AFFDL-TR-72-87

A STUDY OF AIR CUSHION LANDING SYSTEMS FOR RECOVERY OF UNMANNED AIRCRAFT

JOHN M. RYKEN

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FOREWORD

This study was performed under USAF Contract F33615-72C-1175 and Project No. 1369. This contract with Bell Aerospace Company, Division of Textron, Inc., at Buffalo, N. Y., was for a concept feasibility and formulation study of Air Cushion Landing Systems for recovery of unmanned aircraft or remotely piloted vehicles. The study was under the cognizance of Major John C. Vaughan, of the Air Force Flight Dynamics Laboratory, AFFDL/FEM.

Bell Aerospace Company was assisted in the study by Teledyne Ryan Aeronautical, of San Diego, California, manufacturer of the Ryan Model 147G special purpose aircraft which was considered as a possible vehicle for flight test demonstrations of air cushion landing system concepts. Rocket Research Corporation of Redmond, Washington, also assisted by providing data for ejectors which could be used in the air supply system.

This report has been reviewed and approved.

John C Vaughan III
JOHN C. VAUGHAN, III, Major, USAF
Principal Scientist
Mechanical Branch
Vehicle Equipment Division

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ABSTRACT

This report presents results of a concept feasibility and formulation study of Air Cushion Landing Systems for recovery of unmanned aircraft (Remotely Piloted Vehicles). A modified Ryan Model 147G drone or special purpose aircraft was investigated for possible use in a low cost flight test demonstration of air cushion landing gear concepts on an existing unmanned aircraft. Recovery by horizontal landing on an air cushion landing system is compared with recovery with a midair recovery system (MARS).

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SYMBOLS

ACLS	Air Cushion Landing System
C_L	Lift Coefficient, nondimensional
C_m	Pitching Moment Coefficient, nondimensional
C_{n_β}	Coefficient of yaw moment due to sideslip, 1/deg
F/W	Vertical Reaction due to ACLS/Vehicle Weight, g's
$\dot{h}$	Rate of descent, ft/sec
g	Acceleration due to gravity, 32.2 ft/sec^2
L/D	Lift to Drag Ratio, nondimensional
MAC	Mean Aerodynamic Chord, ft
MARS	Midair Retrieval System
N_b	Braking Deceleration, g's
P_c	Cushion Pressure, PSFG (lb/ft^2 GAGE)
P_T	Trunk Pressure, PSFG (lb/ft^2 GAGE)
RPV	Remotely Piloted Vehicle (Unmanned Aircraft)
SL	Sea level
SPA	Special Purpose Aircraft (used interchangeably with RVP or Drone in this report)
scfs	Standard Cubic Feet per Second (Air Flow)
α	Angle of attack, degrees
β	Sideslip angle, degrees
θ	Pitch Attitude, degrees
γ	Flight path angle, degrees

SECTION I
INTRODUCTION

1. OBJECTIVES AND GROUND RULES

This report summarizes results of a conceptual design study of an Air Cushion Landing System (ACLS) for recovery of unmanned aircraft. The effort was oriented toward a concept which can be used for an early and low cost, flight demonstration of an ACLS on an existing unmanned vehicle.

Primary objectives of the study were to determine the best conceptual approaches to using ACLS technology for recovery of unmanned military aircraft and to evaluate potential benefits of using this type of landing system for such applications. In determining the best concept, low initial systems costs, operating costs, and support costs were emphasized, while maintaining high vehicle performance and improving rapid response operations.

One of the ground rules for the study was that it could be assumed that the vehicle will be launched by an entirely different system from the recovery system. This permits use of a concept which is less complex and requires much less air supply power than the ACLS which Bell has demonstrated on a Lake LA-4 aircraft or the system now being developed for the deHavilland CC-115. However, the basic concept can be extended, by relatively simple modifications of the air supply and trunk, to also provide a takeoff capability from runways or other relatively smooth surfaces.

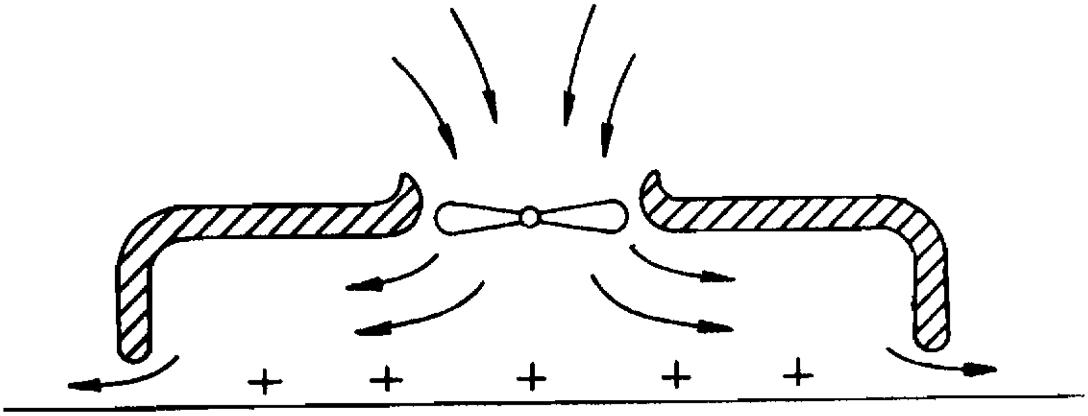
2. BACKGROUND

An air suspension system supports a vehicle on a cushion of air trapped between the vehicle underside and the ground. The vehicle weight is uniformly distributed by the air cushion over a large area. Extremely low ground pressure results. Consequently, such a system offers the potential for operating on extremely soft ground and even water.

