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The Development and Flight Testing of the XC-8A Air Cushion Landing System (ACLS)

David J. Perez
Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base

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THE PURPOSE OF THIS paper is to describe the principal components of the Air Cushion Landing System (ACLS) as applied to the XC-8A and briefly relate the findings of the flight test program.

The ACLS is based on the ground effect principle which employs a stratum of air instead of wheels as the aircraft ground contacting medium. This concept evolved from the Air Cushion Vehicles (ACVs) which are now being used throughout the world for transporting heavy loads across soft ground (Figure 1). The ACLS employs a large expandable tube (Figure 2), over three feet (0.91m) in diameter when inflated, which encircles the bottom of the fuselage providing both an air duct and seal for the air cushion. The bottom of the tube, which is referred to as the trunk, contains over 6 700 nozzle holes through which low pressure air passes into the air cushion cavity. The air source for the system is an onboard auxiliary turbine driven fan. The low pressure, about 1 PSI (6 895 N/m^2), within the cushion cavity times the planform produces a force equal to the weight of the vehicle. Due to these low ground overpressures, this concept allows an aircraft to operate from extremely soft surfaces, including water, and the flexibility of the rubber trunk allows the vehicle to ride at a very low daylight clearance. Prior to the use of trunks, substantial power requirements approaching that of a VTOL aircraft were necessary to provide a practical hoverheight distance between the ground and the vehicle hard structure. In fact, this was the major shortcoming of the Ground Effect Takeoff and Landing (GETOL) concept. The use of the flexible trunk significantly increases the hoverheight of the vehicle, allowing it to traverse obstacles up to 2/3 of the trunk depth without increasing the daylight clearance and lift power.

Figure 3 graphically illustrates the augmentation or lift efficiency of a thin annular jet plotted against variations in daylight clearance and planform diameter. The lifting power of a typical ACV and ACLS is about 50#/hp (0.03 Kg/w) as compared to 12#/hp (0.0073 Kg/w) and 4#/hp (0.0024 Kg/w) for a typical helicopter and tilt wing VTOL in ground effect hover.

Since 1966, the Air Force Flight Dynamics Laboratory has been investigating the application of the air cushion concept to replace the

ABSTRACT

The Air Cushion Landing System is based on the ground effect principle which employs a stratum of air instead of wheels as the aircraft ground contacting medium. The concept has experienced an evolutionary process from Air Cushion Vehicles (ACVs) to an air cushion equipped, 41 000 lb (18 589 KG) Buffalo aircraft, designated the XC-8A. The XC-8A has demonstrated the ability to operate from a variety of landing surfaces and across many types of obstacles. This paper summarizes the XC-8A development and preliminary flight test results.

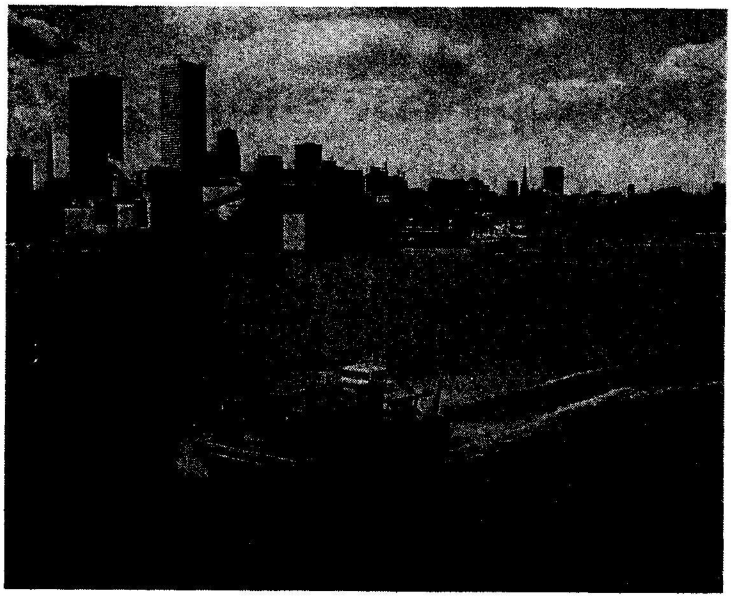

Fig. 1 - Voyageur operating in Toronto Harbor

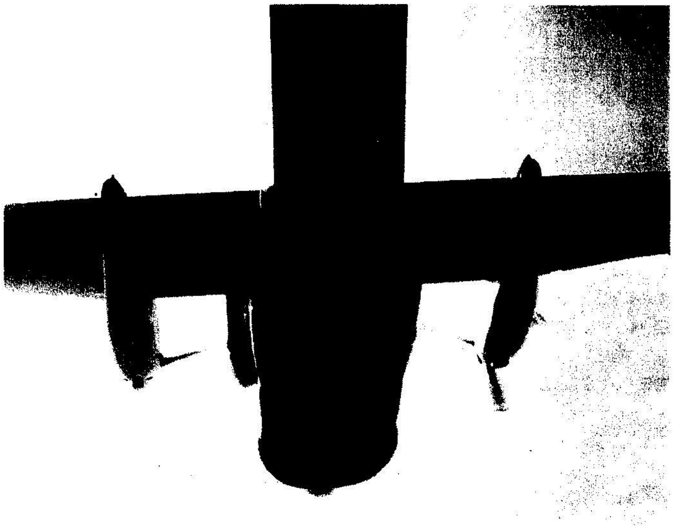

Fig. 2 - Bottom view of XC-8A with trunk inflated

conventional wheel gear landing system. The first ACLS equipped aircraft was the Lake LA-4 (Figure 4) which dramatically demonstrated the unique capabilities of this landing system by operating routinely on snow, ice, rough terrain and doughy mud strips, even under high cross-wind conditions.

As a result of the successful LA-4 tests, the USAF and the Canadian Government initiated a joint cooperative development project in May 1971 to demonstrate the functional capabilities of an ACLS equipped de Havilland Buffalo aircraft (Figure 5). The individual work efforts performed during this program were assigned to four contractors: Bell Aerospace Company assumed responsibility for the ACLS design, de Havilland of Canada performed the aircraft structural modifications, United Aircraft of Canada designed, tested and built the ACLS auxiliary power system, and Hamilton Standard designed and built a Beta propeller system to enhance cushionborne maneuverability.

The XC-8A is currently being tested at Wright-Patterson AFB, Ohio, by the 4950th Test Wing under the direction of the AF Flight Dynamics Laboratory. To date, the XC-8A has been tested over a variety of surfaces and obstacles and has accumulated over 68 hours of trunk inflation time. The Program is currently scheduled to end in March 1977.

XC-8A DEVELOPMENT AND DESIGN

The design objective of this modification has been to install the ACLS without interference to the basic aircraft configuration or function. As a result, the air cushion is designed to support the Buffalo aircraft at the same height as the wheels giving a fuselage ground clearance of about 33 in. (0.84m). In the static hover condition the attitude is slightly nose high, 1.5° (0.03 rad), to account for the negative pitching moment resulting from forward thrust. The positive pitch attitude is also a preventive design measure for plough-in*. The only concession to not interfering with the basic design is that the contractors were not held to a maximum weight limitation. This results in a system weight of over 4 500 lb (2 041 Kg) which is almost twice that of the conventional wheel gear weight of 2 500 lb (1 134 Kg) (See Table 1). This additional weight accounts for about a 35% reduction in the basic XC-8A range.

The design of the Air Cushion System has been tailored to the existing airframe. The forward edge of the trunk starts at the nose-gear door position and terminates at the cargo loading ramp for an inflated length of 32 ft (9.75m). With a cushion area of 240 ft^2 ($22.3m^2$) and an aircraft gross weight of 25 000 lb (15 876 Kg), the XC-8A operates at an overpressure of 135 lb/ft^2 (6 464 N/m^2). This is slightly less than 1 lb/in^2 (6 895 N/m^2) which is several orders of magnitude lower than the XC-8A conventional tire pressure of 45 Lb/in^2 (310 275 N/m^2). At this gross weight, the trunk augments cushion lift by approximately 2 600 lb (1 179 Kg).

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*Plough-in is a technical term used to describe a phenomenon of air cushion dynamics whereby an excessive nose down movement is created by excessive trunk to surface drag. Plough-in is characterized by a rapid deceleration and large negative pitch attitudes which could terminate with hard structure contact with the ground.

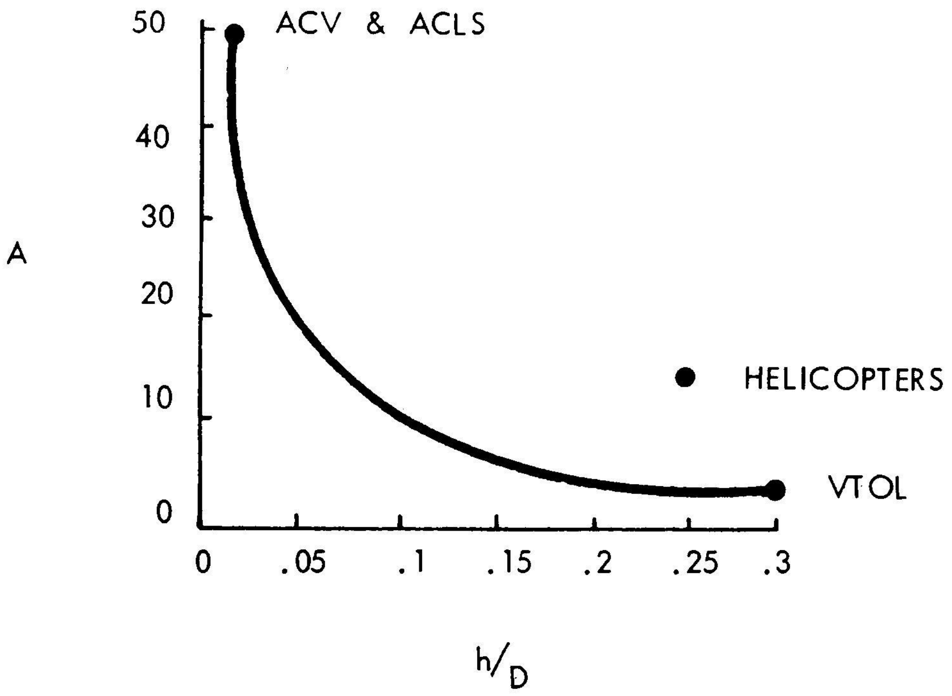

Fig. 3 - Lift augmentation factor

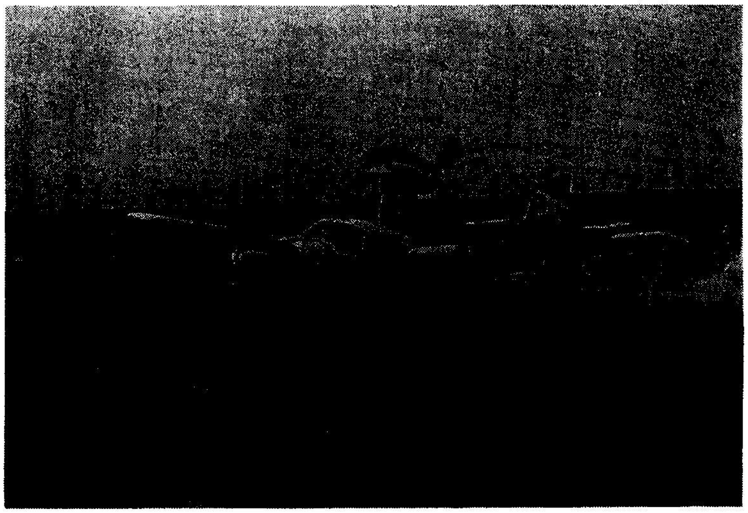

Fig. 4 - ACLS equipped LA-4 operating over water

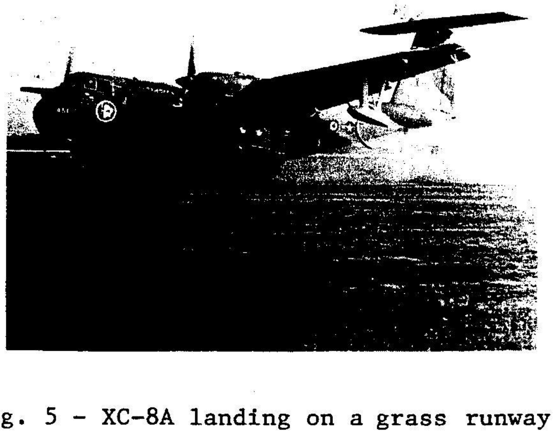

Fig. 5 - XC-8A landing on a grass runway

Table 1 - XC-8A ACLS Weight Summary (3)*

Air Cushion System			1577
Trunk Assembly		890	
Brake Skids	108		
Brake Pillows and Lines	92		
Trim Port Valves and Lines	30		
Pouches	7		
Fasteners	48		
Trunk Sheet	605		
Wing Floats and Skids		322	
Trunk Attachment Rails		230	
Parking Bladders		135	
Auxiliary Power System			1916
Engine, Fan and Shroud	604		
Nacelle Mtg. and Systems	133		
Fan Exit Duct	205		
Muff	12		
Controller	4		
Total Per ASP-10	958		
Aircraft Modification			1088
Structural Modification	557		
Electrical Modification	320		
Pneumatics Modification	147		
Hydraulic	27		
β	5		
Rear Bumpers	32		
Total			4581

*Numbers in parentheses designate References at end of paper.

