Engines	6	8	6	8	4
Range N. M.	1,300	2,520	4,100	5,760	4,180

are required to provide the necessary air flow for an air cushion system, which shows promise as a means of reducing the otherwise large power required to make this design concept airborne. Disadvantages of this design concept are the very large size required in order to obtain sufficient clearance over the water for rough sea states and the previously discussed high-power required for liftoff. Another factor is the extremely low altitude cruise mode, which perhaps precludes its operation as an all weather system.

The unswept spanloader design described in Fig. 7 is configured as a lower technology risk system as compared to that for the swept spanloader design. With the unswept 21% thick wing, the cruise Mach number is reduced to $M=0.60$. The design features a conventional fuselage, T-tail empennage, and bicycle-type landing gear. Two sticks of 8×8-ft cargo containers are loaded for the entire wing span, and, in addition, cargo is also loaded in the fuselage. Four wing-mounted turbofan engines are mounted in nacelles below the wing.

A summary of the basic geometric, weights, and performance characteristics of the several design concepts is given in Table 2 for a 600,000 lb payload and takeoff gross weight limited to 1.2×10^6 lb. Best performance cruise Mach numbers vary from $M=0.17$ for the ram-wing design to $M=0.87$ for the delta-wing design. The data show lowest operating weights for the spanloader-type configurations and highest operating weight for the conventional design. It should be noted, however, that as compared to more conventional design concepts, there is a lack of statistical weights information for the spanloader and ram-wing design concepts; therefore, the weights for these may be optimistic. On the other hand, the ram-wing and spanloader designs indicate substantially better lift-to-drag ratios than those for the more conventional designs; therefore, better aerodynamic efficiency is indicated. Lower power requirements attendant with the higher L/D's are also indicated for the ram-wing and spanloader designs. The high value of L/D for the ram-wing design is a result of flight operation in the ground effect, even though the geometric aspect ratio is about 2.0. The low altitude for the ram-wing in its cruise condition results in suppression of the trailing tip vorties and consequent high values of L/D; as indicated in Fig. 8, for a height to chord ratio h/c of 0.10, the L/D is 30.[12]

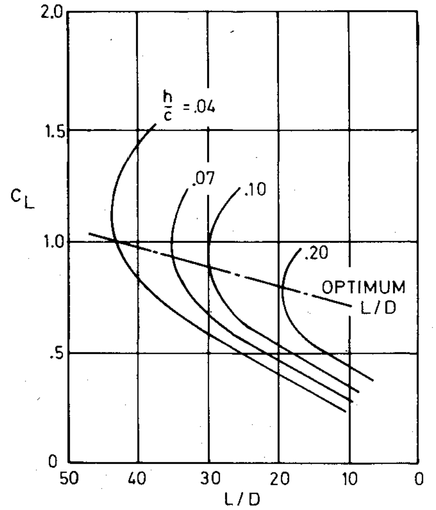

Fig. 8 Ram-wing design – cruise L/D as a function of height to chord ratio.

In lieu of a detailed cost analysis of the design concepts which is not warranted at this time, it is of interest to compare relative costs using, as a first approximation, the fact that development, acquisition, and operating costs are proportional to aircraft operating weight. The ratio of operating weight to takeoff gross weight is presented in Table 3 for the design concepts considered, as well as for a C-5-747F-type design shown at the bottom of the chart.

The data show a 47% reduction in operating weight, and therefore a 47% reduction in system costs for the ram-wing and spanloader-type designs as compared to C-5, 747F-type designs. This cost increment is considered representative, despite the possibility that the weights for these new designs may be optimistic, because the ratio for the C-5, 747F is obtained at gross weights in the region of 730,000-760,000 lb, and growth trends indicate a higher value for the ratio at 1.2×10^6 lb.