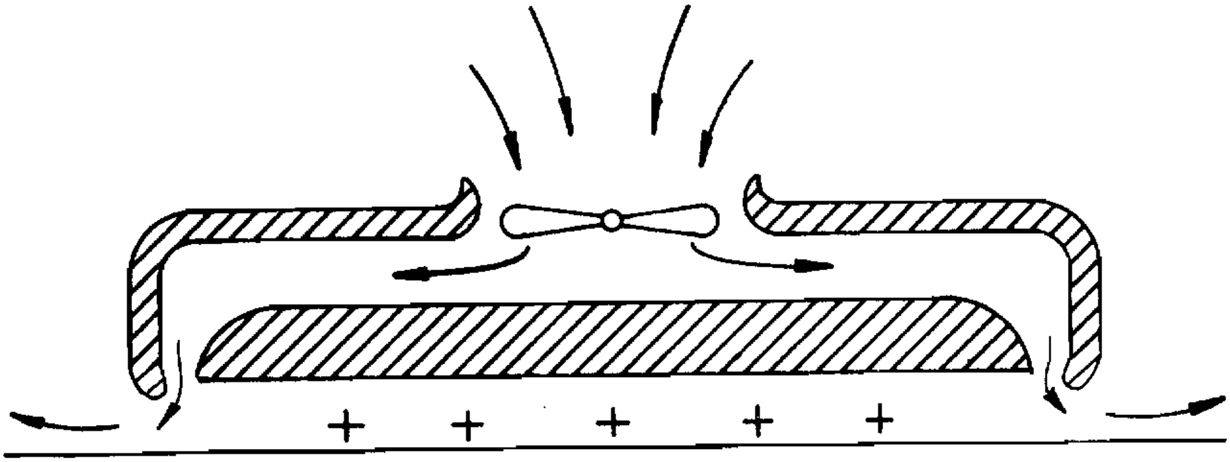
The two most common air suspension systems are known as the plenum chamber and the peripheral jet. These systems are illustrated in Figure 1(a) and (b), respectively. Both systems rely on ground effects for support. In both systems, input power is required to maintain the air cushion. The major difference between the two systems lies in the mechanism by which the cushion pressure is maintained. The plenum chamber utilizes a flow restriction, while the peripheral jet maintains the cushion pressure by a momentum seal.

In the case of the plenum chamber, air is pumped into the cavity under the vehicle and leaks out through a narrow gap between the periphery of the vehicle and the ground. A cushion pressure is maintained in the cavity as a consequence of equilibrium between the pressure differential across the gap and the combined acceleration and frictional forces which limit the flow of air through the gap. The result is a flow restriction at the exhaust plane.

In the case of the peripheral jet, air is vented in a jet at the periphery to form an air curtain seal. The sealing effect of the jet is a consequence of the equilibrium between the pressure differential across the jet and the centrifugal forces in the curved jet airflow. Pressure in the cushion is maintained by this air curtain seal. In a pure peripheral jet air suspension system, all air is introduced at the periphery.



(a) Plenum Chamber



(b) Peripheral Jet

Figure 1. Air Cushion Suspension Systems

The Air Cushion Landing System (ACLS) concept is unique (References 1 through 6). The ACLS principle is illustrated in Figure 2. It utilizes a jet height of less than one inch, thus reducing the power requirements to an acceptable level. The use of a flexible trunk or skirt around the periphery of the air cushion greatly increases the stiffness and energy absorption properties of the system. When not in use for takeoff or landing, the trunk retracts snugly against the bottom of the fuselage.

The ACLS was patented by Bell Aerospace Company, Division of Textron, Inc. The system was demonstrated by test flying a Lake LA-4 aircraft. The first ACLS takeoff and landing was made August 4, 1967. Subsequently, the USAF funded two evaluation test series on the LA-4 (Figure 3).

References 4 and 5 describe the ACLS design employed on the LA-4 and discuss results of the tests. Very successful landing operations were conducted on runways, grass, silt, snow and water. Takeoffs were made from runways and from water. Taxi tests were conducted over plowed fields, ditches, steps, and other obstacles. The 2500 lb weight of the LA-4 is within the 2100 to 3200 lb weight range of the modified Ryan 147G drone. Therefore, the LA-4 provided valuable basic data and experience for the study of an ACLS for this unmanned vehicle.

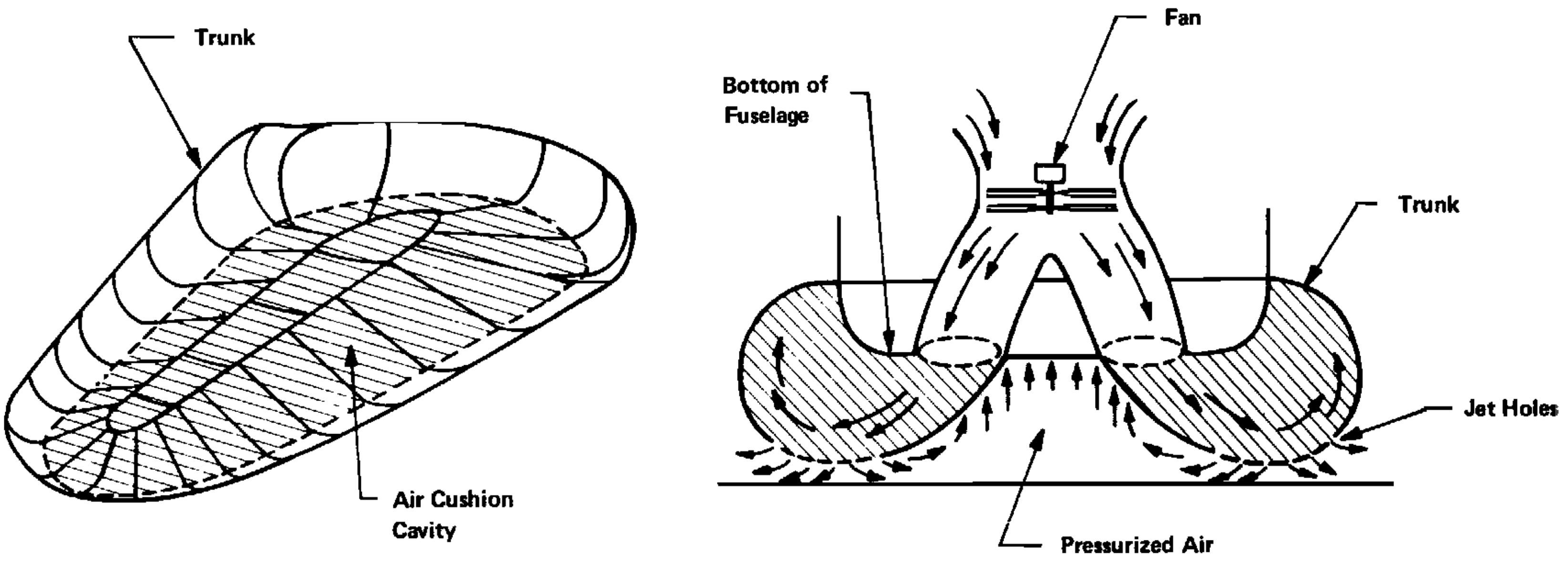
The United States and Canada are presently engaged in an advanced development program to demonstrate an ACLS on the deHavilland CC-115. Figure 4 is a photo of a 1/10-scale dynamic model of this configuration. Reference 6 is an interim report on the program. Although this aircraft (41,000 lb) is much larger than the Ryan 147G, the CC-115 ACLS program has also provided much useful data for the study of ACLS for unmanned vehicles.