Associated with the trunk lift is a drag which can vary from about 1 800 lb (816 Kg), $.5 < \mu > .8$, on concrete to virtually 0 on a grass surface. The drag component occurs on the aft portion of the trunk which is behind the aircraft center of gravity and is therefore directionally stabilizing. Trunk drag on concrete is about equal to the rolling resistance of a conventional aircraft tire (.05).

The cushion/trunk pressure ratio (P_c/P_j) is between .40 to .45 and is based on previous ACV designs and model and computer studies to provide proper roll stiffness and energy absorption. Drop tests conducted on 1/4 and 1/10 scale models verified the analytical analysis and showed that the modification did not significantly alter the original design landing envelope.

An aerodynamic study showed that the total trunk inflated drag for the XC-8A consisted of the following components:

$$C_D = C_{D_o} + \Delta C_{D_o} + K_{C_L}{}^2 + \frac{5.19}{gpVS} + \frac{1.59}{q} \sin \alpha$$

Where C_{D_o} = Basic CC-115 zero lift drag

ΔC_{D_o} = ΔCLS Component Drag

$KC_L{}^2$ = Induced Drag

$\frac{5.19}{gpVS}$ = Momentum Drag Contribution

$\frac{1.59}{q} \sin \alpha$ = Cushion Thrust Drag

With the trunk deflated the XC-8A shows a drag increment of 20% over the clean aircraft due to the addition of wing floats and auxiliary power system. (This increase in drag reduces the range of the XC-8A by 17% over the conventional Buffalo aircraft.) The drag increment of the inflated trunk is approximately equal to the drag of the extended wheel gear.

The requirement for an elastic trunk that hugs the fuselage like a de-icer boot when it is deflated has presented the most perplexing technical problems to this program. The complex geometry of the trunk has necessitated the use of a two-way stretch material with a programmed memory. To accomplish this, the trunk is constructed of a wound nylon tire cord sandwiched in between natural rubber (Figure 6). By varying the number of coils per inch, the individual tapes that make up each ply can be programmed to have elongations from 0 to 300%. The individual tapes, which can amount to over 3 miles (4 828m) in one trunk, are then laid up in plies (Figure 7), radial and peripheral, with each tape corresponding to predetermined stretch and strength requirements dictated by its location within the trunk structure (Figure 8). After molding in nozzles and attachment holes, the trunk structure is complete and the rubber and nylon composite is then cured into a homogenous sheet.

The installation of the elastic trunk onto the fuselage is quite similar to the installation of a de-icer boot (Figure 9). To prevent the trunk from flagellating against the fuselage when deflated it is installed with a 10-15% pre-stretch. This requirement necessitates the use of winches, pulleys and hydraulic jacks to literally stretch the trunk onto the fuselage.

To maintain a proper trunk extension and adequate energy absorption capacity under various operating conditions, both in and out of ground effect and over rough terrain, the trunk pressure must be retained at or near the design level. The XC-8A operating range is presently between 330 lb/ft^2 (15 800 N/m^2) in

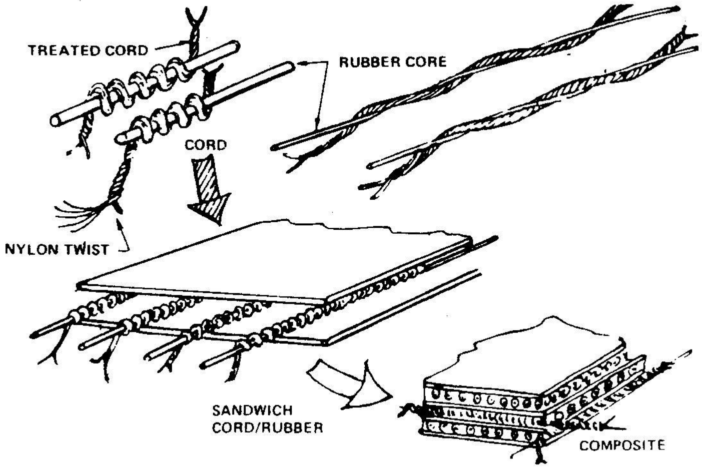

Fig. 6 - XC-8A trunk composite

Fig. 7 - XC-8A trunk under construction

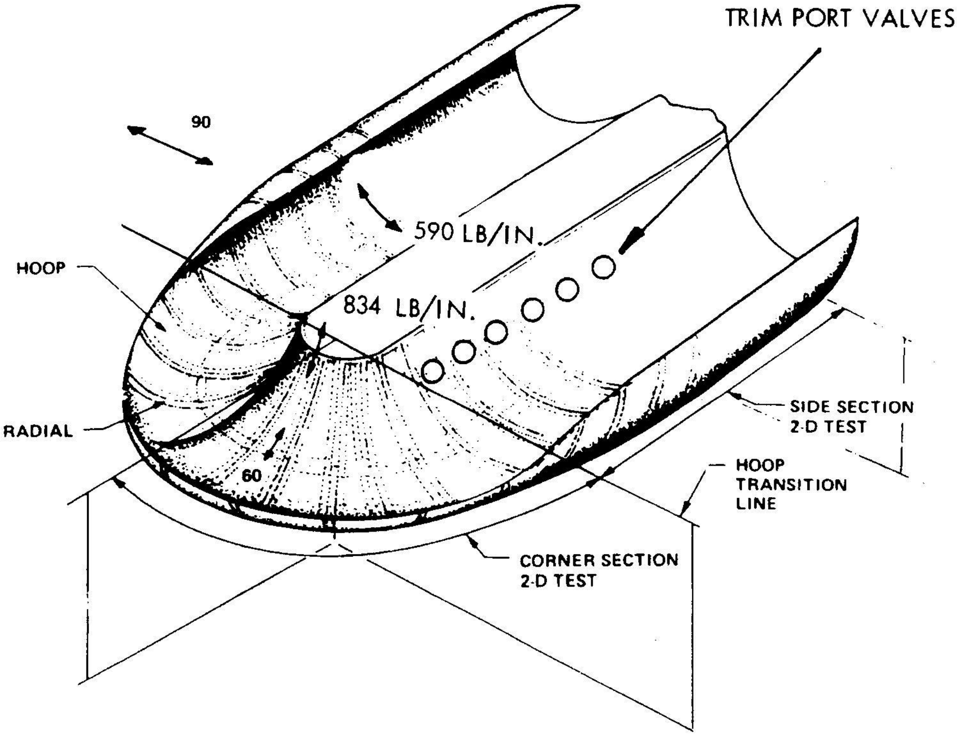

Fig. 8 - XC-8A trunk structure

ground effect and 290 lb/ft^2 (13 885 N/m^2) out of ground effect. The control of trunk pressure can be provided by varying the vent area to the cushion cavity. The effective jet nozzle area in the fully extended trunk is fixed at 1.35 ft^2 (0.125m^2); therefore, a series of six independent, electrically controlled, pneumatically actuated cushion trim valves (CTVs) are provided (Figure 10) on the inner flank of the trunk. The CTVs are controlled from the cockpit and can vary the effective area of discharge into the cushion by an additional 2.794 ft^2 (0.26m^2).

To stop the XC-8A, the bottom of the trunk is equipped with six (steel-impregnated Butyl) skid brakes, each with an approximate footprint area of 346 in^2 (0.22m^2). The brakes are actuated pneumatically (by cooled bleed air) in response to pressure applied by the pilots to the existing toe brakes. The pilots' action inflates a separate bladder (pillow) located above each skid brake (Figure 11). The pillow inflation deforms the trunk reducing the cushion pressure and transferring the load to the sacrificial skid pad. Figure 12 shows typical air cushion system responses to the application and release of the pillow brakes.

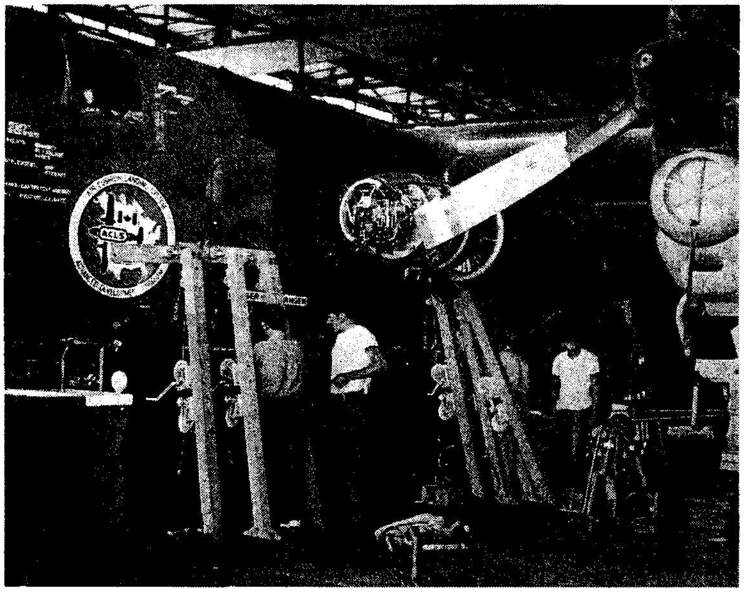

Fig. 9 - Trunk installation

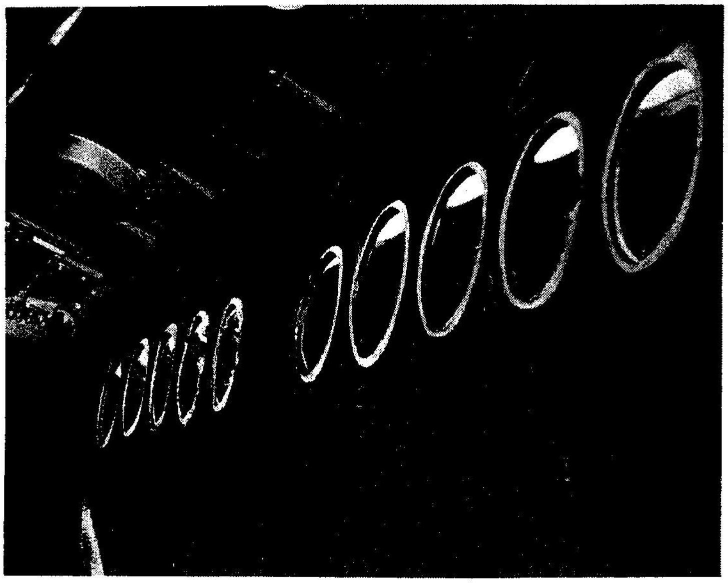

Fig. 10 - Cushion trim valves in operation

The XC-8A parking system consists of six elastic inflatable bladders mounted on the belly of the aircraft. The bladders are inflated with bleed air when the XC-8A is fully cushionborne. Once the bladders are inflated to a preset pressure of between 2.75 and 3.5 lb/in^2 (18 961 and 24 133 N/m^2), the ACLS auxiliary power system is reduced in stages causing the trunk to retract and trunk and cushion pressure to decay. In the final stage of the parking transition, trunk flow is completely blocked by the bladder*, causing the trunk to retract and the aircraft to settle completely on the parking bladders (Figure 13).

The XC-8A power requirements were based on the LA-4 performance. Keeping a constant Froude number ($V^2/g\ell$), the LA-4 aircraft was used as a dynamic model for the XC-8A. Using this analysis, it can be shown that the power requirements vary as the 2.5 or 3.5 powers of the scale factor. The 3.5 power is used if daylight clearance is scaled and the 2.5 power is used if the daylight clearance is identical to that used on the LA-4. Table 2 shows some of the scaling relationships between the LA-4 and XC-8A. For the XC-8A design, it was assumed that the daylight clearance need not be any greater than that for the LA-4. This criterion was used because the jet horsepower requirements from which daylight clearances are calculated are based on thin annular jet theory where the trunk is only air lubricated in the nozzle area. The ACLS uses a distributed jet, thereby providing lubrication over a greater portion of the trunk surface. Assuming a lower trunk drag with a distributed jet, the lower jet horsepower was considered adequate. However, to fully explore the power requirements of the distributed jet, it was decided to install power units capable of supplying

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*By slowly reducing trunk pressure and reinflating the parking bladders, the bladders eventually fill the trunk cavity blocking off flow from the ACLS auxiliary power system forward of the diffusers. This usually occurs at 270 to 250 lb/ft^2 (12 927 to 11 970 N/m^2) trunk pressure. Operating at this low a pressure and suddenly choking off the flow sometimes results in a fan stall causing a somewhat abrupt transition to the bladders.