Table 3 Operating weight comparisons

Design Concept	Operating Weight / T.O. Gross Weight
Conventional	0.36
Delta Wing	0.26
Swept Spanloader	0.23
Ram Wing	0.25
Unswept Spanloader	0.24
C-5, 747F	0.45

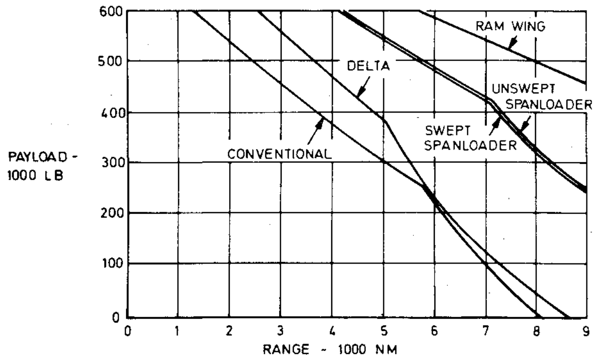

Fig. 9 Payload range characteristics of designs.

Table 4 Derived turbofan engine characteristics

	LH_2	Jet A
Turbine Inlet Temperature, °R	3040	3040
Bypass Ratio	12.85	10.90
Overall Pressure Ratio	35	35
Fan Pressure Ratio	1.51	1.51
Compressor Pressure Ratio	23.3	23.3
Cooling Air, Percent	0	5
Installed Performance Thrust/ Weight	3.7	3.7
SFC - Lb/Hr/Lb	0.20	0.59
Heating Value of Fuel - Btu/Lb	51,590	18,400

Payload range curves for the design concepts given in Fig. 9 show ranges at maximum payload of 1300 naut miles for the conventional design, 2520 naut miles for the delta design, 4100 naut miles for the swept spanloader, 4180 naut miles for the unswept spanloader, and 5760 naut miles for the ram-wing design. The payload range curves indicate the relative aerodynamic/structural efficiency of the design concepts, and the ram-wing design shows the added advantage of reduced specific fuel consumption of its turboprop propulsion system. The data show significant increase in performance of the ram-wing and spanloader design concepts as compared to the more conventional designs.

In summary, innovative design concepts such as ram-wing and spanloader types show the potential for substantial increased productivity and reduced operating costs as compared to conventional designs for future cargo aircraft. These improvements result from higher structural/aerodynamic efficiency, reduced power requirements, and attendant reduced fuel consumption for the ram-wing and spanloader designs, as compared to the conventional designs. Realization of these potential improvements in efficiency are dependent upon the support given to development programs applicable to these design concepts. Although the existing fleet of transport aircraft will serve effectively for many years, planning for the succeeding generation of air cargo aircraft must begin now.

Hydrogen-Fueled Configuration

The energy crisis has promoted increased interest in the use of alternate fuels for aircraft. Hydrogen is one of the more attractive fuels because it can be manufactured from water or coal, utilizing several processes and energy sources; as a fuel for aircraft, it has been shown to provide substantial improvement in weight, performance, energy, and results in reduced pollution of the environment.[13] In recognition of these factors, NASA has funded conceptual design studies of advanced transport aircraft with Lockheed, under Contract NAS1-12972, "Study of Liquid Hydrogen Fueled Long Range Subsonic Transport Aircraft." Data presented from the NASA study cover only the largest cargo transport investigated – the 250,000-lb payload, 5500-naut-mile range, $M=0.85$ cruise-speed design. A jet A fueled cargo transport, designed to perform the same mission, also is included for compaison. Engine cycles considered in this study are advanced design, efficient, high bypass ratio turbofan engines, which could be available for 1990 IOC. The LH_2 and jet A fueled cargo transports require the same basic type of turbine engines, but are different in the manner in which turbine cooling is accomplished. The engine cycle analysis for LH_2 and jet A fueled engines was conducted by Lockheed, using its SYNTHA engine cycle program. Features of the derived engine characteristics are given in Table 4 for sea level, standard day conditions.