Bell Aerospace Company internal research and development programs have included studies and tests of ACLS trunk materials, tread or braking materials, advanced braking concepts, and air supplies. Many of the results of these programs are directly applicable to ACLS concepts for unmanned vehicles and have been used in this study.

3. THE ACLS CONCEPT

The Air Cushion Landing System completely eliminates the conventional aircraft landing gear and replaces it with a cushion of air maintained beneath the fueslage during takeoff and landing. The concept is shown in Figure 2. The elongated doughnut shown on the bottom of the fuselage is called a trunk. The trunk forms the flexible ducting required to provide a continuous curtain of air around the periphery of the fuselage. The trunk and cushion both dissipate vehicle vertical energy at landing.

Air is fed into the trunk from a compressor, fan, or other air source. The air is ducted by the trunk to the fuselage periphery and exhausted through jets in the trunk near the ground tangent to form a jet curtain. This jet curtain seals a pressure of one-half to two psi under the aircraft fuselage when the ground is approached.



- Function of inflated trunk is to contain the pressurized air in the air cushion cavity. This cushion of air supports the weight of the aircraft.

- Air continually forced through the jet holes pressurizes the air cushion cavity. It also provides air bearing lubrication between the trunk and landing surface.

- When not in use the trunk deflates and hugs the fuselage similar to deicing boots.

Figure 2. Air Cushion Landing System Principle

Figure 3. LA-4 With ACLS

Figure 4. 1/10 Scale Model of CC-115 with ACLS

An ACLS braking system is shown in Figure 5. Braking is accomplished by pressing a brake material against the ground. The brake material may be replaced without replacing the air cushion trunk. Brakes are actuated by applying pneumatic pressure to the pillow sections shown on the bottom of the trunk. Steering is accomplished by differential braking as in a Caterpillar tractor. This concept was very effective on the LA-4 and will be used in the CC-115 ACLS.

The mechanism by which roll angles are reacted is shown in Figure 6. The figure on the left shows the approximate footprint pressure of the ACLS under equilibrium conditions. The aircraft is totally supported by the cushion of air maintained under the fuselage. With a large roll angle, the footprint pressure changes so that in addition to the cushion of air, the trunk is supporting the aircraft. The pressure in the trunk is roughly twice the pressure in the cushion. The trunk pressure, acting over the area shown in Figure 6, develops a large restoring moment whenever the bag is flattened against the ground. Negligible scrubbing of the bag against the ground occurs due to the large flow of air which provides air lubrication between the bag and ground. Very low friction results. The phenomena by which pitch stiffness is obtained is identical to that by which roll stiffness is obtained.

The Air Cushion Landing System is an extension of the technology developed for air cushion vehicles (ACV's). Reference 1 shows pictures of U.S. and British air cushion vehicles weighing from 8 to 163 tons, and discusses differences between ACV's and the ACLS.

4. VEHICLE SELECTION

Because of a desire for an early and low cost demonstration of an ACLS recovery system on an existing vehicle, a survey of existing unmanned vehicles in the 2,000 to 12,000 lb weight range was made during the preparation of the proposal for this study.

After this screening of existing vehicles, Bell concluded that there were two primary candidates. Each has advantages and disadvantages. The vehicles are:

(a) The Australian Jindivik (Figures 7, 8)

(b) The Ryan BQM-34A Firebee I (Figures 9, 10)

The following paragraphs briefly discuss each vehicle and the factors that led to Bell's recommendation of the Ryan BQM-34A for this study. Subsequently, because of USAF plans for other unmanned vehicle tests utilizing a Ryan Model 147G drone, it was decided to study a modified Ryan Model 147G instead of the BQM-34A. This vehicle, Figure 11, is also briefly discussed.