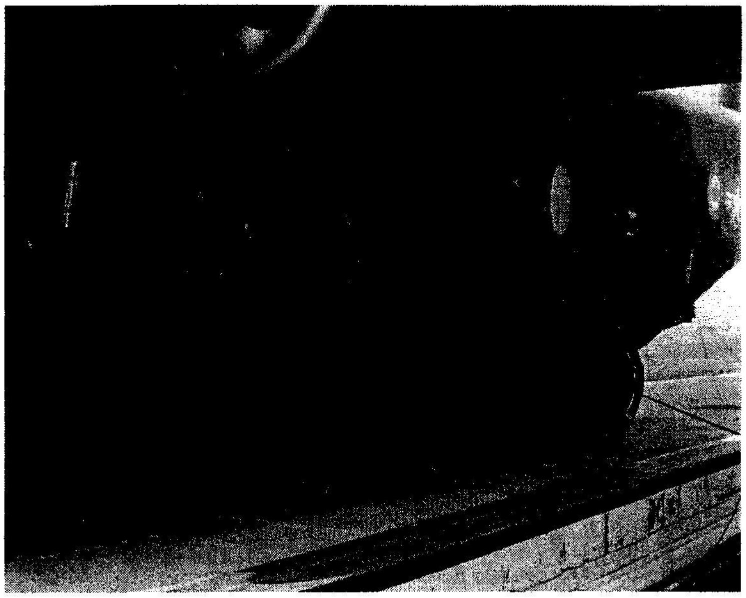

Fig. 11 - Inflated pillow brakes

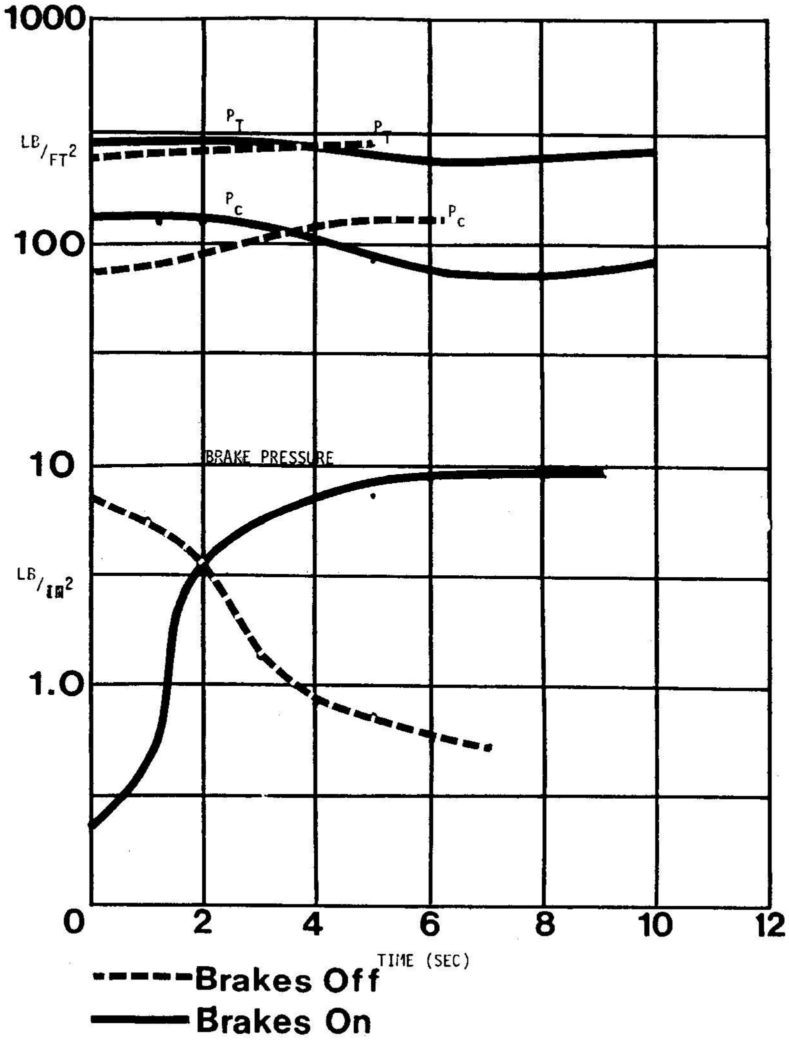

Fig. 12 - ACLS performance during actuation of the pillow brakes

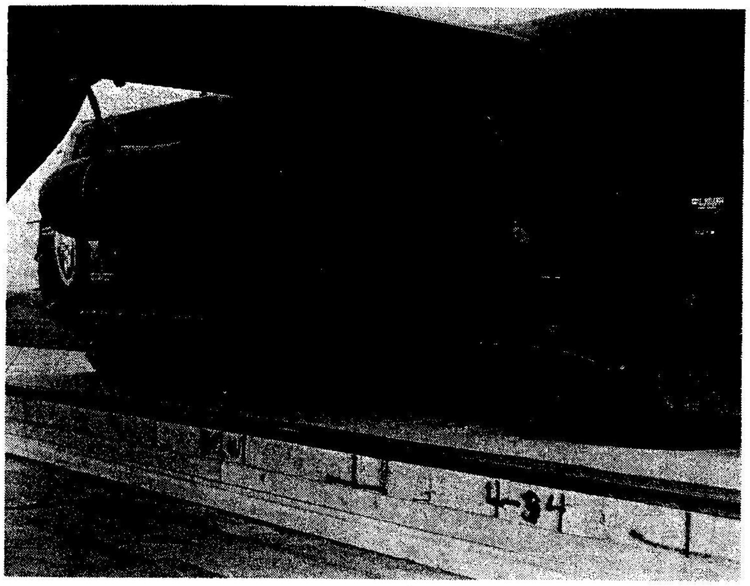

Fig. 13 - XC-8A in full park

Table 2 - XC-8A and LA-4 Scaling Relationship (3)

	LA-4	LA-4 x 2.5	XC-8A
Gross Weight (lb)	2500	39,000	41,000
Wing Span (ft)	38	95	96
Cushion Pressure (lb/sq ft)	60	150	171
Cushion Perimeter (ft)	32	80	65.6
Trunk Outer Radius (in.)	10	25	25
Brake Horsepower	80	1970	1560
Jet Horsepower $(\lambda)3.5$	44	1080	1080
$(\lambda)2.5$	44	435	540

twice that needed for normal operations. A fallout of this design philosophy was a redundant ACLS power system. In the event of an engine failure, the power of the good engine could automatically be increased to maximum thereby compensating for the loss of the other engine.

From the aforementioned analysis, it was determined that a minimum mass flow of approximately 60 lb/sec (27.2 Kg/sec) is necessary to achieve reasonable performance over a smooth level surface. Based on the results of this preliminary design study, which also included extensive dynamic model testing, the air supply package was designed.

Designated the ASP-10 (Figure 14), the power systems consist of streamlined pods which are attached to each side of the aircraft fuselage, where they can deliver pressurized air to the air cushion system. Exterior mounting is used so cargo space is not encroached upon. Two packages provide redundancy. In normal operation, an excess capability is incorporated which will permit investigation into the effect of output power, airflow and terrain traversing capability. A rear mounted fan was chosen since it resulted in lowest frontal area, cost and maximum utilization of existing qualified hardware. The pod consists of three major units: the engine/fan assembly, the engine nacelle/air inlet assembly and the fan exit duct. All other systems that are normally associated with engine installations are incorporated.

The ST6F-70 free turbine engine is a derivative of the very reliable and well known family of PT6 engines and is rated at 800 HP (596 800 W) maximum continuous for this application. Normal ACLS operation requires 640 HP (477 440 W).

A standard 5.33:1 engine reduction gearbox was modified by extending the output shaft and its housing to accommodate the fan and inlet duct. The output shaft is attached directly to the fan rotor. The gearbox is provided at the air inlet end to drive the engine accessories. Oil pump and tank are integrated into the air inlet. A two port exhaust is oriented to direct hot gases away from trunk and aircraft. Other features include heat insulation blankets, disc containment, compressor wash ring, full corrosion protection, and torquemeter. Standard engine mounted controls and protection devices are the proportional solenoid valve signalled from a fuselage mounted electronic control

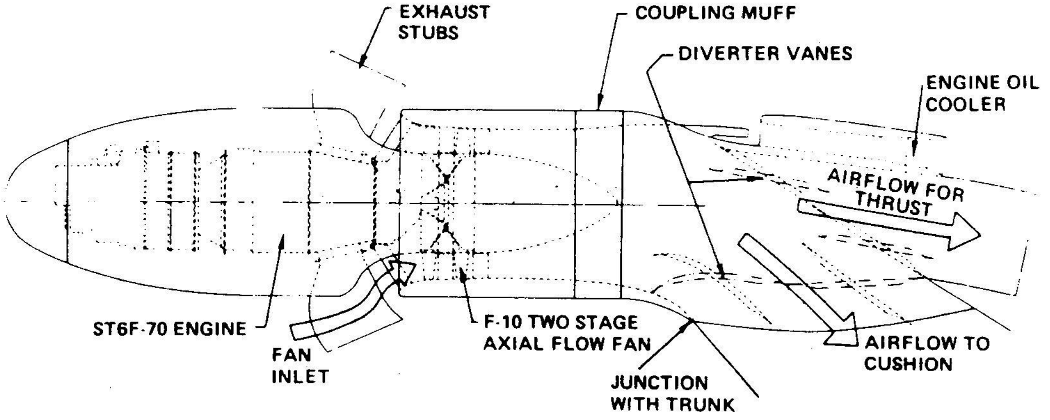

Fig. 14 - ASP-10 air supply package

box, fuel control unit, fan speed governor, torque limiter, and power turbine overspeed trip.

The newly designed fan, designated F-10, consists of two axial stages and is sized to accommodate air cushion system requirements. Design speed is 6 074 RPM, which produces an overall pressure ratio of 1.204:1 and flow of 71.4 lb/sec (32.4 Kg/sec) and has a relative first stage tip Mach No. of 0.75. The rotor is fabricated from titanium and the stators from stainless steel. The airfoils are common in both stages. Air enters the fan via an annulus aft of the engine nacelle. An interesting design requirement was that the fan is expected to frequently operate in transient surge conditions which would be incurred during a high sink rate, zero degree pitch angle landing of the ACLS vehicle. Additionally, operation in austere environments is required. These dictate very robust hardware. The entire engine/fan assembly is attached to the fuselage as a unit by a six restraint frame and link structure with sufficient strength to withstand specification crash loads.

The engine nacelle consists of upper and lower half, removable cowlings and a nosecap to enclose engine and accessories and provide accessibility. The inner section between the engine and fuselage contains the offset engine air inlet duct and is independently mounted to the fuselage. Engine services from the fuselage are also routed through this area. The duct contains an inertial separator and compressor bleed air powered ejector to assist in removal of foreign matter including ice. The nacelle is divided by firewalls into the engine accessories, air inlet, and hot end zones. The engine accessories zone is cooled by convection through nacelle skin louvers. The hot end zone cooling airflow is induced by connecting holes through the fan stator support casing to the low pressure zone immediately forward of the first stage fan blade row.

The fan exit duct is independently mounted to the fuselage and serves to route fan air to the flexible trunk diffuser or to a propulsion nozzle for additional thrust while airborne. Two pairs of diverter vanes actuated hydraulically and signalled from the control system direct the flow to either a cushion or thrust mode. In the inactive shutdown case, both pairs of vanes are closed to reduce fan windmilling during flight. The vanes are aerodynamically loaded so that the cushion and thrust vanes fail open and closed, respectively, to ensure a constant supply of air to the trunk in the event of hydraulic failure. An engine oil cooler is mounted on top of the exit duct. An ejector using fan air as primary air ensures adequate cooling during conditions of static or near static aircraft operation. Easy access to the oil heat exchanger is provided for cleaning. The fan exit duct is connected to the fan inlet/exit assembly by a removable duct section with flexible joints which preclude distortion of the latter by eliminating any load transmissions from the air cushion system via the exit duct.