The liquid hydrogen is utilized as a heat sink for cooling of the turbine blades and nozzle accessories. The jet A fueled engine uses 5% primary air flow for turbine cooling, and this accounts for the difference in the efficiency and design bypass ratio relative to the LH_2 fueled engine.

The general arrangement of the LH_2 design given in Fig. 10 shows a 30° swept mid-wing for $M=0.85$ cruise speed, T-tail empennage, and four wing-mounted turbofan engines. The liquid hydrogen fuel is contained in pressurized tanks located in the upper half of the fuselage as indicated by the shaded areas, and the tanks are nonintegral with the airframe structure. A single tank also is located in the unpressurized aft-fuselage section. The cargo is located in the fuselage section below the hydrogen fuel tanks, and the cargo compartment is sized to accommodate two rows of containerized cargo. A nose visor opening is provided for cargo loading and unloading. The mid-wing position is required to maintain a cargo floor height above ground level of 15.5 ft, and also to provide proper engine nacelle ground clearance. The configuration illustrated in Fig. 10 is not unconventional in its external configuration, and a practical, realistic design is achievable for a hydrogen-fueled transport. A comparison of performance characteristics of the hydrogen-fueled cargo transport of Fig. 10 with those of a jet-cargo transport designed for the same mission capability is given in Table 5.

The data of Table 5 show that as compared to the equivalent jet A fueled transport, the LH_2 is 25% lower in gross weight, 18% lower in engine thrust, 68% lower in fuel required, and 10% lower in energy required per ton mile.

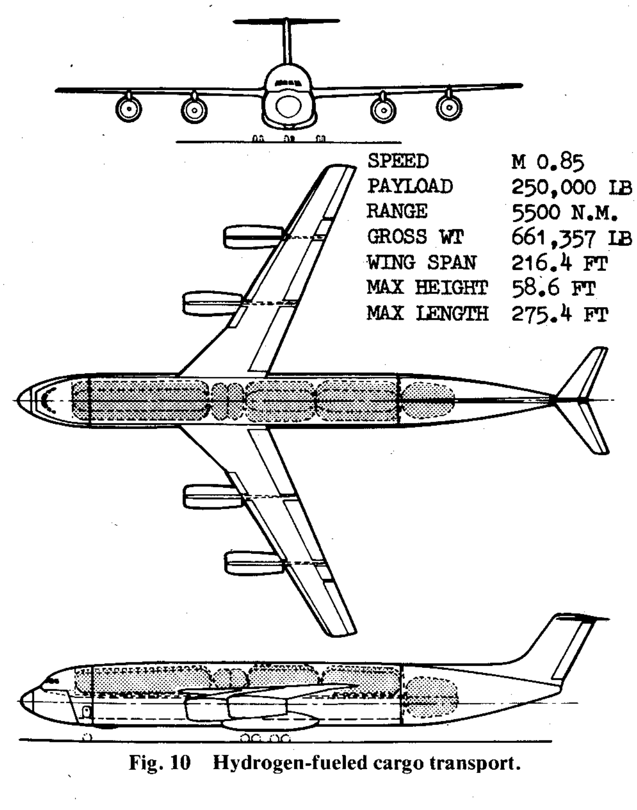

Fig. 10 Hydrogen-fueled cargo transport.

Table 5 Comparison of LH_2 and jet A cargo aircraft.

	LH_2	Jet A	Percent Change
Operating Weight - Lb	305,700	306,100	-0.1
Gross Weight - Lb	661,500	883,800	-25.2
Thrust/Engine - Lb	47,700	58,100	-17.9
Block Fuel - Lb	91,100	285,000	-68.0
Energy/Ton Mile - BTU/ATM	6,836	7,627	-10.4
Price - \$ x 10^6	39.121	37.984	+3.0
DOC - ¢/ATM	4.86	4.47	+8.7

Fuel Cost = \$3/BTU x 10^6 = 15.48 ¢/lb - LH_2
= \$2/BTU x 10^6 = 24.87 ¢/Gal - Jet A

