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Large Wing-in-Ground Effect Transport Aircraft

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A promising innovative design concept is wing-in-ground effect (WIG) where aircraft performance is increased significantly by drag reduction due to ground effect. This paper presents the results of preliminary design studies of large WIG transports utilizing a power-augmented ram system for lift enhancement developed by the David W. Taylor Naval Ship Research and Development Center. These studies include spanloader and fuselage loader designs and cover gross weights up to 1.9 million lb and payloads up to 661, 500 lb. Comparison of performance and economics are made among the WIG and several conventional design transport concepts.

Introduction

THE evolution of today's largest transport aircraft, the 747 and C-5A, has included application of advances in technology and design concepts to meet the requirements for high productivity and minimum operating costs. This evolution, moreover, has shown that as the size of transport aircraft has increased, advances in technology have permitted continuing improvements in performance and economics; however, it is anticipated that further improvements due to size are likely to be obtained in smaller increments.[1] This result has promoted the consideration of innovative design concepts as a means of providing larger incremental improvements in performance and economics of future, larger transport aircraft. One of the promising concepts is wing-in-ground effect (WIG) where aircraft performance is increased significantly by drag reduction due to ground effect.[2] This paper presents the results of preliminary design studies of large WIG transports utilizing a power-augmented ram (PAR) system for lift enhancement developed by the David W. Taylor Naval Ships Research and Development Center (DTNSRDC).[3-7]

Part of the results presented in this paper were generated under continuing preliminary design and system studies by the Lockheed-Georgia Co. and part of the results were sponsored by the Naval Air Development Center under the Advanced Naval Vehicles Concepts Evaluation Project.[8,9] An artist's sketch of the span-distributed loading PAR/WIG configuration developed in the Navy ANVCE study is shown in Fig. 1. On completion of the Navy ANVCE studies, Lockheed extended its Company-funded design studies of PAR/WIG aircraft to include payloads of 661,500 lb. The results of these design studies are included in this paper and cover gross weights up to 1.9 million lb for both spanloader and fuselage loader designs. Comparison of the performance characteristics of WIG configurations and several conventional design aircraft are also provided.

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Index categories: Configuration Design; Structural Composite Materials.

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System Definition

Mission Parameters

The primary mission for the WIG aircraft is envisioned as a water-based logistics system operating over a sea state 3 ocean environment for a range of 4000 n. miles. As illustrated in Fig. 2, take off and landing is made from the ocean surface, cruise altitude is established in ground effect, and the aircraft proceeds to its destination at a cruise speed of Mach 0.40. At this speed the mission time is approximately 15 h. The Mach 0.40 speed was determined as optimum for cruise as a result of the trade studies in the ANVCE study.[8] Maximum payload capability of 441,000 and 661,500 lb is based on transporting four and six M60A3 main battle tanks, respectively, and also standard sea/land commercial containers.

The cruise altitude is determined as a compromise between the ideal altitude specified by the classical ground effect theory shown in Fig. 3 and the operational requirement for sea state 3 with a structural design limit for sea state 4. Flight in ground effect inhibits the downwash induced by the wing lift, thus suppressing the induced drag. This reduction can be expressed as an increase in effective wing aspect ratio. This relationship is shown in Fig. 3, where the ratio of effective aspect ratio A_E to geometric aspect ratio A_G is given as a function of the height of the lowest extension of the wing

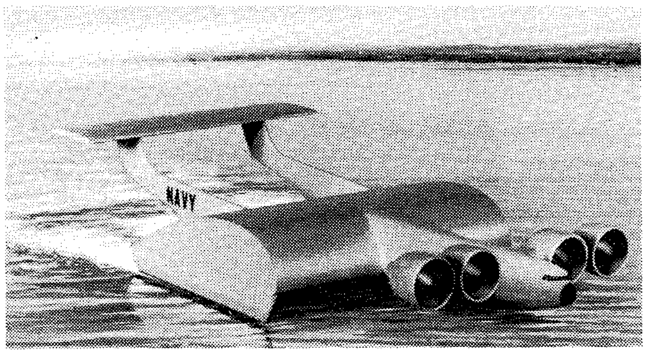


Fig. 1 PAR/WIG transport.

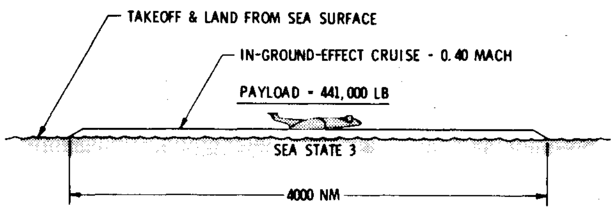


Fig. 2 Logistics mission profile.