One criterion for design of the ACLS is that its command operation should be as simple as the conventional gear. This immediately dictates a high degree of automation. Consequently, an electronic control box has been developed specifically for this system which controls, upon command from the crew, stop/start cycles, engine speed by signals to the proportional solenoid valve, diverter vane position, and anti-icing features. Upon command from the overspeed trip, the control box automatically shuts down the overspeeding engine, commands the remaining engine to maximum power simultaneously disarming the shutdown feature, and executes appropriate diverter vane action to maintain trunk inflation. Limited operation with only one air supply package operating at maximum output is possible. The control box also transmits signals of firewarning, fan airflow, rotor speeds, engine oil temperatures and pressures to the cockpit panel and various parameters to the test instrumentation system.

The starting/ignition, oil, fuel, fire protection, and compressor wash systems are designed in accordance with normal aircraft practice.

A comprehensive test program was conducted on the power supply package and consisted of the following:

1) engine exhaust stub test - to check no inlet airflow detachment,

2) fan inlet case test - a 1/3 scale model was tested to again ensure no flow detachment up to 150 knots (77 m/sec),

3) fan exit duct tests,

4) stress tests - vibration bench tests were conducted in samples of rotor blades and first stage stations. Rig tests were conducted on the gearbox front case which carries the fan rotor loads and the fan inlet case which carries the fan stator assembly. Both were found capable of sustaining maximum crash loads,

5) flight clearance tests - the ASP-10, including the flexible diffuser, was subjected to a 50 hour simulated flight operation test cycle. It operated with no problems under conditions of full flow, no flow and surge. The latter case simulated landings under conditions of zero degrees pitch and high sink rates where the airflow is completely choked. Pre- and post-test checks of the fan were made to ensure that no degradation of fan performance occurred.

An ASP-10 performance map is shown in Figure 15.

The changes and additions to the CC-115 structure to accommodate the Air Cushion System result from five sets of imposed conditions:

1) Localized tensions and distributed pressures applied by the trunk and the diffuser ducts.

2) Fuselage shell loads applied by the ASP-10 nacelles.

3) Stiffening and sealing for overwater operations.

4) Penetrations and supports for added and relocated systems.

5) Wing provisions for float/skid outriggers.

The trunk edge is clamped at the outboard attachment rails, and back-up structure has been added to the fuselage to hold the rails at a series of discreet points. Along the straight portions of the fuselage, the rails are bolted through to each frame and are riveted to skins between frames. The longitudinal inboard attachments are made to coincide with existing keel members under the floor, and the trunk attachment bolt loads are distributed into the corrugations of the keel webs; special semi-circular structures were added at each end where design loads are highest.

The structural additions required to handle the trunk loads are shown in Figure 16, and consist of the rail back-up structure mentioned above, longitudinal stiffeners and added bending material on some frames. The rail back-up structure was kept to a minimum. Minor compromises in trunk geometry resulted in load paths within the fuselage which were in several instances already provided by existing structure. The toroidal ends of the

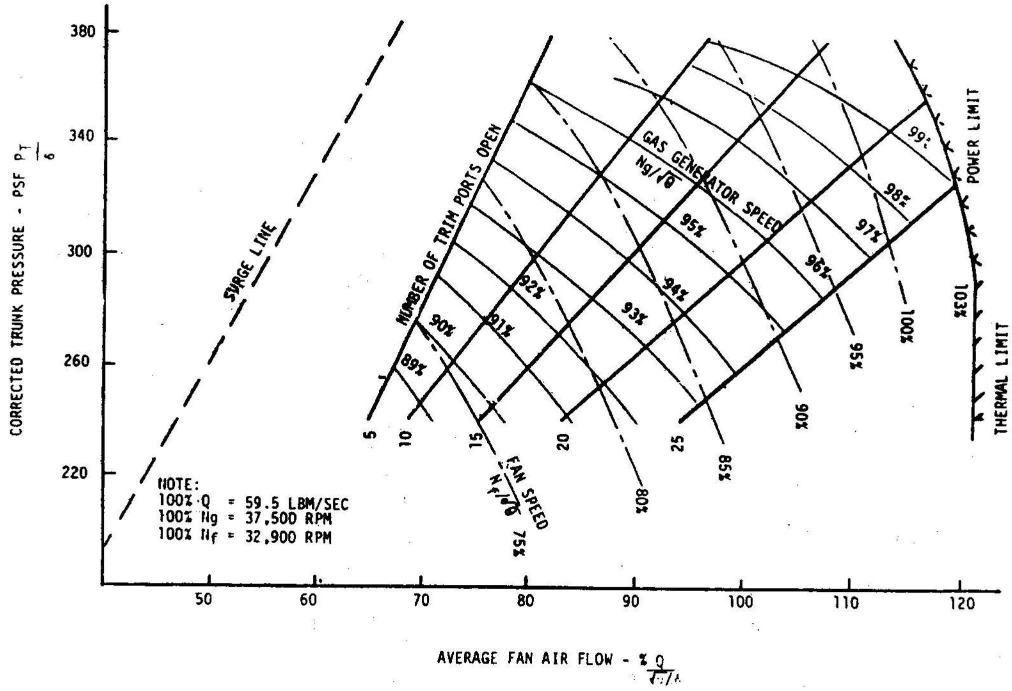

Fig. 15 - ASP-10 fan performance map

trunk required completely new structural additions of some complexity. The longitudinal external stiffeners on the fuselage bottom serve a double function - they prevent collapse of the fuselage skin under the trunk pressure by dividing the existing panels into smaller elements, and they provide space between skin and retracted trunk for such essential components as brakes, brake ducts, trim valves and their supply ducting, and for parking bladder attachments.

The frames which required the most attention to enable them to resist trunk loads were those in the neighborhood of the toroidal ends. Figure 17 illustrates the load pattern. In the parallel portion of the trunk, there is a reduction in the pressure applied to the bottom skin along a central strip some 18 in. (0.46m) wide; here the pressure from the cushion is only about half of that applied by the trunk air. This reduces the severity of the bending loads on the bottom frames. In addition, the membrane tensions from the inflated trunk apply loads in the opposite sense to the pressure loads. This pattern results in no requirement for additional bending material in these frames. At the toroidal ends, however, the full trunk pressure is applied right across the frame, and there are no relieving tensions from inboard attachments; additional bending material was required on the lower caps of two frames, and this was applied externally.

The additional structure to support the compressors was all found to fall between the upper and lower longerons. The engine mounts are supported by five lugs added to each side of the fuselage. The intake and cowling for each engine/fan unit and the diffuser elbows are attached to simple brackets and angles provided on the fuselage. Skin penetrations for services such as fuel supply, engine control circuits and hydraulic lines are grouped to provide not only reasonable access but also minimum structural penalty.

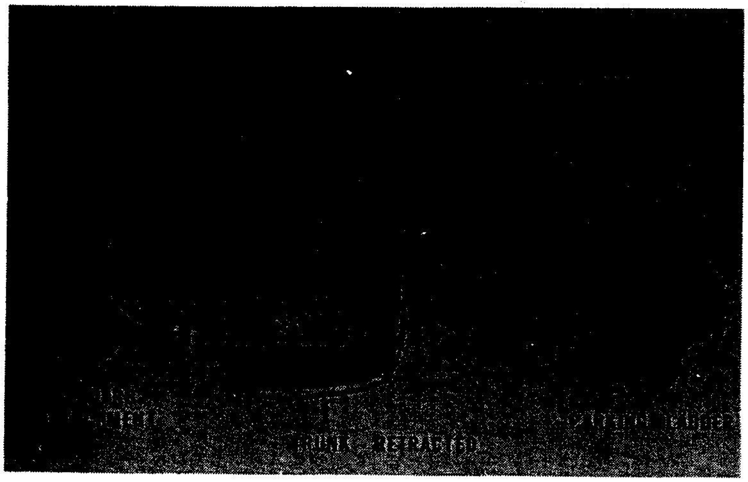

Fig. 16 - XC-8A fuselage structural modifications

To meet the overwater conditions, several changes are introduced. First, the weather radar system is removed; it was not considered economical on the test aircraft to redesign the nose installation to withstand wave impacts, so the radome is removed and a sturdy fiberglass nose cap has been substituted. This new nose cap has provisions to prevent flooding of the intakes for the environmental control system.

The forward lower fuselage has been considerably stiffened by adding new subframes, replacing skin panels with thicker material and providing more rugged hinges and stops for the nose wheel doors. The sealing of all apertures and drains in the fuselage bottom has been carried out to a level 15 in. (0.38m) above the cabin floor except at the aft end where the cargo door mechanism prevents this; to avoid flooding, therefore, a removable dam can be quickly positioned at the aft end of the cabin behind the last cargo tie-down points. Making provisions for the services such as electrical wires, fuel, bleed air and hydraulic pipes, and relocated antenna mounts follows accepted aircraft practices.

Wing tip floats have to be provided for overwater operations, with shock absorbing fiberglass skids to stabilize the aircraft in roll and protect the floats during rough terrain tests. This task has been accomplished without disturbing any wing primary structure and with no reduction of outer wing fuel capacity. The float outrigger assemblies are attached to the wing at just three points on each side. At each point the interface joint is made with a special bolt which is designed to fail at a predetermined and pretested load. This insures that should the outrigger inadvertently experience loads in excess of design loads, it will fall completely away rather than break the wing.

The systems principally affected by the ACLS modifications are as follows: bleed air system, electrical system, hydraulic system, communication and navigation system, fire protection, and fuel system.

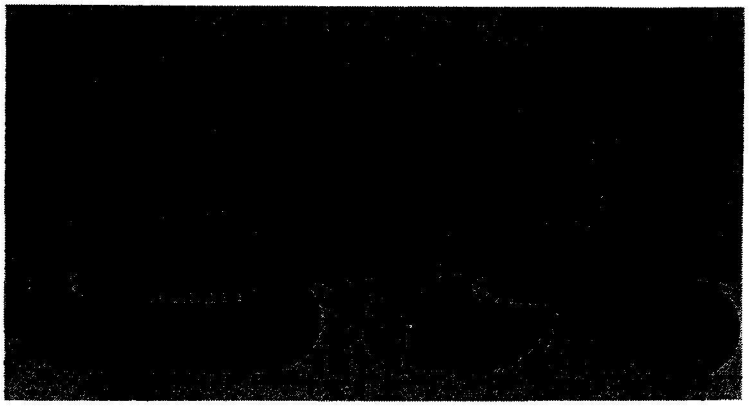

Fig. 17 - XC-8A fuselage load patterns

The bulk of the changes and additions to the bleed air system is located under the cabin floor. The bleed air from all onboard sources is manifolded, with suitable non-return provisions, and passes through an air-to-air heat exchanger. The secondary air for this heat exchanger is obtained by bleeding off a small portion of trunk air at the diffuser duct and dumping it into the cushion cavity; the primary air temperature is thus kept below 250°F (122°C) which is the upper operating limit for ACLS brakes and parking bladders. The other service supplied through the heat exchanger provides control air to the cushion trim valves. The air that has performed its function in the brakes, trim valves and parking bladders is dumped back into the fuselage, where provisions are made to disperse it through the aircraft's ventilating outlets.

All the added pneumatic and hydraulic valves are controlled electrically and the auxiliary engines are controlled by electrical signals throughout their entire duty cycle. In view of the limited dc capability in the CC-115, two more batteries are added complete with control and charging equipment for starting the ASP-10 engines.

An interesting problem is the need to provide all the required electrical signals during the operations on the air cushion and with the wheeled gear retracted. Information normally supplied by landing gear switches for deployment of spoilers and other essential services is now provided by cushion pressure switches. Electrical circuits have been provided which made it possible to use either the ACLS or wheels mode.

Hydraulic circuits have been added for ACLS brakes and for vane operation in the ASP-10's. Signals are taken from the existing foot brakes to modulate the air pressure supplied to the pillow-type brakes built into the trunk; in this manner both proportional and differential braking are achieved.

Communication and navigation equipment remains much like that originally installed in the CC-115. As mentioned earlier, the weather radar system has been removed; the space vacated by the cockpit display is now occupied by the control panel for the ASP-10's. The ADF sense antenna has been moved from its ventral location, where it interfered with the trunk, and has been replaced by a rod-type mounted on the upper aft fuselage.

The fuel system for the PT-6 engines has been kept as simple and as straightforward as possible. Fuel is drawn from the crossfeed gallery in the basic aircraft fuel system. Off-the-shelf filters and firewall shutoff valves are provided on each side. The single point refuel/defuel nozzle was relocated due to its being covered by the ACLS trunk. A completely new installation has been provided in the starboard main engine nacelle behind the wheel well.