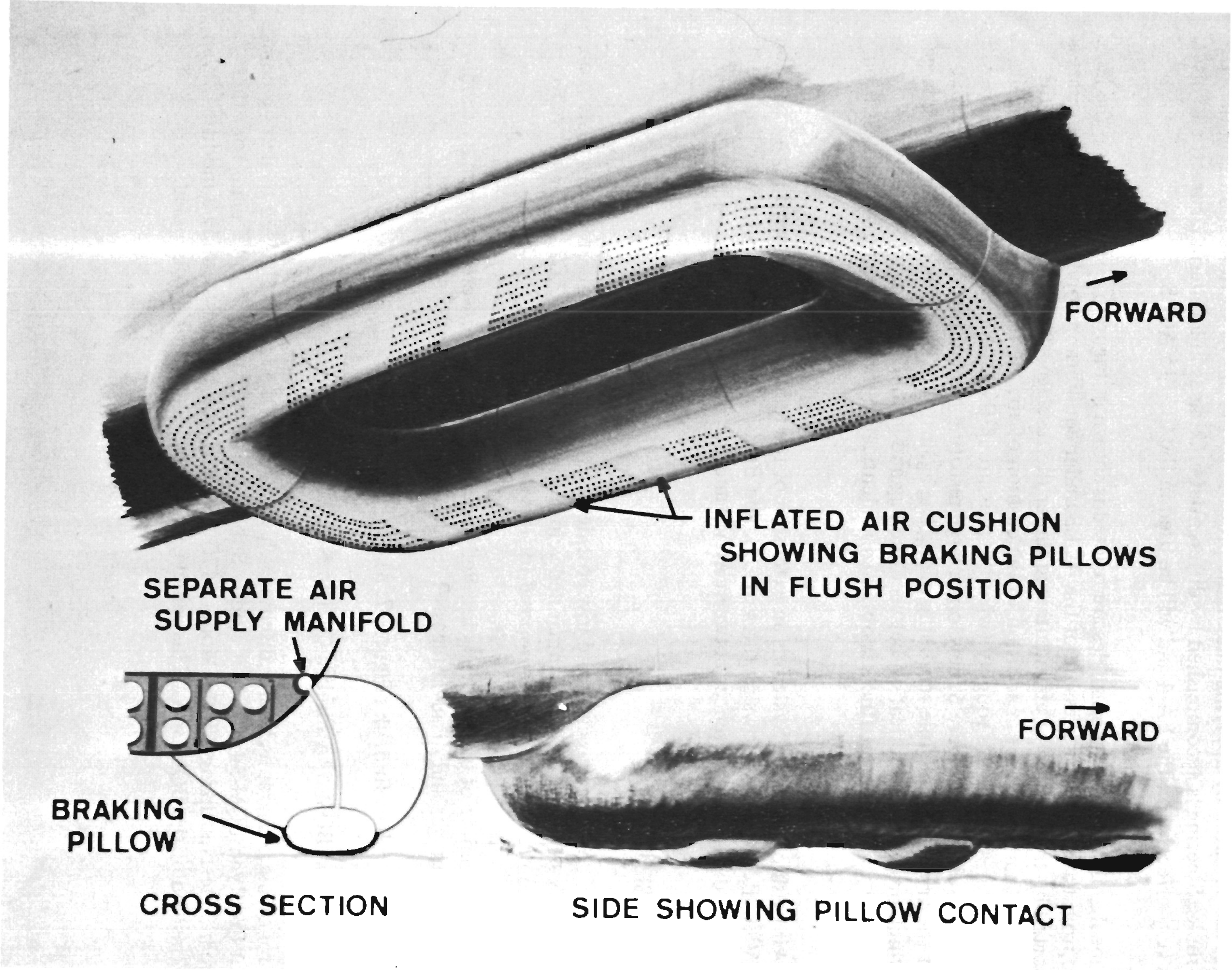


Figure 5. ACLS Pillow Brake System

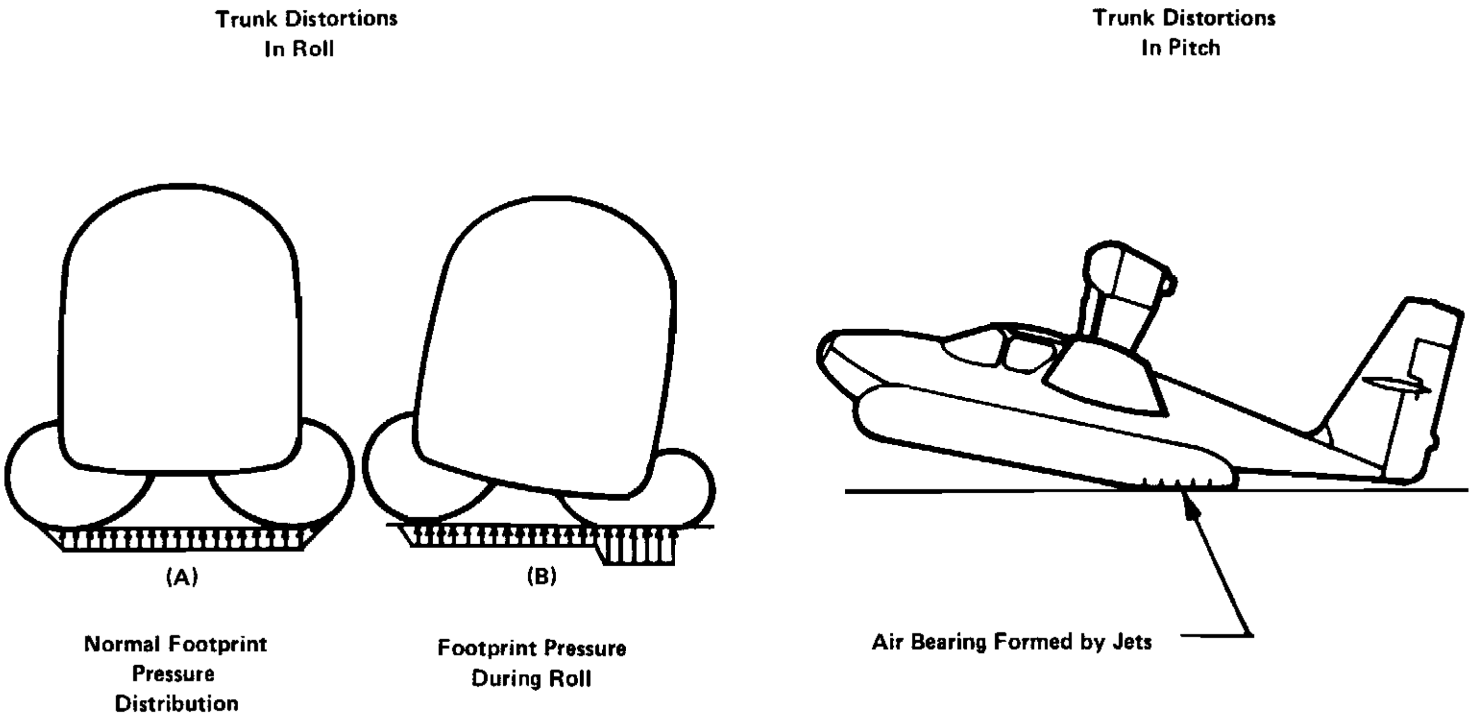


Figure 6. ACLS Footprint Pressure Distribution

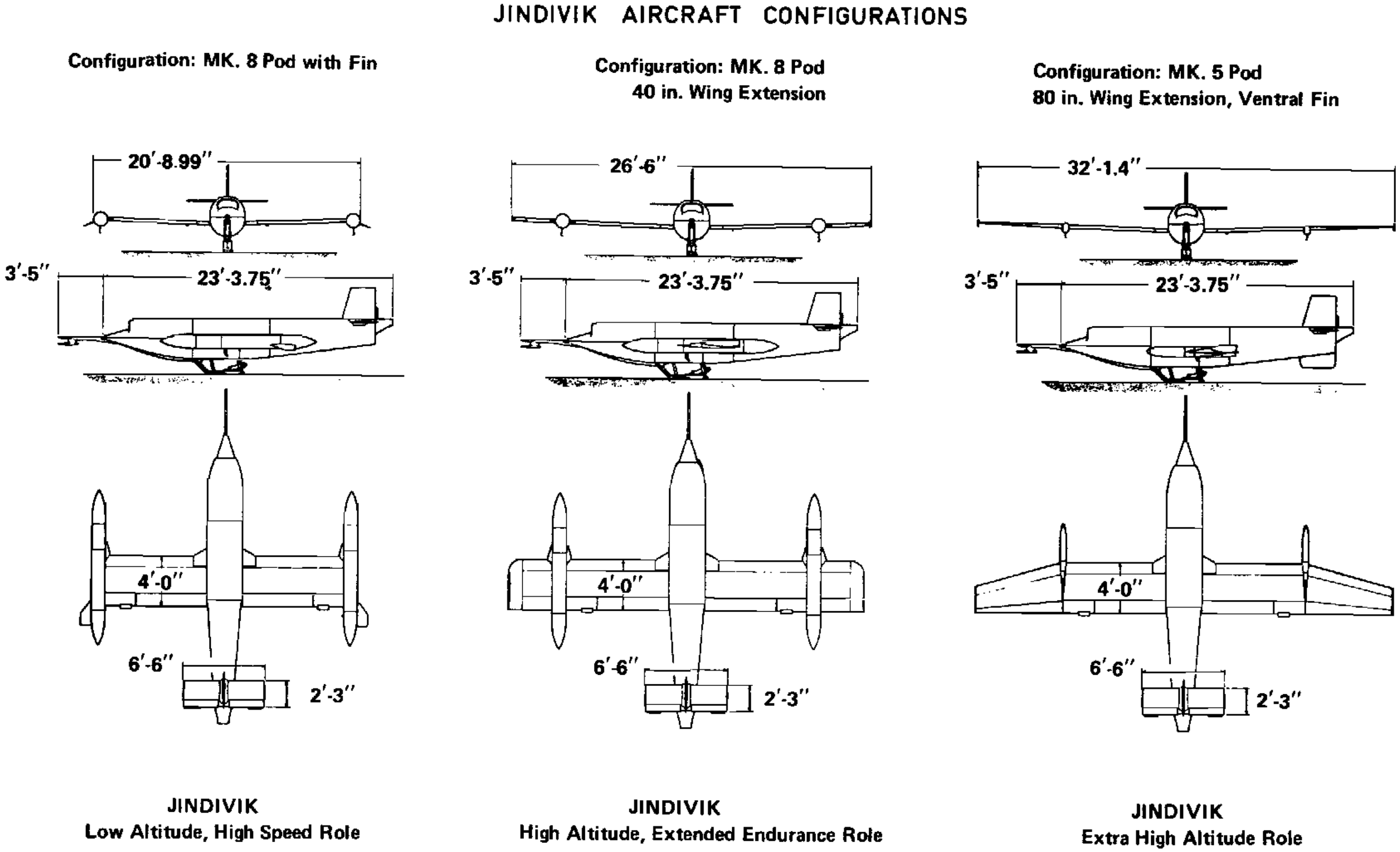


Figure 7. Jindivik Aircraft Configurations

Maximum Gross Weight = 3650 lb

ACLS Data

Cushion Area - 32.7 sq ft
Cushion Perimeter - 25.5 ft
Cushion Pressure - 112.0 lb/sq ft
Trunk Pressure - 224.0 lb/sq ft