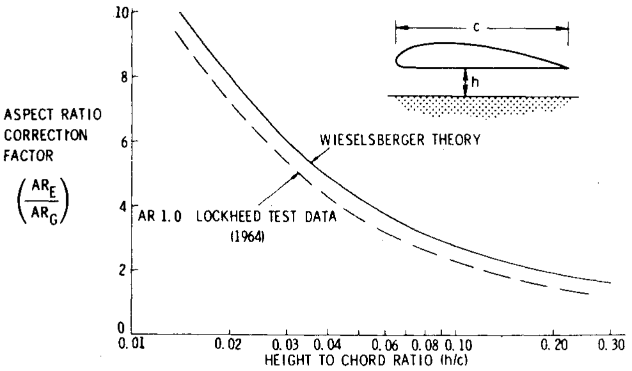
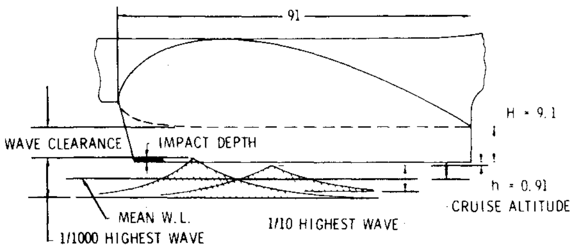


Fig. 3 Ground effect theory.



ALL DIMENSIONS IN FEET

WAVE HEIGHT			CRUISE	IMPACT	WAVE
SEA STATE	1/10	1/1000	ALT	DEPTH	CLEARANCE
3	5.8	8.88	3.81	0.63	8.47
4	8.7	13.32	5.26	1.40	7.70

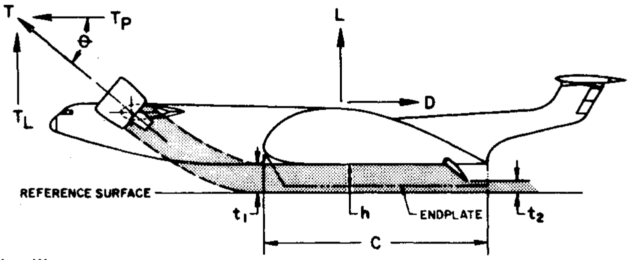
Fig. 4 Cruise altitude definition.

surface, including endplates h above the water surface divided by the wing chord c. The solid line represents Wieselsberger's theory and the dashed line is extracted from wind tunnel tests.[10] Data for both sea states and a diagram of the wing/endplate profile in the cruise condition are provided in Fig. 4. Cruise altitude is based upon clearing the one-tenth highest wave crest and impacting the one-thousandth wave crest to a depth of 0.63 and 1.4 ft for sea states 3 and 4, respectively. A minimum clearance of 3.0 ft is maintained between the one-thousandth wave crest and the wing lower surface primary structure during cruise operations in either sea state. It is generally accepted that one-thousandth waves are sufficiently representative of the entire wave spectrum, and the "most probable" value of the one-thousandth wave height represents the maximum.[11,12]

Technology

All transport aircraft discussed in this paper incorporate advanced technolgy—especially in power-augmented ram (PAR) lift, propulsion system, and structural materials—considered to be compatible with an initial operational capability (IOC) of 1995-2000. Basic to the design of the WIG aircraft discussed here is the application of PAR lift based upon the pioneering investigations of the DTNSRDC on water-based ground effect vehicles.[3-7] These investigations showed that the PAR system can be used to provide lift enhancement during takeoff and landing so that the wing loading of the WIG can then be optimized for cruise performance conditions. Furthermore, by means of PAR lift during takeoff and landing the contact speed between the water and the primary structure is reduced by about 60%; hence, there is no need for a a hulled surface and the structural weight of the aircraft is reduced.

PAR lift augmentation during takeoff and landing is illustrated in Fig. 5 for the spanloader PAR/WIG configuration. The engines are rotated so that the primary propulsion efflux is directed toward the cavity under the wing formed by the wing lower surface, wing endplates, wing trailing edge flaps, and the water surface. In this manner lift



$L = W$

$L_{PAR} = W - T_L = W - T \sin\theta$

$T_{PAR} = T\left(\frac{1+\cos\theta}{2}\right)$

REF: ASED 365

Fig. 5 PAR lift augmentation.

up to six times the installed thrust can be obtained while still recovering 70% of the thrust for acceleration. A complete description of the theory and experiments on PAR is given by Gallington and Chaplin.[3]

The propulsion system selected for the PAR/WIG aircraft consists of advanced technology bypass ratio 30 turbofan engines installed in short duct/separate exhaust nacelles. The performance, weight, and other characteristics of these engine/nacelle installations assume technology and materials that are expected to be available by the year 1990. The selected propulsor resulted from the aircraft sizing efforts using parametric propulsion data developed by Lockheed. The parametric engine data are comparable, at the same bypass and fan pressure ratios, with the STF477 turbofan engine defined by Pratt & Whitney Aircraft at the conclusion of their study, conducted under contract from NASA Lewis Research Center, for low energy consumption turbofan engines of the 1990's.[13] Thus, for the point design aircraft, the selected engine thermodynamic cycle is assumed to be similar to a low rotor modification of the STF477 engine. The high-pressure compressor, the combustor, and the high-pressure turbine characteristics of the basic STF477 core would be retained while the low-pressure spool is modified to meet the selected bypass and fan pressure ratios. The resulting engine configuration is assumed scaleable to the design point maximum thrust level of 95,600 lb.