In common with air cushion vehicles, the XC-8A encounters directional control problems under ground traversing conditions which border on frictionless. The Beta control modification contributes significantly to the solution of the ground control problem. The advantages of Beta are exhibited in two general areas: in approach and touchdown, and in ground maneuvers.

The conventional CC-115 system provides for blade angle movement from +75° (1.3 rad) (Feather) to -27° (-0.47 rad) (Reverse). There are also three selectable fine pitch settings: Normal Flight Pitch +17° (0.3 rad), Approach Fine Pitch +7° (0.12 rad) and Ground Fine Pitch -2° (0.04 rad). At each of these fine pitch settings, thrust variations are commanded by appropriate settings of both the power lever and the fuel lever. Under these conditions the precise control of thrust is less than ideal for the following reasons:

1) The response of the engine and propeller to command changes of RPM is slow, due to engine and propeller inertia effects.

2) Thrust response can be momentarily opposite to that anticipated, e.g., selection of reverse pitch from ground fine can produce an initial transient positive thrust before negative thrust is developed due to the design of the power level linkage.

3) Reverse thrust rarely occurs exactly simultaneously on both propellers, resulting in undesirable yawing moments which require prompt pilot attention.

4) In the Ground Fine Pitch setting and a lightly loaded aircraft, the minimum controllable thrust level is so high as to require constant use of brakes when taxiing downwind.

5) The thrust produced at the various settings of pitch and power will vary with aircraft speed.

The modifications incorporated on the XC-8A do not affect the pitch settings of Feather and Full Reverse, nor the constant speed governing range. In the range from approximately Normal Flight Pitch back to Reverse Pitch, the blade angle (beta) is under the direct control of the pilot, through a suitably modified pitch change mechanism in each hub. The effects as far as thrust response is concerned are as follows:

1) Rapid and proportional change of thrust with movement of power level, since blade angle changes far more readily than engine and propeller RPM;

2) Infinitely variable control of thrust over the beta range;

3) Ability to apply rapid and proportional differential thrust at various levels;

4) Elimination of undesirable transients; and

5) Direct control of thrust as aircraft speed changes.

The instrumentation on the XC-8A is an anolog system which continuously records nine channels and seventy-eight commutated parameters on magnetic tape. They include all T-64, ASP-10, ACLS and basic aircraft performance parameters. Each parameter is sampled 30 times per second. A twelve channel visicorder monitors selected data for immediate readout of test or trend information. The test engineer also has displayed at his station ten indicator units with alarms to monitor critical parameters.

STRETCH ANNEAL TEST

Before the XC-8A could be tested cushionborne, the elastic trunk had to be stretch annealed. The annealing process is a prestretch of the trunk composite to a higher initial loading (approximately 67% greater) than normally used. This softens the material and allows it to attain a proper inflated size and shape at the design loads.

In order to obtain the trunk loadings required during this operation, the XC-8A trunk must be inflated Out of Ground Effect (OGE). This necessitates suspending the XC-8A from ramps above the ground (Figure 18). The trunk is then inflated and measured in increments up to a pressure necessary to attain the proper annealing loads. Depending on the ambient temperature, this could require trunk pressures over 400 lb/ft^2 (19 152 N/m^2).* Following the stretch anneal, the trunk is reinflated to verify that the annealing process is completed. Figure 19 shows trunk material characteristics for a typical straight section during the first stretch anneal cycle, post-anneal and the 5th inflation cycle.

XC-8A PARK

The bladder parking system on the XC-8A has been successfully tested a number of times. The original system was intended to support the XC-8A at a height equal to its conventional wheel gear; however, monetary constraints necessitated reducing the full potential of this feature to that depicted in Figure 13. Here we can see that the aircraft is fully supported on 6 bladders, four in the front and two at the rear. At heavier gross weights and aft C.G. conditions, a pair of bumper pads augments the lift of the rear bladders.

In a typical bladder inflation, the XC-8A is taxied to the park location and the pillow parking brakes are inflated. The aircraft's APU is started and the main propulsion engines (T-64s) are shutdown. The cushion trim area

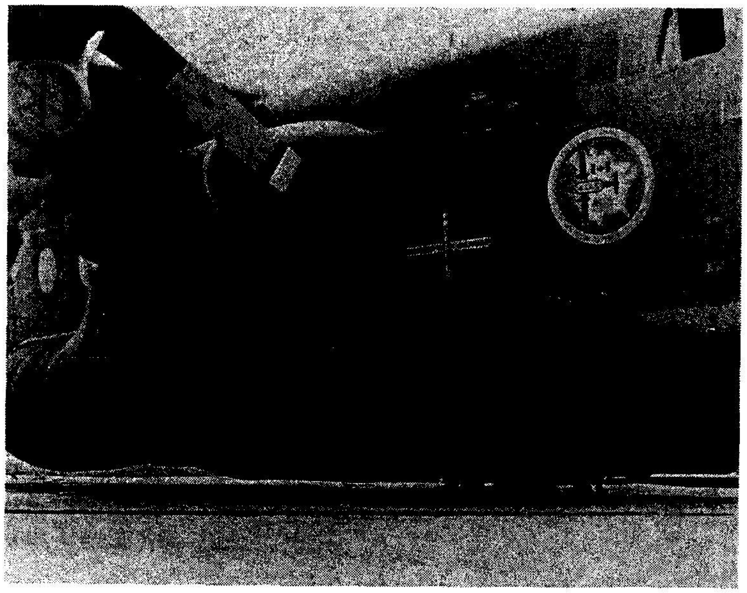

Fig. 18 - Trunk inflated OGE during stretch anneal test

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*The OGT stretch anneal test also serves as a qualification test for the structural integrity of the turnk. This is due to the trunk being exposed to the highest loads (excluding obstacles) that it will encounter during normal EGE and OGE operations.

is increased by 2/3* to enable operation at higher flow rates, which keeps a safe margin between the ASP-10 surge and operating lines (Figure 15). The next step is the inflation of the parking bladders which automatically switch off when the pressures are between 400-430 lb/ft^2 (19 152-20 588 N/m^2). The inflation sequencing of the bladders is forward, aft and mid to minimize choking off the fan and stalling the ASP-10 fans prematurely. When the bladders have been inflated, the trunk pressure is reduced by decreasing the ASP-10 fan speed and the bladders are reinflated. This cycle is continued until a fan stall takes place and the XC-8A comes to rest on the bladders. Recycling the bladder inflation while lowering trunk pressure increases the size of the bladders and assures proper footprint pressure.

A parking sequence normally takes approximately 90 seconds to accomplish. With the aircraft supported by the parking system, the belly clearance is approximately 6 in. (0.15m) at the rear and 20 in. (0.5m) at the forward end of the trunk. Figure 20 shows a typical park sequence graphed on a fan map.

ROLL, PITCH AND HEAVE DYNAMICS

Observation of XC-8A cushionborne maneuvers leads one to the conclusion that the vehicle has little roll stiffeners. This is primarily due to the reduced track of ACLS versus the conventional landing gear** and the lower stiffeners of the trunk over the conventional shock strut. As described earlier in this paper, outrigger fiberglass skids were installed on each wing tip to alleviate this problem. However, the skids were not long enough and this resulted in excessive taxi crab angles in crosswinds and exaggerated roll excursions below 50 Kts (25.7 m/sec). Although the pilots commented that these conditions were disturbing, they were not unduly concerned and easily adapted to the required compensatory operations.

The resolution of this problem can take many forms, from a simple extension of the skids to a more complicated arrangement requiring control augmentation through the use of thrust deflectors on the wing tips or design changes to trunk geometry and pressure.

Using expedience and simplicity as the criteria for the selection of a fix, the AF chose a deeper wing skid design. The new wing skids are about 18 in. (0.46m) longer, equipped with wheels and will restrict roll excursions to 1.2 degrees (0.02 rad) before skid contact. The short skids allowed roll angles of 4 degrees (0.07 rad). The new skids will be evaluated before March 1977.

On 8 April 1975, during a medium speed grass taxi operation, the XC-8A traversed a section of undulating terrain which set off a non-convergent pitch oscillation. The oscillations were quite severe, at least to the flight crew, and resulted in pitch excursions of plus and minus 4° (0.07 rad). The oscillations terminated after 12 cycles with the application of brakes and reverse thrust. This phenomena was observed in earlier 1/4 scale model tests both at the Flight Dynamics Laboratory and during drop tests conducted by NASA. However, the model was not truly representative of the XC-8A in that aerodynamic damping was not included; therefore, the pitch oscillation was considered to be a minor consequence on the full scale vehicle. As a result of the 8 April test, new emphasis was placed on pitch dynamics.

A series of tests, both static and dynamic ramp traverses, were conducted on the XC-8A. The purpose for the tests was to obtain data on aircraft damping, to duplicate the 8 April tests under controlled conditions and to develop a configuration or method to reduce or eliminate this problem. The results of these tests indicated the following:

1) The damping factor is greatest at a zero forward velocity; therefore, stopping the aircraft when this problem occurs is beneficial (Figure 21).

2) There was no indication from the data collected that a particular forward velocity caused the pitch oscillation.

3) Damping can be increased by closing CTVs and/or decreasing trunk pressure.

4) Damping decreased with brake application.

5) The pitch oscillation that occurred on 8 April 75 could not be duplicated.

Although the pitch dynamics tests did not provide an exact cause for the 8 April 75 phenomena, they did establish a technique for stopping the condition if it developed; namely, decelerate using reverse thrust and close CTVs and/or reduce trunk pressure if possible.*

Heave oscillations have been encountered during both static and taxi operations. The cause of the static heave is still under investigation; in the interim, high cushion flow rates (>20 CTVs) are avoided since it is suspected that this may have been a contributing

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*The XC-8A normally operates with 15 CTVs open; however, during the park sequence, 10 more cushion trim ports are opened.

**The ACLS width is 14 feet (4.27m) while the track of the conventional CC-115 gear is over 30 feet (9.1m).

*During one of the pitch oscillation tests, the co-pilot, who has charge of the CTV configuration and ASP-10 controls, had great difficulty in controlling these functions due to the movement of the aircraft.