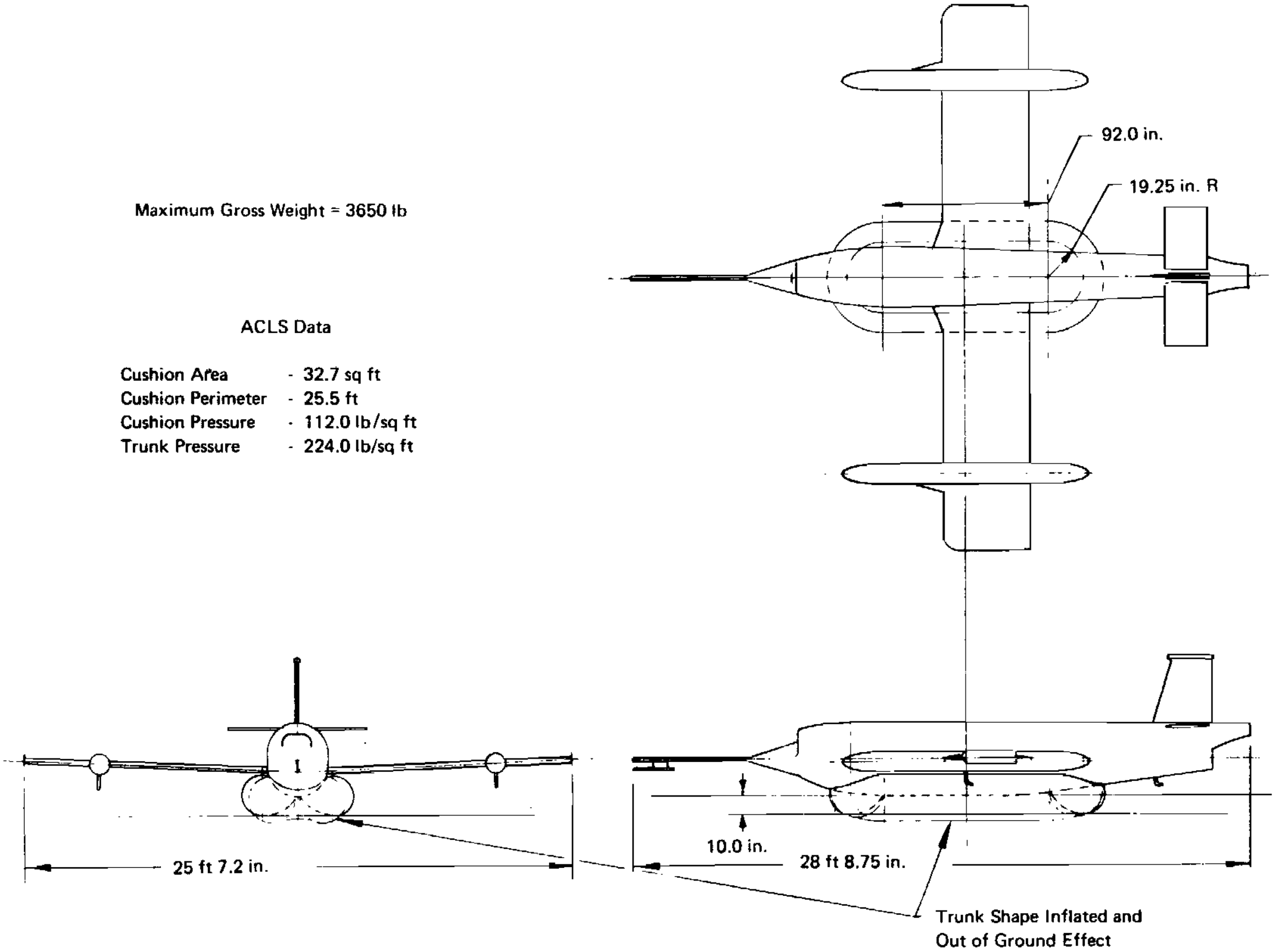


Figure 8. The Australian Jindivik with ACLS