The design point engine assumes a dual rotor configuration with a variable pitch, single stage, 1.15 pressure ratio fan and booster compressor stages gear coupled to a low-pressure turbine and a high-pressure compressor driven by an air-cooled turbine. The performance and geometry characteristics of this variable pitch fan are estimated to be similar to those available from an advanced Hamilton Standard "Q-Fan." A low emissions, two-stage vortex burning and mixing combustor will provide a 2600° F maximum average combustor exit temperature. Characteristics of this engine are shown in Table 1.

The PAR/WIG thrust vector system allows the entire engine/nacelle/pylon installation to rotate as a unit to provide the powered ram for takeoff and landing and the thrust vectoring for low-speed pitch control.

Table 1 Engine characteristics

Bypass ratio	30
Turbine inlet temperature	2600°F
Engine inlet airflow	6160 lb/s
Engine dry weight	14,070 lb
Overall pressure ratio	45:1
Specific fuel consumption	
Max. continuous power and 0.4 Mach	0.427 lb/h/lb
Max. continuous power, 0.4 Mach and $\eta = 0.65$	0.457 lb/h/lb
Max. power at sea level	95,600 lb
Bare engine length	14.2 ft
Bare engine max. diameter	16.3 ft

Table 2 Weight reduction factors

Component	Factor
Wing	0.61
Fuselage	0.81
Empennage	0.74
Pylon-nacelle	0.79

Table 3 Structural materials usage

	Materials distribution (% component weight)			
Structural component	Filamentary composites	Aluminum alloys	Steel alloys	Titanium alloys
Wing	85	9	4	2
Fuselage	50	35	10	5
Empennage	66	28	4	2
Nacelle and pylon	35	25	25	15
Endplate	0	0	0	100
Hydrofoil	0	0	0	100

A more complete description of the design and operational features of the propulsion system installation and the waterborne maneuvering system is contained in previous reports.[8,9]

A major part of the PAR/WIG structure utilizes graphite epoxy composites in the primary structural components which are considered compatible with the 1955 IOC of the aircraft.

The weight reductions for the primary aircraft components in composite materials as compared to the equivalent aluminum structures given in Table 2 were obtained from earlier Lockheed parametric studies of advanced technology transports.[14]

The components are weighed as aluminum structure by known statistical methods and then reduced by applying the factors shown. Whereas the primary structural material is graphite epoxy composites, some parts of the aircraft such as the endplates and hydrofoil must be in contact with sea water; therefore, these components are constructed of titanium for corrosion resistance. The distribution of several structural materials in the structure of the PAR/WIG aircraft is given in Table 3.

Preliminary Design

The unconventional general arrangement of the spanloader PAR/WIG aircraft shown in Fig. 6 is the result of the unusual characteristics of the system. These characteristics include PAR lift augmentation for takeoff and landing, cruise flight only in ground effect, payload contained in the wing, and all operations accomplished on or above the ocean surface. An additional constraint imposed in the ANVCE study was a span limitation of 108 ft to allow use of facilities sized for the majority of contemporary naval vessels. The resulting transport configuration has a very low aspect ratio wing, rotatable engines mounted forward on the fuselage, a wing area of 9828 ft^2, a takeoff gross weight of 1,362,000 lb for a payload of 441,000 lb, and four engines with sea level static thrust of 95,600 lb each. Twin vertical tails and an all-movable horizontal tail provide aerodynamic control. This aircraft has a relatively low operating weight empty as compared with its takeoff gross weight.

There are a number of structural features which are determined by the configuration or by the specific nature of the PAR/WIG aircraft. These features, as illustrated in Fig. 7, include the basic wing, wing endplates and flaps, static flotation structure, hydrofoil, and the primary propulsion system rotation support structure.

In order to satisfy system needs for efficient low subsonic cruise speed, cargo compartment size for the spanloader

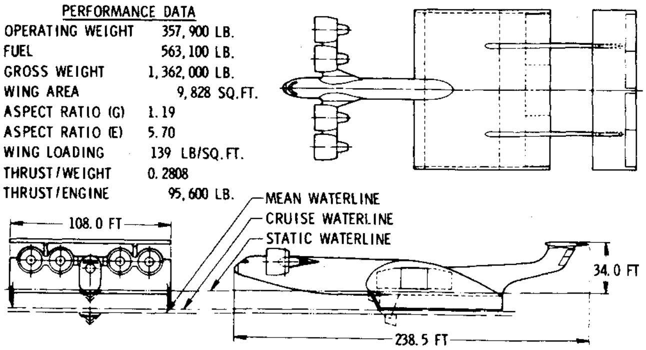


Fig. 6 PAR/WIG spanloader general arrangement (441,000 lb payload).

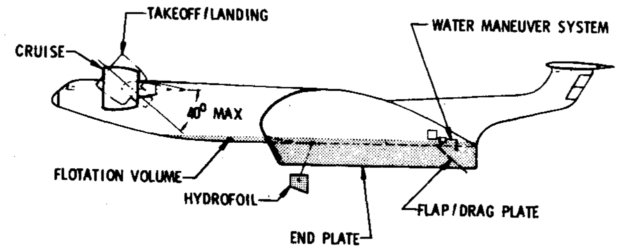


Fig. 7 PAR/WIG design features.

design, and a flat lower surface for the PAR lift augmentation, a modified Clark Y airfoil with a thickness ratio of 25% is used on both the spanloader and fuselage loader designs. The wing flaps are a simple hinge, split surface type used as both control surfaces and as hydrodynamic drag surfaces during the landing mode. A load relief system is incorporated into the flap system to prevent excessive loads should maximum allowable water contact speed be exceeded during landing operations. The outer flap panels also act as ailerons.