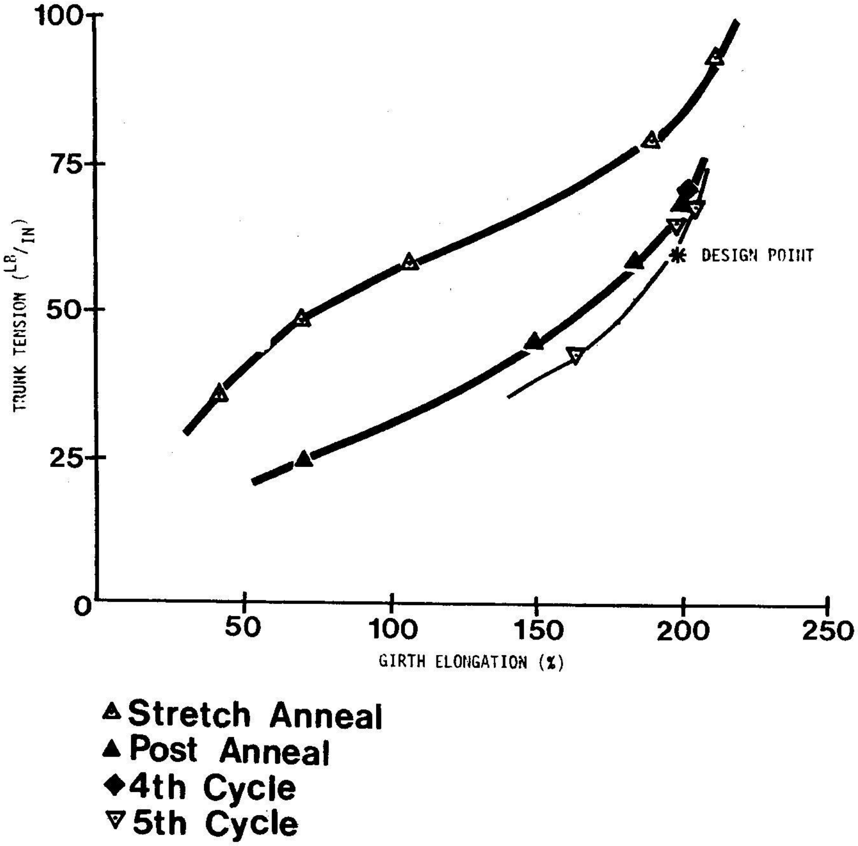

Fig. 19 - Trunk material characteristics during the stretch anneal

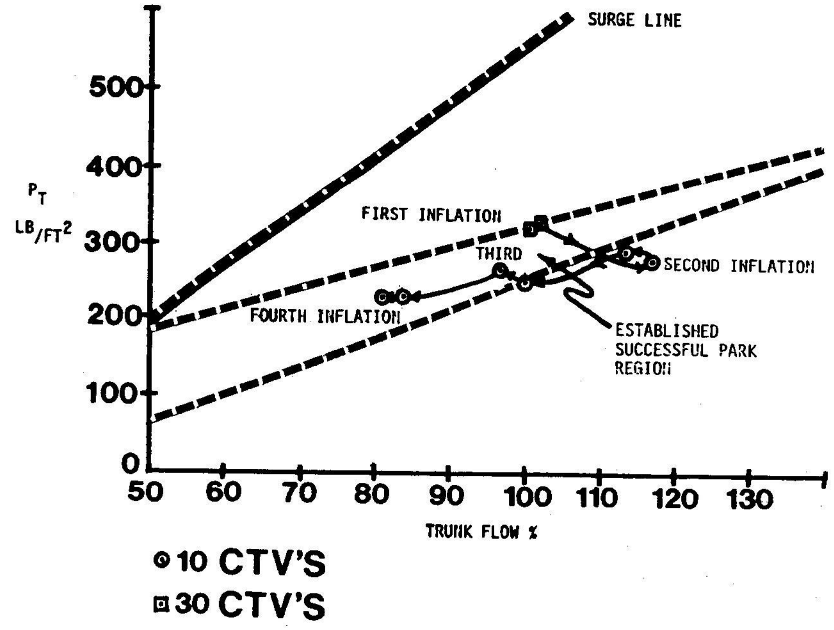

Fig. 20 - Typical park sequence

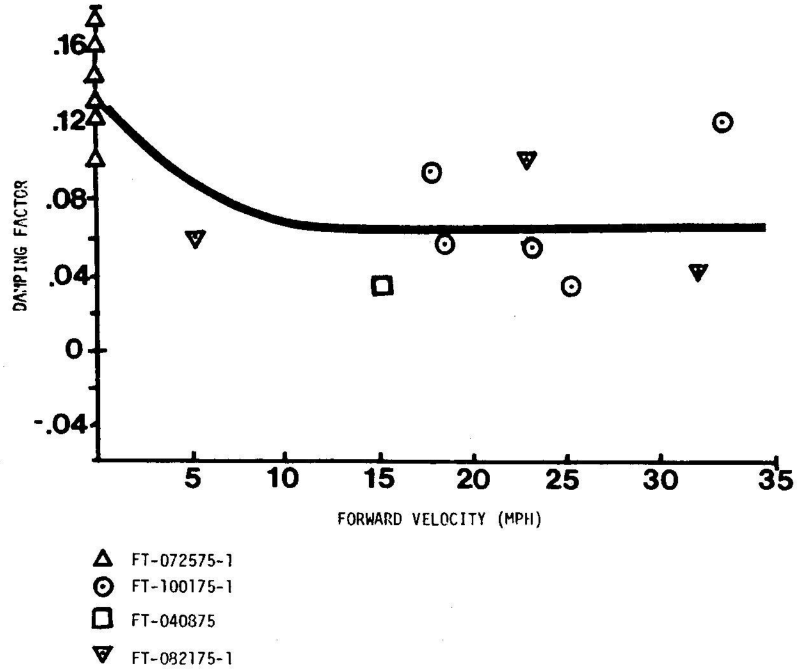

Fig. 21 - Damping factor vs forward velocity

cause of this oscillation. The heave, which occurs while taxiing, is excited by the terrain and is most likely pitch coupled. Here again the pilots have become accustomed to this movement over the period of this test program and have no particular objections. However, if this condition worsens, an effort could be undertaken to resolve the problem. One suggestion which has merit is an automatic (pressure sensitive) trunk bleed off valve similar to the CTVs.** These valves would sense unusual differentials in trunk pressures and compensate by exhausting the air into the cushion cavity or to the atmosphere.

INGESTION

In the course of testing the XC-8A, ingestion has surfaced as a major problem. To date, the XC-8A has experienced three main propulsion engine (T-64s) replacements, one ASP-10 engine failure and several test terminations because of Foreign Object Ingestion and/or Damage. As a result, XC-8A operations have been significantly restricted.

Due to this problem, several modifications, operational techniques and studies have evolved which may significantly improve on the XC-8A's ability to operate on all types of surfaces.

The first point that must be made is that the basic CC-115, from which the XC-8A evolved, has a T-64 ingestion problem. The installation of the ACLS worsens this problem by ejecting great quantities of surface debris in the vicinity of the ASP-10 and T-64 power plants (Figure 22). At higher speeds the problem is less significant because the flow pattern is behind the intakes.

The first encounter with ingestion occured during the initial operations on grass. Even with the inertial separators operating lightweight, grass particles were sucked in and eventually blocked off the screen intake of the PT-6 engine and the ASP-10 oil coolers. To remedy this condition, a screen was placed over the oil cooler and the ejector intake was rerouted. Grass operations were restricted to light grass clouds and restrictions were placed on ASP-10 fan speed decays (<2%) and corresponding drops in fan flows (<3%).

The ingestion problems on the T-64s are similar to the ASP-10 but are aggravated by the fact that the intakes are located in close proximity to the forward exhaust area of the cushion. A study made of the flow patterns over snow during the XC-8A cold weather tests provided a proven technique for minimizing T-64 ingestion. The technique requires a slight amount, about 5° (0.09 rad), of positive blade angle during cushionborne operations where FOD may be a problem. The positive thrust tends to redirect debris around the T-64 intakes via the propeller slipstream. The flexibility of this technique is limited because it completely rules out all cushionborne maneuvers at very low forward velocities. As a result, a modification has been studied which would provide each T-64 with nacelle inlets fitted with Donaldson strata tube

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**It is quite possible that the CTVs could even be designed to serve this additional function.

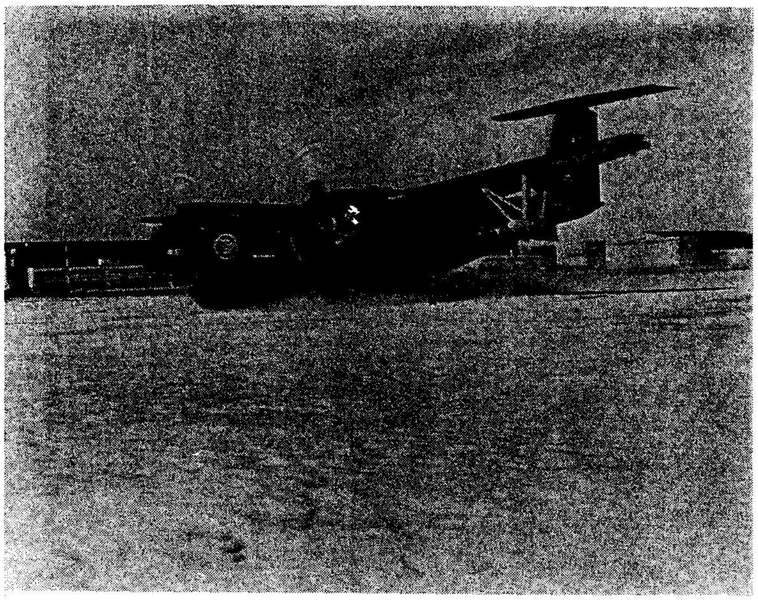

Fig. 22 - XC-8A snow landing

separators. This installation would allow the XC-8A to operate over all surfaces presently used by air cushion vehicles.

TRUNK DURABILITY

Some trunk wear has been observed during all cushionborne tests on the XC-8A. The amount of wear has varied and is dependent upon a number of factors, the most important being the type of surface on which the vehicle is operating. The first concrete takeoff test, conducted on 31 Mar 75, produced the most significant trunk wear, while numerous operations on grass surfaces have shown little wear.

Regardless of the surface, trunk wear follows a definite pattern. As shown in Figure 23, trunk wear is usually confined to the ground tangent area. As a result, replaceable urethane wear plugs have been installed into the nozzle holes to protect the trunk.

The nozzle plugs have shown reasonable success in extending trunk life; however, the more important problem is the limited life of the trunk carcass.

The first trunk installed on the XC-8A was replaced after 23.5 hours of inflation test time, the second trunk after 45.4 hours (Figure 24) and the third trunk, being almost identical in design to the second, should last another 45 hours.

The actual mechanisms of failure for the trunk are not completely known; however, it is suspected that fatigue is a primary factor.

An analysis of trunk failure data has revealed the following:

1) Trunk damage, excluding obstacle contact, has been limited primarily to rubber failures either splits or delaminations. The cord structure from which the trunk composite gets its strength is usually not harmed.*

2) Trunk cumulative damage follows a predictable exponential failure rate (Figure 25).

3) Trunk temperature, in the range of 40° to 150°F, was not shown to be a contributor to trunk damage.

4) Ozone deterioration is minimal, even though the trunk has been installed on the aircraft for 2 years with a 10-15% prestretch.

Although trunk damage is a limiting factor to the overall life of the trunk, successful repairs have extended trunk life to its maximum capability. By vulcanizing rubber patches onto the trunk under both heat and pressure, splits in the carcass and massive skin delaminations have been mended. This process for rejuvenating the trunk could have extended the number two trunk life beyond 45 hours. However, the down time required for an extensive number of repairs did not justify the return in actual test time.

On the positive side, some material experts contend that elastic trunk life can be extended as much as 150 to 300 hours by a reduction of

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*The rubber failures, if severe enough, can be the cause of leakage outside the ground tangent area, impacting the ASP-10 performance and safe operational cushionborne time. As a result, even though the structural integrity of the trunk is not compromised, the damage must be repaired. Calculations based on the test results of XC-8A trunk number one shows that damage of approximately 6 ft^2 (.557 m^2) can be tolerated before the safety factor provided by redundant ASP-10 engines is voided.

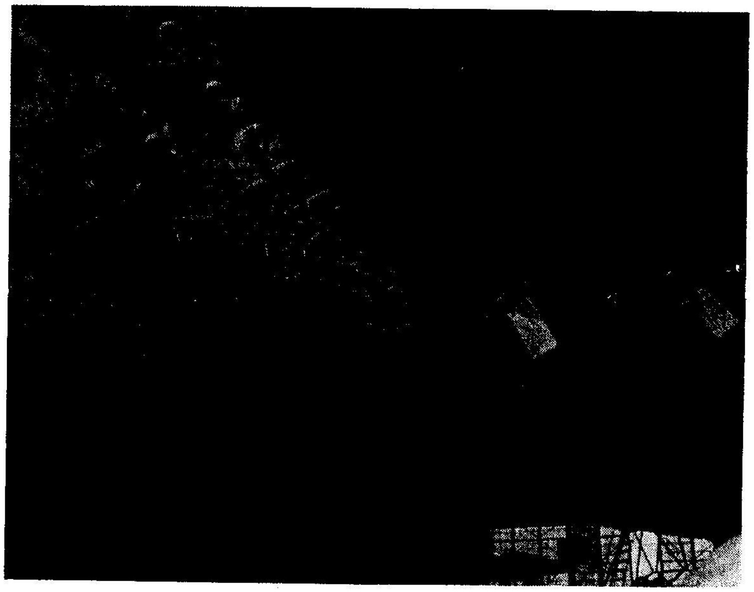

Fig. 23 - Aft trunk ground tangent area after several grass cushionborne operations

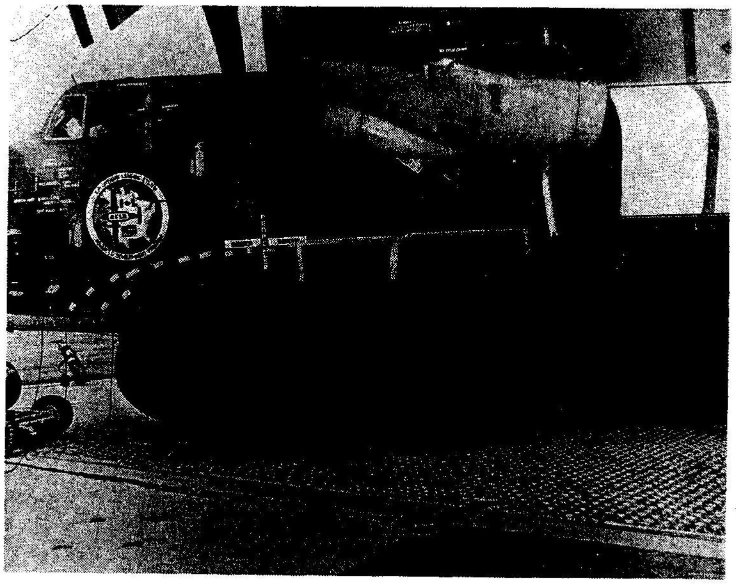

Fig. 24 - Trunk No. 2 with large surface delaminations after 45.4 h of testing

composite strain and judicious material substitutions.