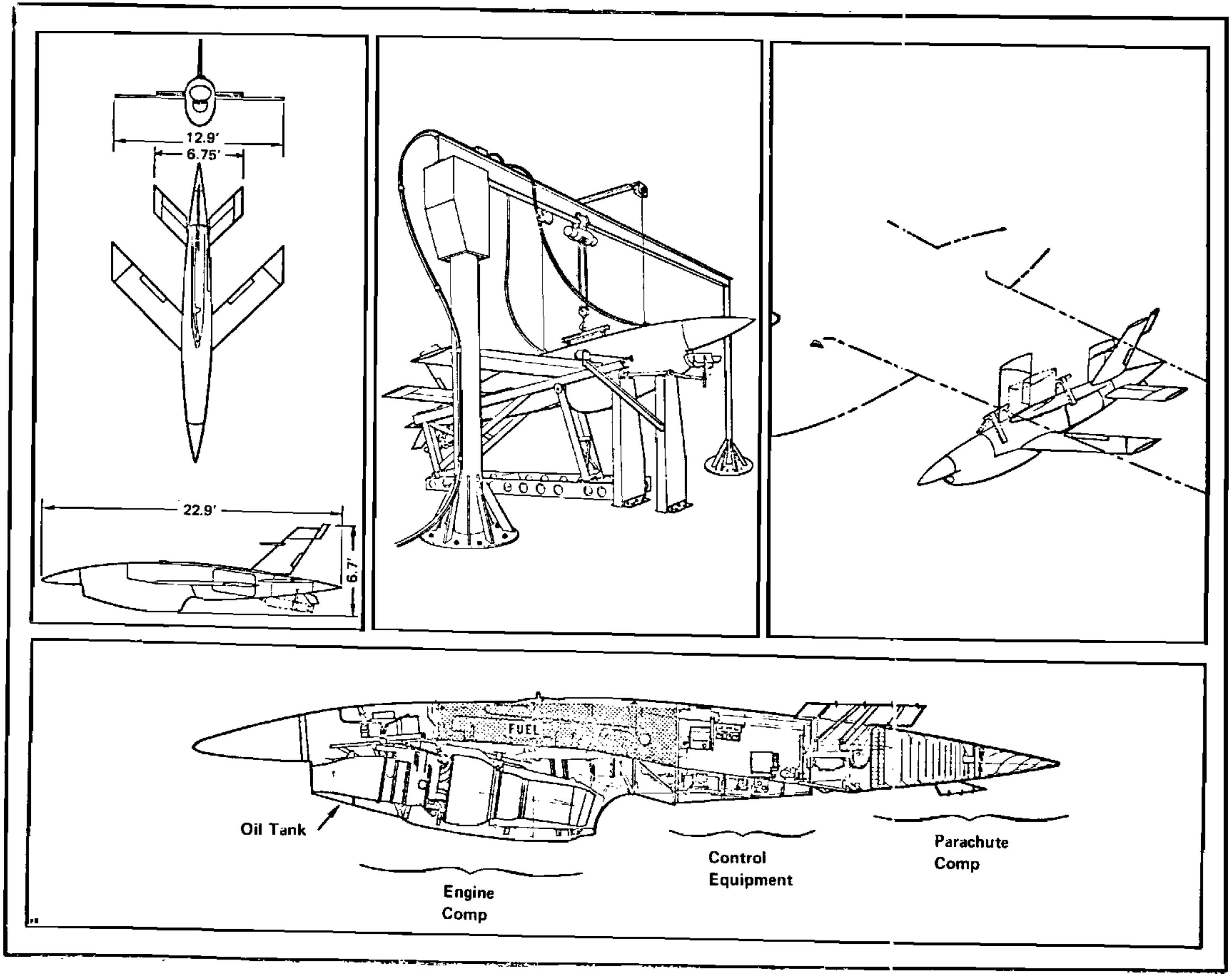
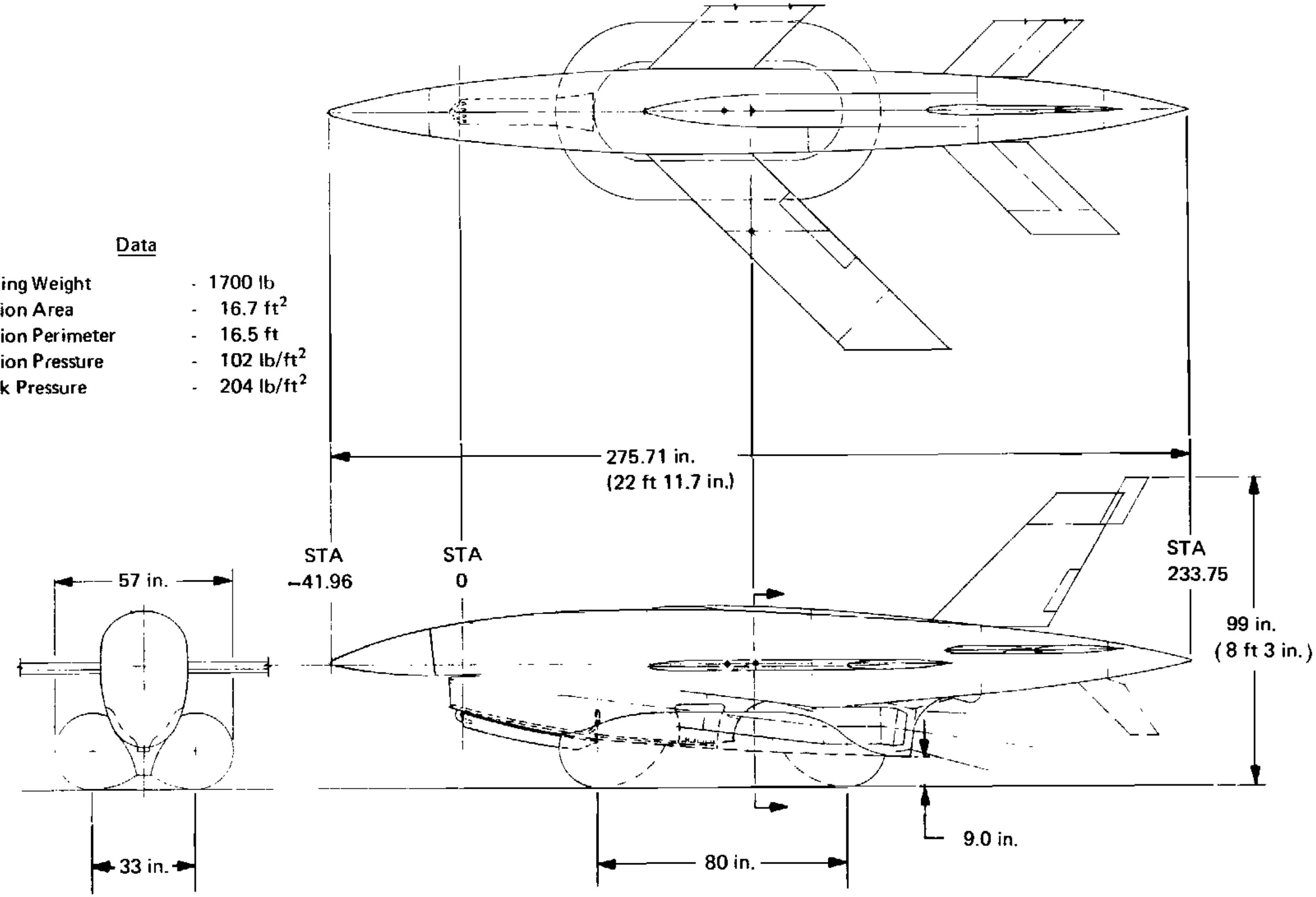