The hydrodynamic and structural configuration of the wing endplate is critical to the feasibility of the PAR/WIG aircraft, since this is the only structure required to impact the water at cruise speed. The endplate shown on Fig. 6 is 91 ft long, 9.1 ft high, and has a 2 ft beam width. The leading edge has a sweep angle of 30 deg and is wedge shaped.

The endplate design was determined from the results of the analysis of endplate loads due to drag and side force at $M=0.4$ speed and utilizing experimental towing tank data. Details of this analysis are covered in the previous PAR/WIG report.[9]

Static flotation is provided by the aircraft displacement volume located beneath both the wing cargo compartment floor and the forward fuselage crew area floor. These volumes are compartmentalized and sealed to allow the aircraft to remain afloat should the wing or fuselage lower surface suffer impact damage from floating debris.

The hydrofoil used to provide both lift and drag during the landing mode has lift and drag coefficients of 0.3 and 0.1, respectively. Extension speed is 150 ft/s and maximum lift and drag loads of 505,000 and 168,000 lb are developed upon complete submersion at 125 ft/s. The structural design philosophy of the hydrofoil is one of a simple brute strength approach with a massive titanium plate weighing 62.7 lb/ft^2 supported by heavy backup structure.

The engine mounting arrangement on the forward fuselage is the most unusual feature of the fuselage structure. A continuous torque box spans the fuselage width and supports all four engines. Engine rotation is accomplished by actuating the torque box and thus all engines are rotated as a single unit. A fuselage weight penalty of 10% is assumed to account for this engine mounting arrangement.

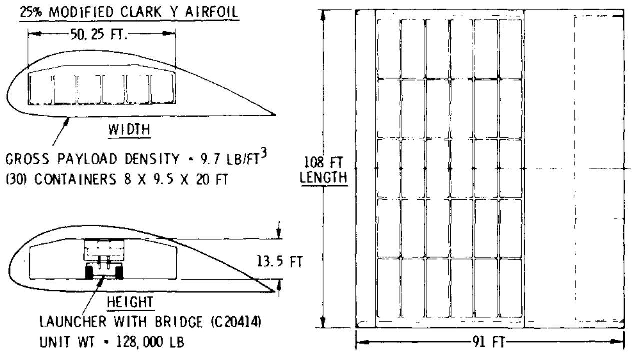


Fig. 8 Spanloader cargo compartment sizing.

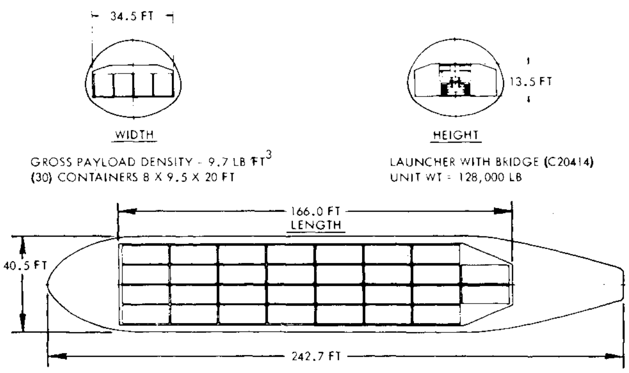


Fig. 9 Fuselage loader cargo compartment sizing.

Aircraft Sizing

The cargo compartment is sized to transport either of two logistics payloads. The first is the capability to transport standard commercial sea/land containers 8 ft wide, 9.5 ft high, and 20 or 40 ft in length at a gross payload density goal of 10 lb/Ft.[3] The second payload definition includes the transport of U.S. Army or U.S. Marine Corps standard vehicles. The 1976 H series Army Table of Organization and Equipment is used to identify this equipment. A compartment height of 13.5 ft is required to transport the launcher with bridge, the maximum height vehicle to be transported. Maximum payload capability of 441,000 and 661,500 lb are established based on transporting four and six M60A3 Main battle tanks with necessary shoring and restraint hardware, respectively.

Cargo compartment width and height for the spanloader design are selected as shown in Fig. 8. The 108 ft wing span allows sufficient length for each container row to consist of five 20 ft containers. Thirty containers, or six rows, are required to provide the contained volume necessary to meet the gross payload density of 10 lb/Ft.[3]The compartment width required for six container rows is 50.25 ft for the 441,000 lb payload.

The cargo compartment sizing for the fuselage loader design for a 441,000 lb payload is shown in Fig. 9. The 166 ft long cargo floor accommodates 30 containers in four rows at seven containers per row plus two on the tapered aft section. Compartment width of 34.5 ft is based on four container rows with necessary allowances.

Operational Characteristics

Flight operational characteristics of the PAR/WIG aircraft is described by pictorial representations of the takeoff and landing sequences shown in Figs. 10 and 11, respectively. The following conditions applicable to these figures are noted. First, altitude as given by these figures is measured from the mean water line to the base of the wing endplate; therefore, for static conditions, negative altitudes occur. Second, pitch control is maintained by variable engine thrust vector up to a speed of 72 ft/s where aerodynamic control surfaces become effective.