These reductions are a direct result of the higher energy content per pound of the LH_2 fuel relative to jet A fuel. The unit price, based on a fleet size of 350 aircraft, is slightly higher for the LH_2 aircraft because of the higher cost of LH_2 peculiar subsystems, such as fuel tanks and fuel systems. The higher direct operating costs for the LH_2 aircraft are, in part, because of the assumption made for the cost of LH_2 and jet A fuels, i.e., #3/10^6 Btu for LH_2 and #2/10^6 Btu for jet A. Study results show that hydrogen-fueled cargo aircraft became more competitive with jet A fueled aircraft with increase in payload and range. They also show that equal DOC's are possible for the large LH_2 and jet A cargo transports when jet A fuel costs are increased by about 50¢/gal. A comparison of the plan views of the LH_2 and jet A fueled cargo transports given in Fig. 11 shows the smaller span and 36% reduction in wing area of the LH_2 transport relative to its counterpart jet A transport. The LH_2 transport is slightly longer to accommodate the volume required for the fuel and achieve a satisfactory fuselage fineness ratio.

The maximum cargo payload of 250,000 lb utilized in the NASA hydrogen-fueled transport study is not large enough to allow a performance improvement to be shown when the spanloader design concept is applied. For a payload of 600,000 lb considered in this paper, preliminary study indicates that both the ram-wing and spanloader design concepts will provide performance improvement over that for conventional designs.

Nuclear-Powered Configurations

Some thought again is being given to nuclear-powered aircraft. The military sector has always had interest in the potential for long endurance and long range capability inherent with nuclear power. Eventually, civil use of nuclear aircraft will be advantageous for civil logistics, surveillance, and scientific investigations. The recent renewed interest, however, is a result of the energy crisis.

Nuclear technology has progressed significantly in recent years since the termination of the ANP program in 1959. Today there are longer-life nuclear fuel, improved heat-transfer systems, lighter, more compact shielding, and a feasible reactor containment system for high-speed impact. The status of these and other technologies applicable to nuclear aircraft is available.[7,14] The brief discussion in this paper will concern itself only with aircraft design concepts.

Lockheed studies and growth projections indicate that a nuclear-powered cargo aircraft designed to provide a useful payload will have at least a takeoff gross weight of 1.5×10^6 lb, or about double that of large transport aircraft. This is a result of the large weight of the reactor, shield, and containment system consistent with the required reactor power level for propulsion.

A conventional design nuclear aircraft, shown in Fig. 12, is similar in external appearance to a C-5, but has a takeoff gross weight of 1.58×10^6 lb. Consistent with the weight increase, the wing area is more than double that of the C-5, and the fuselage is ten feet longer than the C-5 fuselage to provide an adequate moment arm for the empennage to assure satisfactory stability and control.

A cruise speed of Mach 0.85 at 30,000 ft alt is achieved through use of a supercritical wing design with a lift-to-drag ratio of 23. Propulsion is provided by four wing-mounted turbofan engines capable of producing 52,500 lb of thrust when operated on chemical fuel for takeoff and landing.

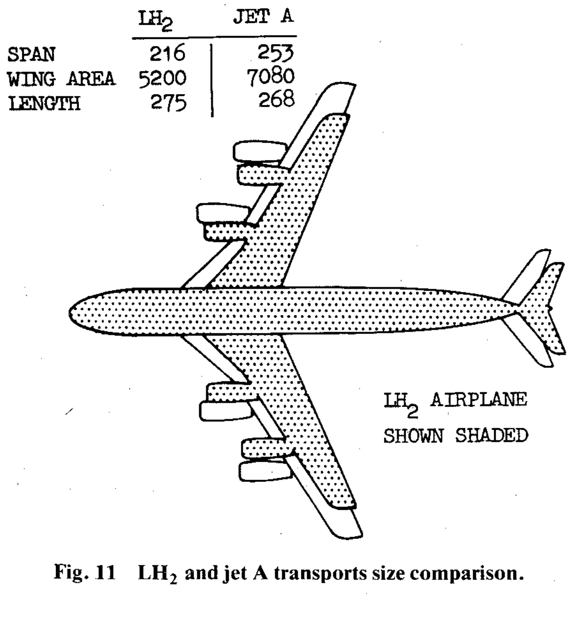

Fig. 11 LH_2 and jet A transports size comparison.