Due to their know durability, inelastic trunks are strong contenders for application to a future ACLS design. However, more research must be undertaken in the area of inelastic trunk retraction before the full potential of this type of trunk can be realized.

TRUNK FLUTTER

During the initial contractor static tests conducted on the XC-8A, the trunk exhibited an excessive trunk flutter well below the design trunk pressure of 342 lb/ft^2 (16 375 N/m^2). Bell resolved the problem by installing a set of rubber strakes to either side of the trunk ahead

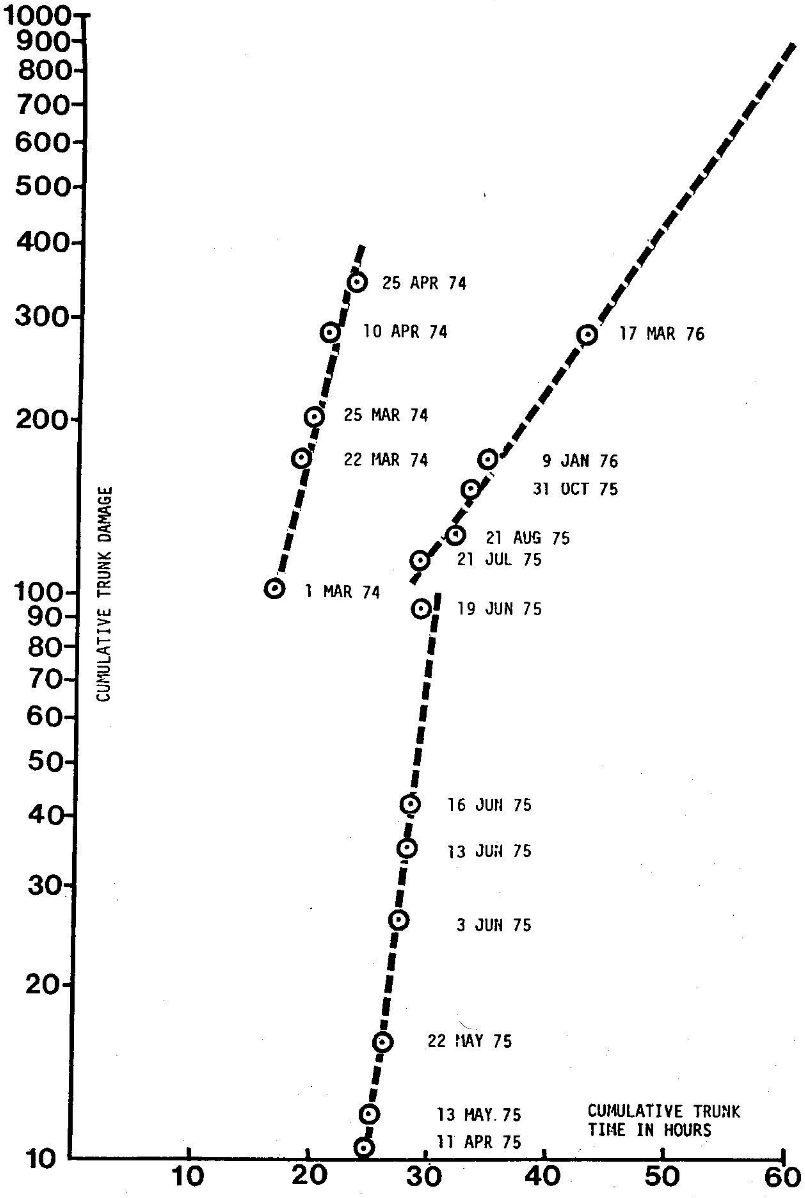

Fig. 25 - Cumulative trunk damage vs cumulative trunk inflation time

of the brake skids (Figure 26). There are several theories as to why the strakes work: One attributes trunk vibration to vortex shedding of cushion flow past the trunk outside the ground tangent area; as a result, the strake acts as an aerodynamic tripper strip.* Another theory suggests that trunk vibrations can be related to the resistance to flow beneath the trunk, i.e., increasing the resistance to flow by the addition of strakes or similar devices creates a positive pressure distribution and prevents the trunk from being sucked down. Whichever theory is correct, and it may be a combination of all of them, the strakes worked and were used during the entire program. However, as time passed, the Bell strakes became less effective and additional measures had to be taken. Mass dampers (Figure 27) were installed and tested on the forward outside flank of the trunk. The dampers did not eliminate the vibration, only reduced the amplitude. The dampers were finally rejected when it was discovered that they caused severe trunk damage after a short period of operation.

Following the failure of the mass dampers, the strakes were extended beyond their original location using an AF design (Figure 28). This

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*A tripper strip, similar to the strake, located on the aft section of the trunk torus, is used to overcome severe yaw oscillations. The perturbations were attributed to random vortex shedding from the inflated trunk in conjunction with flap downwash.

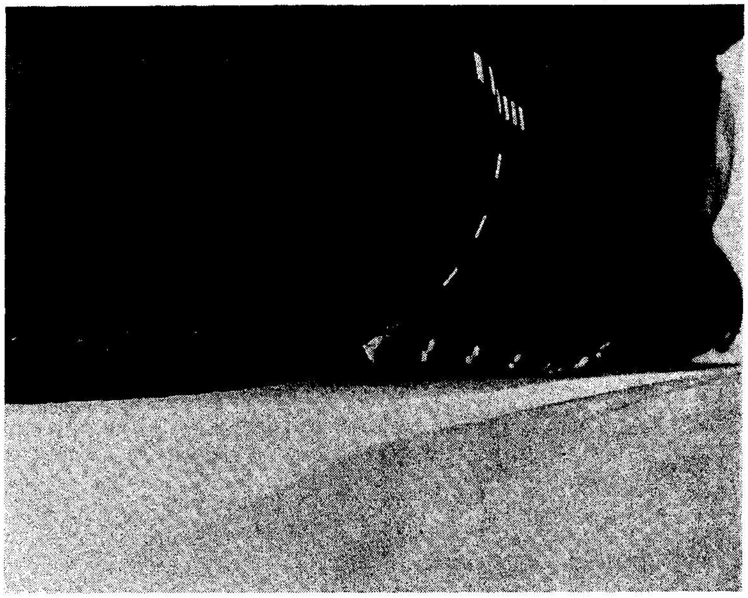

Fig. 26 - Strakes installed on XC-8A trunk

Fig. 27 - Mass dampers installed on XC-8A trunk

again proved successful, but only for a limited time.*

The last fix, which has proven to be the most successful, is a variation of a design used to solve a similar trunk vibration problem on ACVs. The modification consists of a diaphragm between the ground tangent line and outer attachment rail (Figure 29). The diaphragm extends from the forward brake skid around the front torus to the other side. The purpose of the diaphragm is to put a slight tension on the trunk and restrict motion in the vertical plane. Bell Aerospace engineers who designed the fix deduced from computer simulations and 1/4 scale model tests that restraining either the vertical or horizontal modes of trunk motion will eliminate trunk vibrations.

Unfortunately, the elastic trunk (No. 2) had to be replaced before this modification could be evaluated on the XC-8A. Reinstallation and evaluation of this fix on trunk num-

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*While fixes for the trunk vibration problem were being investigated, the XC-8A was restricted to grass surface operations where the vibration was significantly damped due to sporadic contact between the undulating terrain and the trunk.

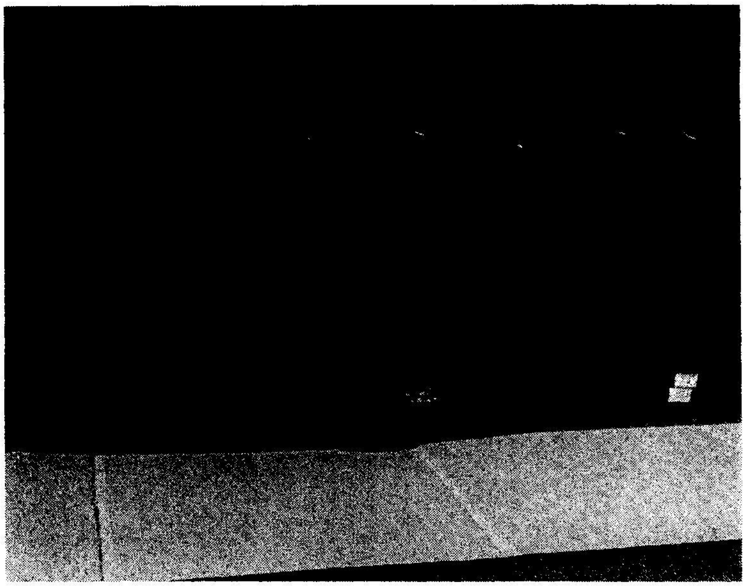

Fig. 28 - Extended strakes installed on XC-8A

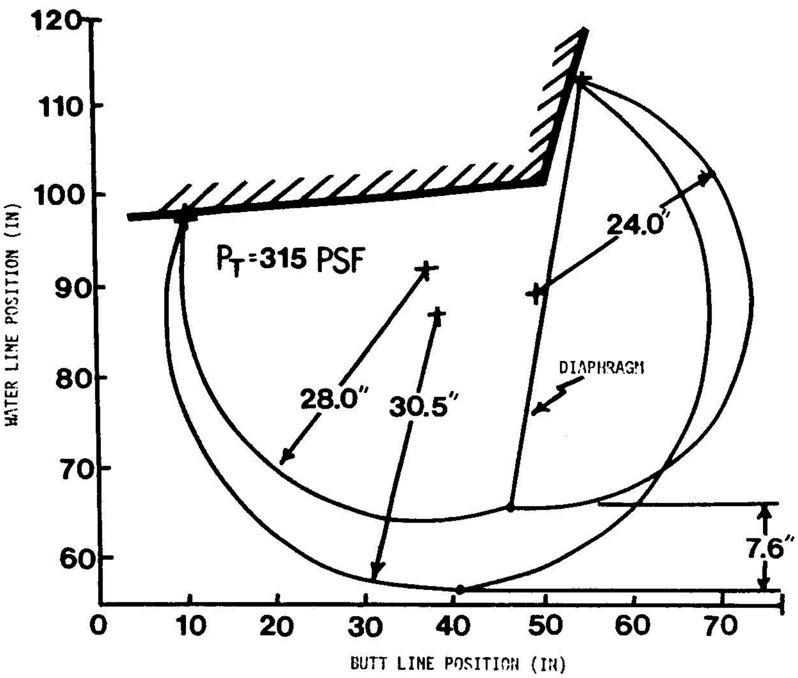

Fig. 29 - Cutaway drawing showing diaphragm installation to reduce trunk flutter

ber three will depend on the extent of the vibration problem on the new trunk and the flight testing to be completed before the end of this program which is presently scheduled to end in March 1977.

COLD WEATHER TESTS

As part of the environmental testing, the XC-8A was exposed to -20°F (-29°C) in northern Canada during the winter of 1976. The primary objective of this test program was to evaluate the ACLS components.

The results of these tests were very encouraging. With the exception of a malfunction in one ASP-10 electronic control box and one parking bladder inflation valve, no major failures were encountered.

However, as expected, the trunk material did show some sensitivity to the frigid temperatures. The first phenomenon is a condition that I refer to as "Bag Sag" or trunk relaxation. It is analogous to "creep" which occurs in both metallic and non-metallic materials. In the case of trunk material, the sag is

Fig. 30 - XC-8A in flight at onset of trunk flagellation

temperature dependent and results from crystallization of the particular rubber which is used to fabricate the trunk. "Bag Sag" increases with lower temperatures and recovery time is temperature dependent. At standard temperatures the "Bag Sag" is slight and recovery occurs within a few hours. At lower temperatures the deformation is more severe and recovery requires a much longer period; for example, after a test at 0F (-17°C) the XC-8A was left outside and "Bag Sag" was still evident after 5 days. It should be noted that "Bag Sag" is only a temporary condition. Also, the temperature rise (35°F, 19.4°C) across the ASP-10 alleviates this problem at moderate temperatures.

The "Bag Sag" problem itself is not very serious; the increase in drag caused by a slight extension of the bag when airborne would be minimal. The major problem is trunk flagellation* which can delaminate the trunk carcass and/or damage components between the trunk and fuselage. Flagellation onset with the trunk stretched tightly across the fuselage is about 155 Kts (80 m/sec). With the trunk loose on the fuselage, trunk flagellation can be expected to be more severe and occur at a lower airspeed. Figure 30 shows the XC-8A in flight. The trunk sag at the forward end of the trunk is extended 8-12 in. (0.2-0.3 m) from the fuselage and was the result of a cushionborne test at -20°F (-28°C). During this test, the onset of flagellation was approximately 138 Kts (71 m/sec).