The total takeoff run for the PAR/WIG aircraft is defined as that distance covered from the static rest position to that point where cruise speed and altitude are achieved.

The aircraft is designed such that the loss of one engine while airborne will not prevent a safe landing; therefore, the landing sequence given in Fig. 11 is representative of the one engine out condition. This condition requires unsymmetrical thrust settings on the remaining engines to maintain a constant heading.

To initiate the landing maneuver from the cruise mode, the engine vector angle is rotated to 30 deg, flaps are set at 40 deg, and power setting is reduced to 70%. This configuration provides the necessary lift from the PAR system; however, the horizontal thrust available under these conditions is more than sufficient to maintain a velocity of 89 knots and it becomes necessary to increase configuration drag by the use of a hydrofoil. At speeds of less than 37 knots, the wing endplates and flaps are allowed to contact the water and provide additional drag. Not until the aircraft is slowed to a speed of 16 knots is the primary structure, wing or fuselage lower surface, allowed to impact the water.

Mission performance is based upon operations over sea state 3 conditions. The aircraft structure is designed to withstand sea state 4 conditions; however, in this sea state, mission capability is degraded.

The center of gravity envelope for the spanloader design is presented in Fig. 12. The balance characteristics of the aircraft are somewhat unusual due to the configuration and the takeoff procedure. The power augmentation concept requires that the engines be mounted well forward of the wing. This forces the operating weight to be the most forward point on the envelope, about 10% M.A.C. The payload is loaded at the centroid of the cargo compartment, and the fuel is located under the cargo floor. The fuel location is chosen specifically in order to keep the aircraft center of gravity within the specified envelope. The forward and aft limits of the envelope are developed from balance requirements during the low-speed segment of takeoff. For normal flight and landing conditions, the envelope is significantly wider; however, since the fuel and payload must be loaded to conform to the takeoff limits, there is no particular advantage in specifying limits for other conditions.

Flying-in-ground effect in close proximity to the water surface prevents normal banked maneuvers; therefore, obstacle avoidance maneuvers must be accomplished by sideslip maneuvers. Figure 13 shows the turning radius and the time to achieve a 1000 ft lateral displacement as a function of side acceleration. At cruise speed, 0.40 Mach, 10 deg of sideslip produces a side acceleration of 5.5 ft/s^2 at takeoff gross weight. A reduction in weight increases this acceleration proportionately. An acceleration of 5.5 ft/s^2 yields a turning radius of about 36,500 ft and 19 s to achieve a 1000 ft lateral displacement. The distance traveled during this displacement maneuver is approximately 8500 ft.

Aircraft Performance

Basic to the estimation of the performance of the PAR/WIG aircraft is the determination of the effective aspect ratio of these configurations. The effective aspect ratio is determined by applying correction factors to the geometric aspect ratio to account for endplating and ground effect. Hoerner[15] provides an equation for calculating the effective wing aspect ratio resulting from endplating AR_{EP} as a function of geometric aspect ratio AR, endplate height H, and wing span b as follows:

$$AR_{EP} = AR[1.0 + 1.9(H/b)]$$

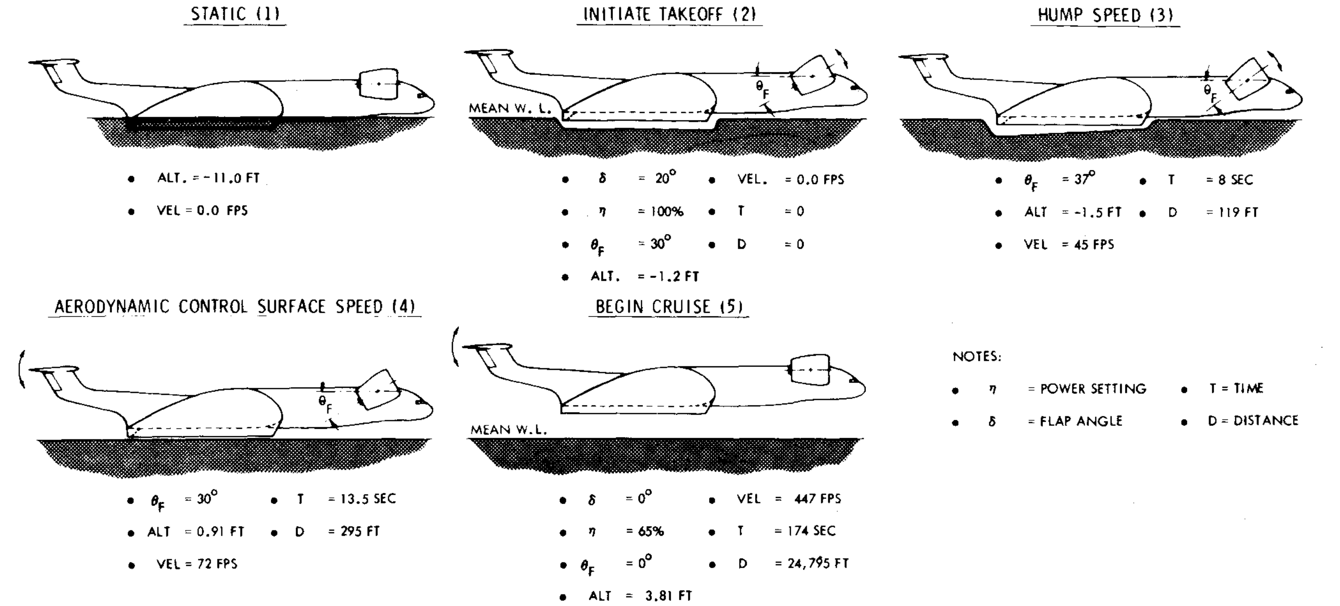


Fig. 10 Takeoff sequence.