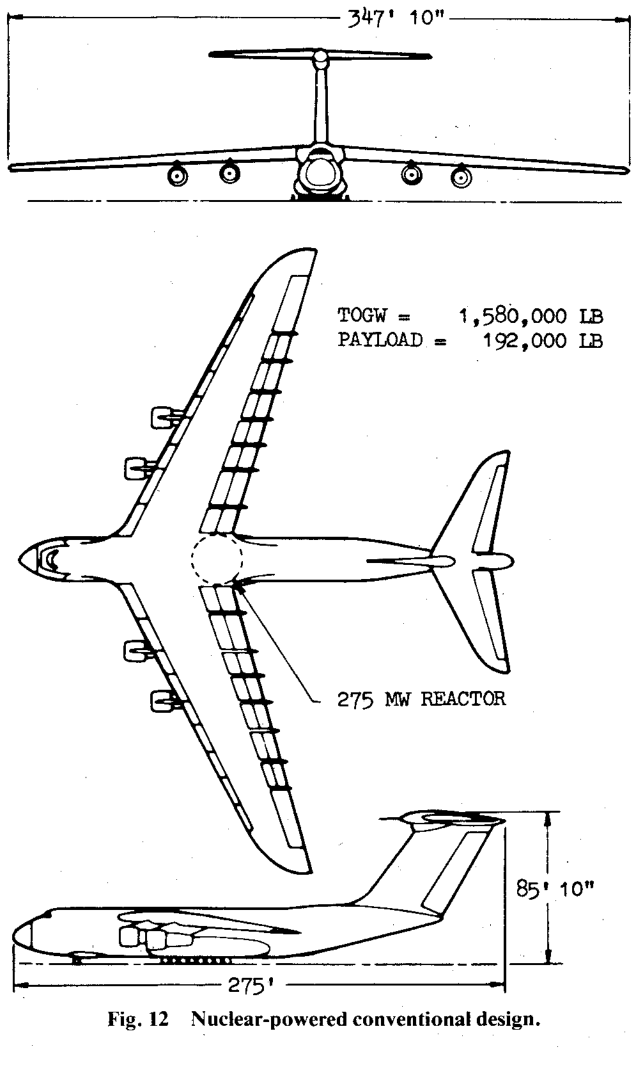

Fig. 12 Nuclear-powered conventional design.

Table 6 Comparison of chemical and nuclear fuel costs

	Chemical Fuel	Nuclear Fuel
Unit Cost	\$0.33/Gal	\$10/Gram
Heating Value - 10^6 BTU/Lb	0.019	30,000
Lifetime Fuel Cost - Millions \$	156	9

Nuclear heat for cruise is supplied by a 275-Mw reactor mounted in the fuselage at the aft center of gravity position of the airplane. For a takeoff gross weight of 1.58×10^6 lb, the operating weight empty is 1.28×10^6 lb. Included in the operating weight is 500,000 lb for the reactor, shield, and containment system.

With a 192,000-lb payload capacity, the airplane is adaptable to either a long range cargo supply mission or a long endurance patrol mission. Doors and ramps are required at both ends of the fuselage for cargo movement because the reactor, shield, and containment system are located in the middle of the cargo compartment.

A discussion of system and operating costs for nuclear-powered aircraft is not warranted at this time, but there are other cost implications that are of interest. For example, a comparison of nuclear and chemical fuel costs are given in Table 6. Lifetime costs are based on the 10,000-hr lifetime of nuclear fuel elements and indicate better than an order of magnitude reduction in fuel costs for nuclear fuel as compared to chemical fuel.