Figure 9. The Ryan BQM-34A Firebee I



Data

Landing Weight	- 1700 lb
Cushion Area	- 16.7 ft^2
Cushion Perimeter	- 16.5 ft
Cushion Pressure	- 102 lb/ft^2
Trunk Pressure	- 204 lb/ft^2

Figure 10. Firebee I (BQM-34A) With ACLS

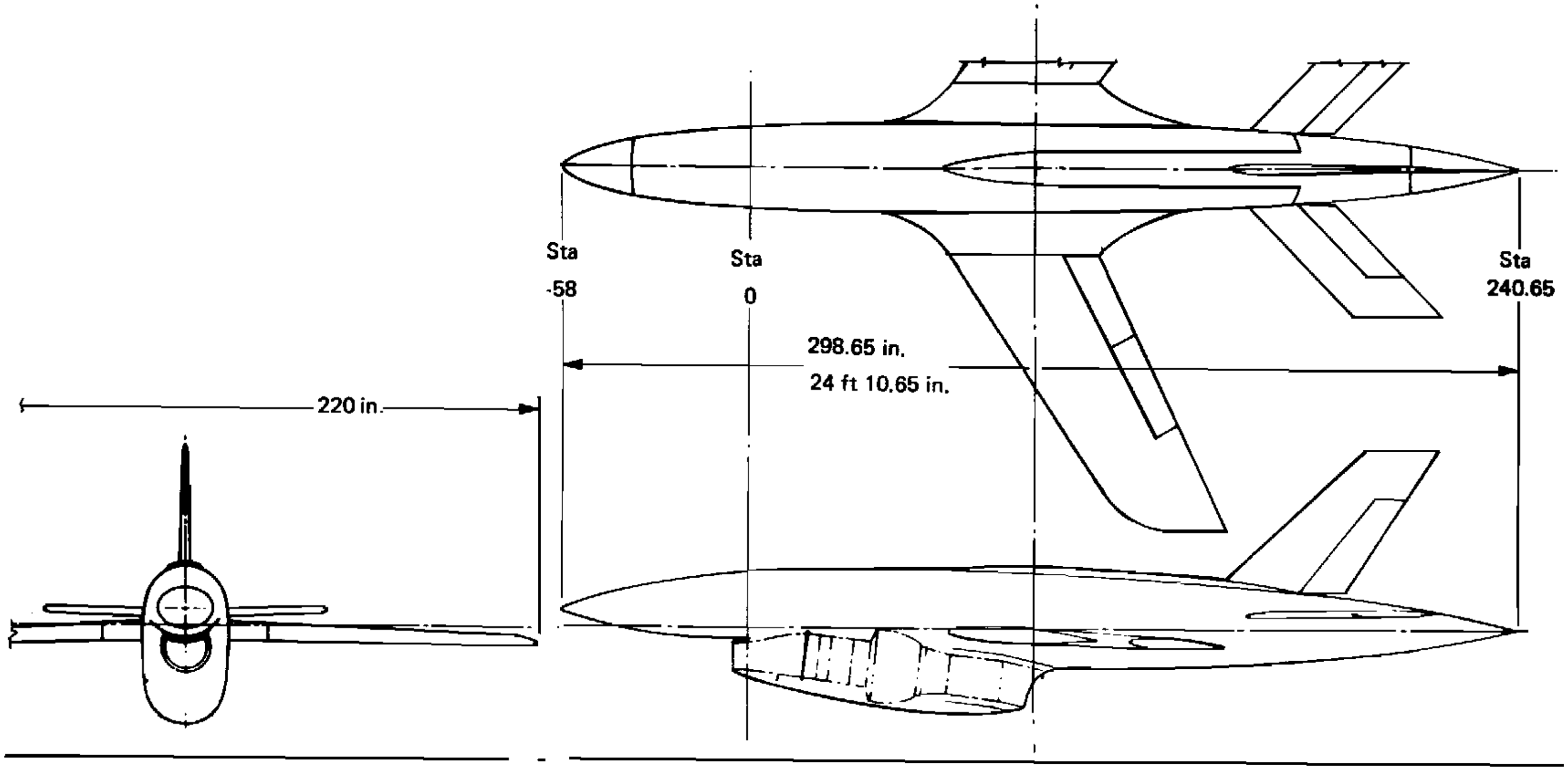


Figure 11. Modified Ryan Model 147G (Short Fuselage)