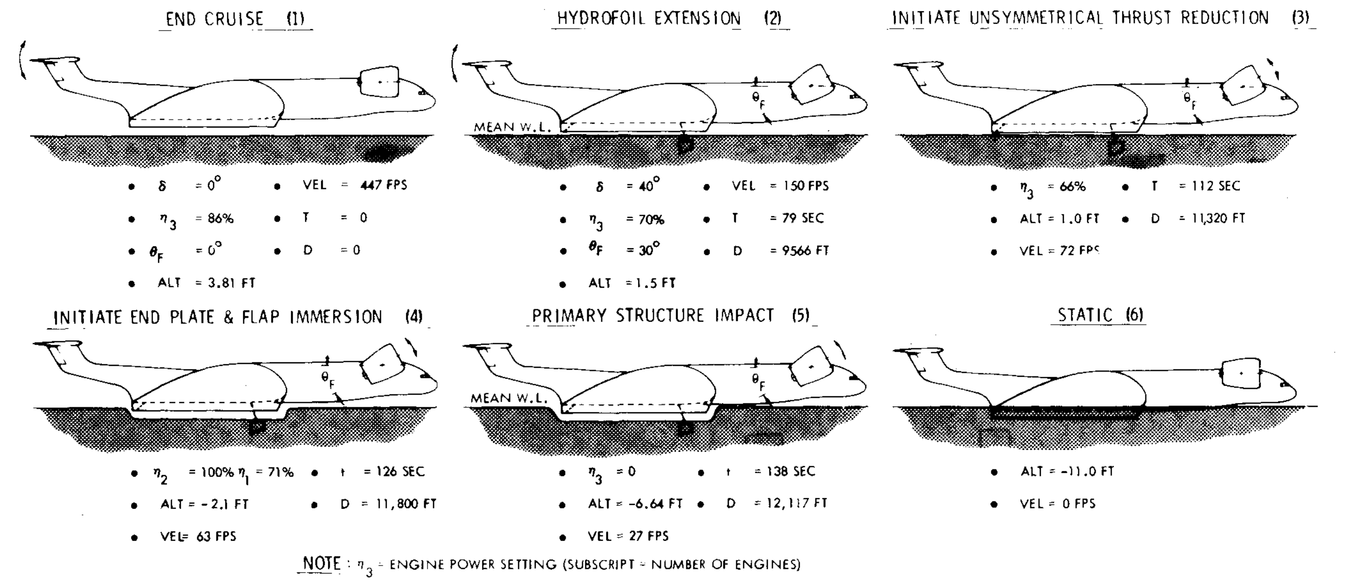


Fig. 11 Landing sequence.

The influence of flight-in-ground effect is given by the dashed curve given in Fig. 3. The combination of endplating and ground effect influence on the geometric aspect ratio of 1.19 for the spanloader design of Fig. 6 results in an effective aspect ratio of 5.7 for sea state 3 conditions. A discussion of the lift and drag characteristics of the PAR/WIG designs is given in a previous report.[9]

The alternate fuselage loader PAR/WIG design developed includes differences from the spanloader design in that the payload is contained in the fuselage, the restriction on wing span is removed, and the number of engines is increased from four to six. The resulting design of the fuselage loader with a payload of 441,000 lb is shown in Fig. 14. The aircraft has an effective aspect ratio of 11.02, a takeoff gross weight of 1,196,200 lb, and six engines with a sea level static thrust of 50,400 lb each. The data for the spanloader and fuselage loader design characteristics presented in Table 4 show that as compared to the fuselage loader the spanloader is 9% heavier in operating weight, is 14% heavier in gross weight, uses 33% more fuel, and has 25% lower cruise efficiency. Part of this deficiency in performance of the spanloader design is attributed to the restriction of the wing span to 108 ft and the attendant effect on the wing aspect ratio.

In order to assess the capability of WIG-type transports with more conventional transport designs, preliminary designs were developed for a conventional land-based military transport and a catamaran-hulled seaplane of the type developed in the Navy ANVCE program.[16] All designs have the capability for payloads of 441,000 lb and ranges of 4000 n. miles. The characteristics of the several design concepts are given in Fig. 15. In this somewhat cursory comparison the conventional high subsonic speed, land-based, advanced technology transport has the highest productivity and best cruise fuel efficiency as expected. The fuselage loader WIG, however, has minimum operating and gross weights and second best fuel efficiency and compares favorably with the conventional transport.