During the cold weather tests in Canada a fix was investigated for the "Bag Sag" problem. It consisted of a ducting system which manifolded bleed air at a temperature of 250°F (122°C) to the front torus of the trunk. Although the tests were not conclusive, the cursory data indicated that trunk heating in combination with a trunk suckup system could conceivably resolve the "Bag Sag" and flagellation problems.

The other significant result of the cold weather trials on the XC-8A was the establishment of an operating pressure profile for the trunk. It was known that a higher pressure would be required at lower temperatures to assure proper trunk size; however, the predictions were based on laboratory samples. The actual results summarized in Figure 31 show the modulus to be lower than predicted and compatible with the ACLS power system.

ENERGY ABSORPTION

One of the most important functions of the ACLS is energy absorption during the landing impact. Computer simulations and actual model tests of the landing impact, which were made during the initial feasibility studies, indicated that the ACLS was an excellent shock absorber. To verify this, a series of high sink speed landings were conducted on the XC-8A. The landings consisted of various combinations of sink speeds up to 8.3 feet per second (2.53 m/sec) and positive pitch attitudes up to 7° (0.12 rad).

The actual execution of this flight test series was somewhat unnerving to the crew because the pilot had to literally fly the aircraft into the ground* to obtain this data.

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*Trunk flagellation is a movement of the trunk relative to the aircraft. It resembles a flag waving in a breeze.

*The XC-8A is normally flared before touchdown; during this test series it was not.

Normal operation of this type of aircraft would not extend beyond the shaded boundary of Figure 32 with the exception of a maximum performance landing. The STOL and CTOL lines were derived from the basic CC-115 aerodynamic data and represent a maximum effort to keep the aircraft flying with power off. To actually land at the outer edges of the envelope the pilot could have to mismanage the aircraft. The high sink speed landing tests as shown in Figure 32 exceed normal operating conditions.

The accelerations that the XC-8A recorded at the C.G. during these tests are summarized in Figure 33. The fuselage clearance at the aft trunk torus is shown in Figure 34. Both figures show reasonable correlation with the earlier predictions of full scale performance made from model and computer simulations.

XC-8A PERFORMANCE

In order to minimize trunk inflation time and optimize ACLS performance, the XC-8A has only been tested at one gross weight, 35,000 lbs (15 876 Kg), and one c.g. location, 28.1% MAC.

Stability and control investigations were conducted in both takeoff and landing configurations, power on and off, trunk deflated and inflated. The differences between the handling qualities of the aircraft trunk inflated and deflated were insignificant. Static and dynamic longitudinal stability remained unchanged; however, the aircraft does experience a slight nose down pitch attitude when the trunk is inflated. This is because of the increased profile drag and results in a decrease in airspeed of 7-10 Kts (3.6-5.1 m/sec).

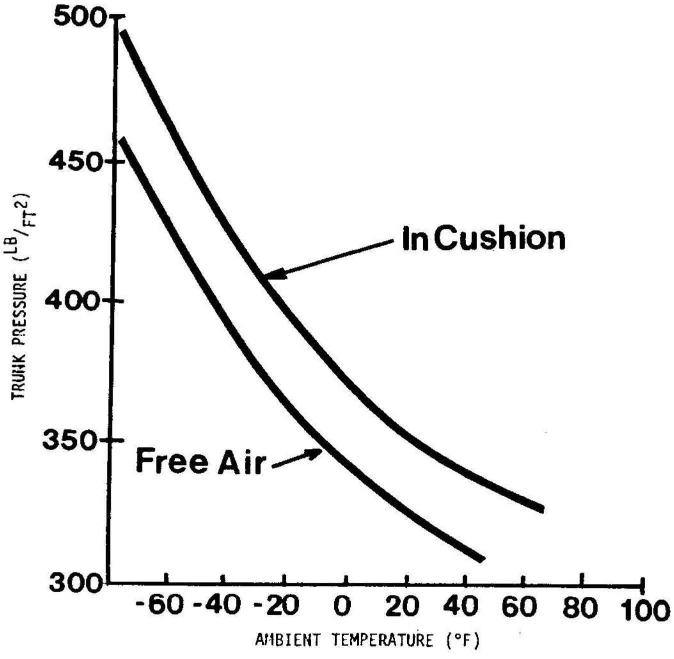

Fig. 31 - Trunk operating pressure vs ambient temperature

To maneuver the XC-8A on the ground, differential thrust is more responsive than brakes. Here again the moment arm of the propellers is over twice that of the pillow brakes and the force generated by the brakes, especially over a slippery surface such as grass, is much less than T-64 thrust. Using differential thrust the XC-8A can be maneuvered to a specific spot along a line within ±3-5 ft (±0.9-1.5m). Reverse thrust has been used as the primary method for deceleration; the brakes are used to hold the aircraft static and for deceleration at very low speeds.

The pilots have found that with a little practice the wind can be used to help maneuver the aircraft to a desired location.

Simulated T-64 engine failures have shown that the XC-8A yawed moderately into the failed engine and depending on the crosswind, power setting and ground speed, the aircraft would deviate up to 150 ft (45.7m) from the centerline of the runway.

For takeoff, the XC-8A is aligned on the runway centerline, crabbed into the wind and differential power is applied. As the aircraft is accelerated, the control surfaces become effective and the XC-8A weight is transferred from the cushion to the wings. Elevator power is sufficient for normal rotation.

The approach for landing the XC-8A is similar to that used for the conventional gear. However, as the aircraft completes its slideout, it must be crabbed into the wind to prevent the vehicle from sliding off course.

As discussed previously in this paper, the XC-8A exhibits poor roll stiffness with the short wing tip skids. This causes the aircraft to rock back and forth at speeds below 50 Kts (25.7 m/sec). In addition, a vertical heave has been observed during most of the cushion-borne maneuvers on grass and snow. Attempts have been made to dampen the heave motion by discreet application of spoilers, reverse

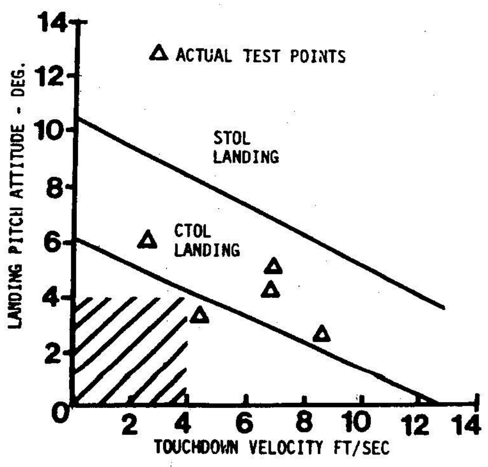

Fig. 32 - XC-8A landing envelope

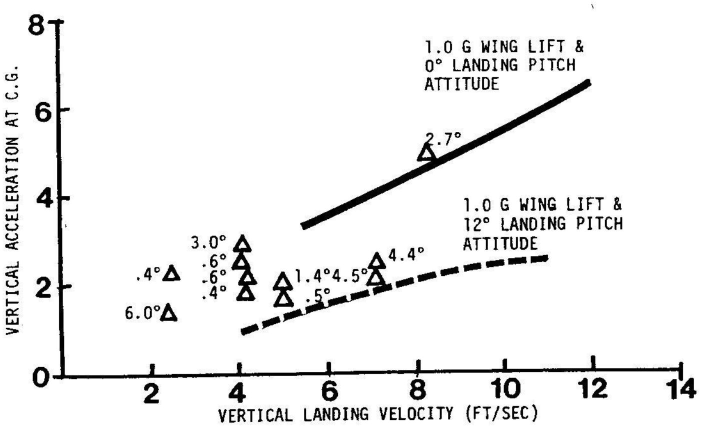

Fig. 33 - Vertical acceleration vs vertical landing velocity

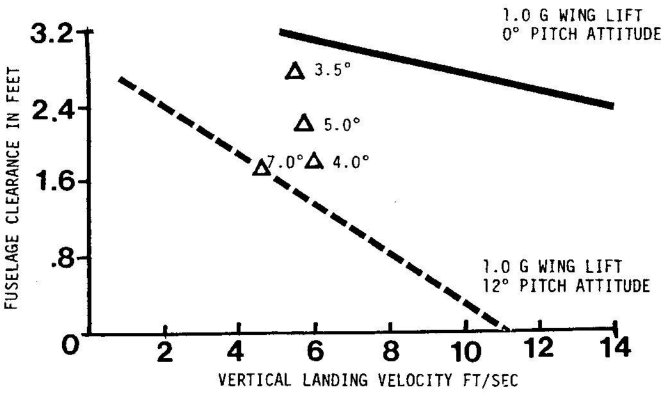

Fig. 34 - Fuselage clearance vs vertical landing velocity

thrust, brakes and flaps but none of these techniques have resolved this relatively minor problem.

To date, the XC-8A has completed 68.5 hours of testing with the trunk inflated. This includes over 20 miles (32 180 m) of taxiing and 32 takeoffs and 37 landings from grass, snow and hard surfaced runways. The XC-8A has successfully negotiated surface obstacles such as craters 6 feet (1.83 m) in diameter and 2 feet (0.61 m) deep as well as a ramp with a 5% grade and 9 in. (0.23 m) dropoff.

CONCLUSIONS

The ACLS represents a technological breakthrough in aircraft design and the importance of the XC-8A flight test program cannot be overemphasized. The XC-8A has provided the first tangible information on operational performance, maintenance and crew training. The primary purpose of the XC-8A program is the demonstration of an ACLS on a large transport aircraft. To this end, the program has been successful. However, the XC-8A has also shown that there is still much work to be done. As a retrofit, the XC-8A designers were severely limited by the scope of the modification; as a result, many of these limitations surfaced as deficiencies in the system. Therefore, designers must look to the XC-8A with vision and understanding if the full potential of this unique concept is to be attained. For example, several weaknesses were described earlier in this paper which merit concluding remarks:

1) XC-8A Range - Due to the additional weight and drag of the ACLS modifications, the range of the XC-8A has been reduced to approximately 50% of the basic CC-115. However, parallel studies have shown that if the ACLS is included in the basic design of the aircraft an actual weight savings of up to 10% can be realized. This is made possible by eliminating the conventional landing gear system and associated back up structure and by using bleed air from the main propulsion engines to power the ACLS.

2) Roll & Pitch Stability - The XC-8A stability in both pitch and roll could be improved considerably if the location, shape and size of the cushion could be optimized. Here again, the designers were constrained to work with the basic CC-115 fuselage.

3) Ingestion - As discussed earlier, the basic CC-115 has a problem with ingestion when operating from austere sites with the conventional wheel gear. In a future design, the severity of this problem could be reduced by relocation of the propulsion engines or intakes away from possible cushion spray.

Aside from the retrofit limitations, the XC-8A flight test program has pointed out obvious areas where continued research is necessary before a follow-on program can be addressed. These areas include improved trunk dynamics, trunk durability and complete evaluation of the ACLS overwater and brake operation. As a perfect test-bed, the XC-8A can be instrumental in providing this design criteria which is a vital prerequisite to incorporation of this revolutionary new concept to a larger transport such as the C-130 or Advanced Medium STOL Transport.

LIST OF SYMBOLS AND ABBREVIATIONS

A_g	Augmentation factor $= \dfrac{\text{lift}}{MV_j} = \dfrac{MV_j + P_c A_c}{MV_j}$
A_c	Cushion Area
D	Diameter
M, Q	Mass Flow
P_c	Cushion Pressure
P_T	Trunk Pressure
V_j	Jet Velocity

LIST OF SYMBOLS AND ABBREVIATIONS (CONT'D)

h	Daylight Clearance
CTOL	Conventional Takeoff and Landing
STOL	Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing
ACV	Air Cushion Vehicle
ACLS	Air Cushion Landing System
β	Beta (Propeller Blade Angle)
CBR	California Bearing Ratio
psf	Pounds Per Square Foot
N_f	Fan Speed
N_g	Gas Generator Speed
θ	Temperature Ratio
Δ	Logarithmic Decrement = Ln (Decay in Pitch Rate)
ζ	Damping Factor $^{\zeta}/4\pi^2 + \Delta^2$
π	Constant 3.14159
C_D	Total Drag Coefficient
C_{D_o}	Zero Lift Drag Coefficient
C_L	Lift Coefficient
g	Acceleration Due to Gravity
V	Velocity
ℓ	Length
IGE	In Ground Effect
OGE	Out of Ground Effect
q	Dynamic Pressure
K	Induced Drag Coefficient
P	Density
δ	Pressure Ratio
S	Wing Area

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