Several innovative design concepts for nuclear aircraft are discussed,[7] and one of the most promising is the swept spanloader design shown in Fig. 13. This design requires a 220 Mw reactor to provide nuclear heat for cruise at Mach 0.75 and 35,000 ft alt. The physical size of the configuration is appreciably smaller than the conventional design illustrated in Fig. 12, and the 250,000-lb payload capability gives a payload to gross weight ratio of 21% as compared to 12% for the conventional design. The reactor location, coincident with the aircraft center of gravity, permits easy access for installation, maintenance, and replacement, through the aft fuselage door. This reactor location does not impede loading and unloading of the cargo compartments as is the case for the conventional design.

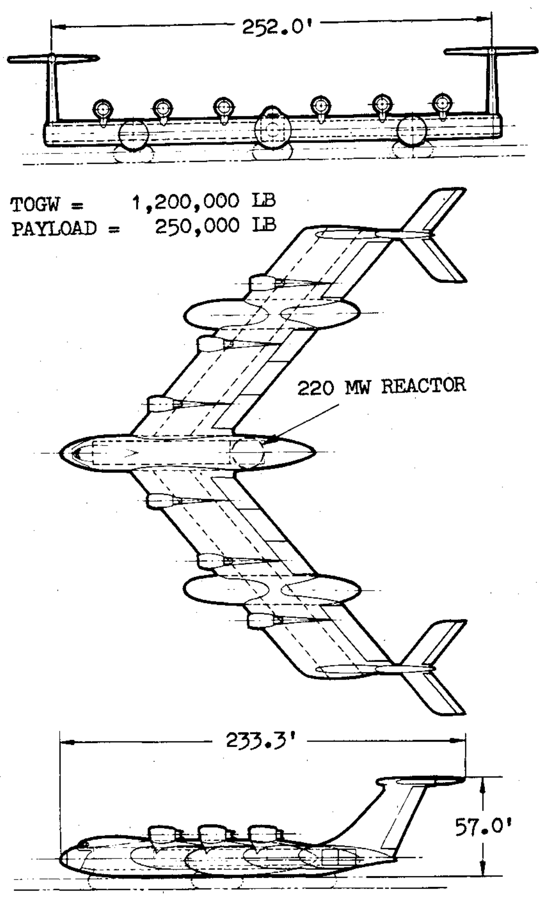

Fig. 13 Nuclear-powered swept spanloader design.

Table 7 Comparison of chemical and nuclear ram wing designs

	Chemical	Nuclear
Take-Off Gross Weight - Lbs	1,800,000	1,800,000
Operating Weight - Lbs	550,000	890,000
Payload - Lbs	850,000	910,000
Fuel - Lbs	400,000	-
Range - NM	3,000	Unlimited
Propulsion	Turboprop	Turboprop
Reactor Power - MWT	-	100

The ram-wing concept also is a promising design for nuclear aircraft, primarily because of the inherently large size of the vehicle and increased safety due to operation over water or remote arctic areas. NASA studies of nuclear powered air cushion vehicles are published.[15] A comparison of performance characteristics of chemical and nuclear-powered ram-wing designs is given in Table 7. The data show a relatively low reactor power requirement, 100 Mw, for the ram-wing design, which results in unlimited range capability for high payloads.

IV. Conclusions

Innovative design concepts, such as the ram wing and spanloader, are shown to have the potential for significant weight, 47%, and attendant cost savings for very large cargo aircraft as compared to conventional designs. Whereas the best available methods are used to determine the weight and performance of these novel design concepts, there is a lack of statistical and experimental data to validate the performance estimates. These innovative design concepts also show large potential performance improvements when applied to large cargo aircraft utilizing hydrogen fuel and nuclear propulsion. It is felt, therefore, that the potential gains to be derived from these novel design concepts warrant the pursuit of research and development activities pertinent to the establishment of the technology data base for these design concepts.

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