Preliminary designs were developed for both PAR/WIG transports for design payloads of 661,500 lb in order to assess the effects of increase in size on performance characteristics. The spanloader and fuselage loader general arrangement drawings are given in Figs. 16 and 17, respectively. In this

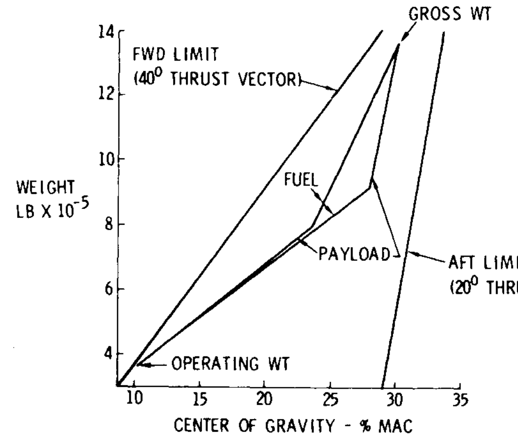


Fig. 12 Center of gravity envelope.

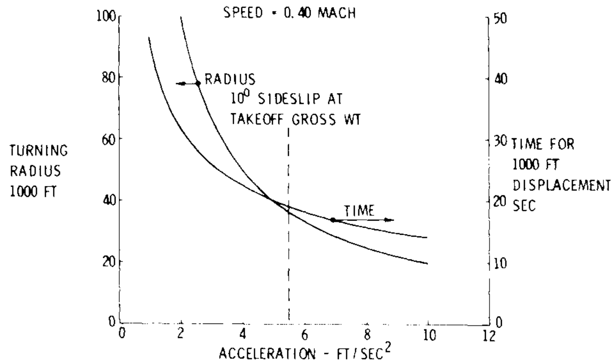


Fig. 13 Cruise maneuver performance.

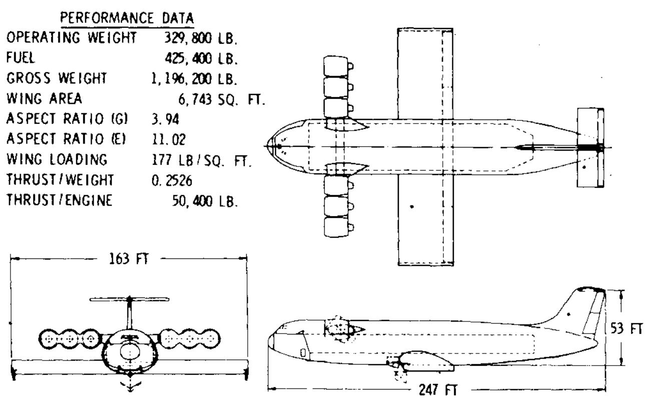
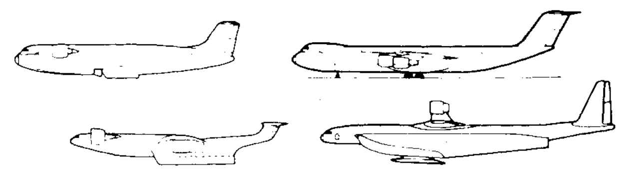


Fig. 14 PAR/WIG fuselage loader general arrangement (441,000 lb payload).



RANGE = 4000 NM

PAYLOAD = 441,000 LB	WIG SPANLOADER	WIG FUSELAGE LOADER	SEAPLANE	CONVENTIONAL
CRUISE SPEED - MACH	0.4	0.4	0.7	0.85
CRUISE ALTITUDE - FT	SL	SL	34,000	36,000
CRUISE L/D	15.59	19.79	18.33	20.86
NUMBER ENGINES	4	6	5	4
EFFECTIVE ASPECT RATIO	5.70	11.02	8.15	11.40
OPERATING WEIGHT - LB	357,900	329,800	599,700	542,000
BLOCK FUEL - LB	524,600	394,700	443,100	355,300
GROSS WEIGHT - LB	1,361,900	1,196,200	1,196,200	1,368,800
TON-MILES/LB FUEL	1.68	2.23	1.99	2.48

NOTE: ANVCE CONTRACT ENGINE DATA & PERFORMANCE GROUND RULES

Fig. 15 Design concepts comparison.

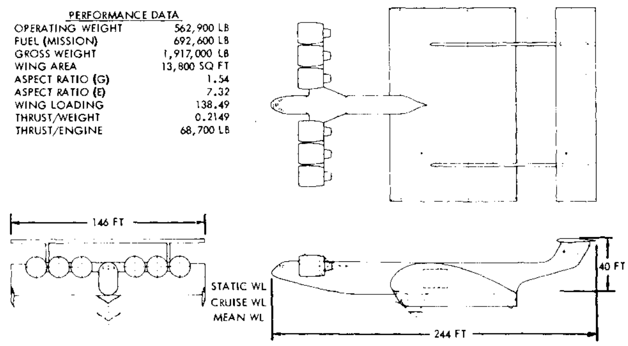


Fig. 16 PAR/WIG spanloader general arrangement (661,500 lb payload).

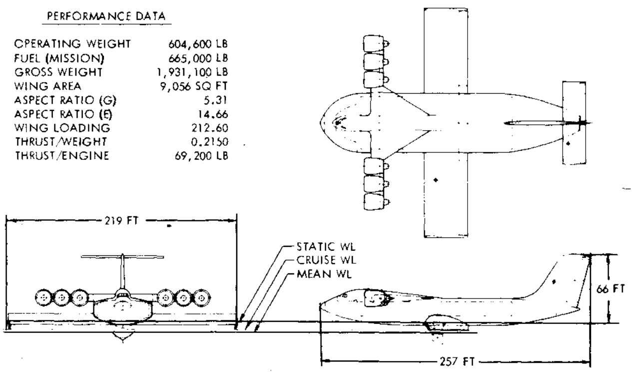


Fig. 17 PAR/WIG fuselage loader general arrangement (661,500 lb payload).

Table 4 Comparison of spanloader and fuselage loader designs (441,000 lb payload, 4000 n. mile range, Mach 0.4 speed, sea level cruise altitude)

	Spanloader	Fuselage loader	Δ%
Geometric aspect ratio	1.19	3.94	−70
Effective aspect ratio	5.70	11.02	−48
Cruise L/D	15.59	19.79	−21
Number engines	4	6	−33
Thrust/weight ratio	0.2808	0.2526	+11
Cruise power setting	0.65	0.57	+14
Operating weight, lb	357,900	329,800	+9
Block fuel, lb	524,600	394,700	+33
Gross weight, lb.	1,361,900	1,196,200	+14
Payload/gross weight	0.324	0.369	−12
Ton-mile/lb fuel	1.68	2.23	−25

Table 5 Comparison of spanloader and fuselage loader design (661,500 lb payload, 4000 n. mile range, Mach 0.40 speed, sea level cruise altitude)

	Spanloader	Fuselage loader	Δ%
Geometric aspect ratio	1.54	5.31	−71
Effective aspect ratio	7.32	14.66	−50
Cruise L/D	18.34	20.40	−10
Number engines	6	6	−0−
Thrust/weight ratio	0.2149	0.2150	−0−
Cruise power setting	0.72	0.65	+11
Operating weight, lb	562,900	604,600	−7
Block fuel, lb	642,900	616,200	+4
Gross weight, lb	1,917,000	1,931,100	−1
Payload/gross weight	0.345	0.343	+1
Ton-mile/lb fuel	2.06	2.15	−4

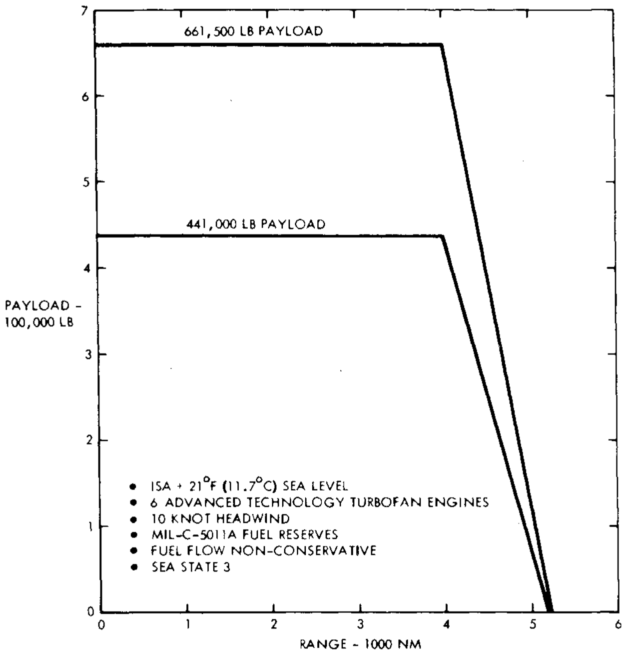


Fig. 18 PAR/WIG payload-range curves.

study the span constraint of 108 ft on the spanloader design was relaxed and the aspect ratio was optimized for minimum weight. The comparison of characteristics given in Table 5 shows a large improvement in spanloader WIG weight and performance relative to the fuselage loader WIG such that its gross weight is 1% lighter than that for the fuselage loader and its fuel efficiency is only 4% lower. These are significant improvements in spanloader WIG performance as compared to that obtained at 441,000 lb of payload. It should also be noted that the fuselage loader WIG is slightly lower in fuel efficiency at this higher payload condition.

Payload range curves for the spanloader WIG transports at 441,000 and 661,500 lb of payload are given in Fig. 18 with a design range of 4000 n. miles. The data assume 10 knot headwinds and MIL-C-5011A fuel reserves.

Conclusions and Recommendations

Based upon the preliminary investigations made to date, the PAR/WIG transport aircraft described in this paper show relatively low operating, empty, and gross weights and only slightly lower cruise fuel efficiency than a high subsonic speed, land-based conventional advanced technology transport. The WIG aircraft show potential for use as strategic systems because of cruise operations entirely at very low altitudes.

A number of investigations are needed to provide an increased confidence level in the conceptual analysis of PAR/WIG type aircraft. Examples of these investigations include:

1) An expanded definition of the relationship between PAR performance and configuration characteristics such as engine location, vector angle, engine out effects, engine pressure ratio, wing loading, and airfoil section.

2) Flight path dynamics while in ground effect so as to provide stability and control criteria.

3) Various hydrodynamic configurations of the wing endplates to provide maximum structural strength and minimum drag.

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