a. The Australian Jindivik

Figure 8 shows the Jindivik with an ACLS. Its gross weight ranges from 3200 to 3650 lb. A typical landing velocity is 120 knots.

This drone would be a near ideal vehicle for an ACLS application. However, it is not in flight status in the U.S. Its advantages are:

(1) Near ideal geometry for installing an ACLS airbag or trunk. It is a midwing design with a near circular fuselage cross section. There are no fins, engines or other protuberances on the lower surface.

(2) Designed for landing, so no major modifications of the guidance and control systems and related support equipment are needed. (It may be necessary to add yaw control for ACLS landings in crosswinds, see "disadvantages").

(3) No flight tests are required to check out guidance and control systems or techniques for landing. Hence, demonstrations of an ACLS on Jindivik, in Australia, should cost less than demonstrations with a vehicle which has never been landed. Also, risks should be less for Jindivik.

(4) Engine inlet is on top of the vehicle, so ingestion of debris should be minimal.

(5) The only known pilotless vehicle using a metal skid as a landing gear, so it provides a base for comparison of ACLS derived concepts with a skid-type gear.

(6) Uses a dolly for takeoff with its own propulsion engine, so, no launch aircraft or jato bottles are needed and operations costs of a demonstration program would be reduced.

(7) The propulsion engine has a bleed air system which could be used to provide air for an ACLS.

Its principal disadvantages are:

(1) Not now available in the U.S. (Not a major disadvantage if demonstrations are conducted in Australia; can be purchased fully equipped for approximately $200,000.)

(2) Liaison with the manufacturer would be complicated because the Jindivik is made in Australia; inevitably this would increase ACLS study and design time and cost.

(3) To bring one or more Jindiviks and support equipment here to perform flight demonstrations could increase the cost of a test program.

(4) No rudder for directional control in crosswinds.

b. The Ryan BQM-34A Firebee I

Figure 10 shows the configuration of this vehicle with an ACLS. It normally weighs from 1493 to 2300 lb; with special mission equipment it weighs up to 2670 lb. Its maximum velocity at sea level is 600 knots. Minimum landing speed would be about 125 knots at a weight of 1700 lb, with $\alpha = 14\text{-}1/2$ degrees.

The lower fin can be removed for a landing system test program and the engine pod and tailpipe can be extended to the rear to provide a structure for support of the trunk as shown in Figure 10.

Principal advantages of the BQM-34A are:

(1) Now in production and many are now in flight status in the U.S.

(2) Cost is low.

(3) Landing speed is sufficiently low so that modifications to the guidance and control system to permit remotely controlled landings with ACLS should be minor if any are required. (The vehicle has flown as low as 50 feet.) The ACLS increases vehicle tolerance for the landing maneuver. (As for the Jindivik, it may be necessary to add yaw control).

Principal disadvantages are:

(1) Extension of the engine pod will be needed to support the ACLS trunk.

(2) Analysis, and possibly a modification of the guidance and control system, will be needed for landing.

(3) No rudder for directional control.

(4) Because of the low inlet, there is the possibility of ingestion of debris if landings are made on unprepared surfaces. (Ryan has used inlet screens for ground testing; a screen will reduce the risk of engine damage without impairing the ACLS test program.)

(5) No jet engine bleed air is available

c. Ryan Model 147G

Prior to the beginning of this ACLS study, it was decided to investigate a modified Ryan Model 147G, instead of a BQM-34A as a possible vehicle for the study and a possible flight demonstration program. The USAF Flight Dynamics Laboratory plans to modify one or two Ryan Model 147G drones for flight tests to investigate equipment, operating procedures, and capabilities of unmanned vehicles. It is planned to initially recover these vehicles with a mid air recovery system (MARS) utilizing a parachute and a helicopter. Subsequently, the MARS recovery system may be replaced by wheels, metal skids, an ACLS, or another recovery system to permit evaluation of an alternative recovery technique.

The features of the modified Ryan 147G of most significance for ACLS design (fuselage geometry and propulsion system characteristics) are quite similar to the BQM-34A. (Figure 11 versus Figure 9.) The somewhat higher weight (approximately 2200 lb empty; 2800 lb gross) of the 147G is compensated by a larger wing. USAF planned modifications include the addition of a rudder and a three axis proportional flight control system.

At the time the ACLS study was initiated it was also planned that the fuselage between the wing and the tail would be shortened by approximately 30 inches. Figure 11 shows the modified 147G with this shortened fuselage, which was used for this study. It was later decided to retain the long fuselage (Figure 12). This will improve the stability and control characteristics relative to those of the short fuselage configuration, but otherwise should not affect conclusions relative to feasibility of the ACLS for this application. The estimated weight of this vehicle, designated "REPEX", ranges from 2075 to 3158 pounds.

Because the modified 147G vehicle will be in a research flight test status, and the modifications planned by the Air Force would make it more suitable for landings, it was decided to base the ACLS study on this vehicle even though only 1 or 2 of the modified vehicles will be available. It was anticipated that the ACLS concepts developed for the modified 147G would be applicable, with minor modifications, to the BQM-34A, the Jindivik, or other unmanned vehicles in the 2,000 to 12,000 lb weight range, in the event another vehicle is later selected for a demonstration program.

Data	
Cushion Area	21.5 sq. ft.
Cushion Perimeter	20.9 ft.

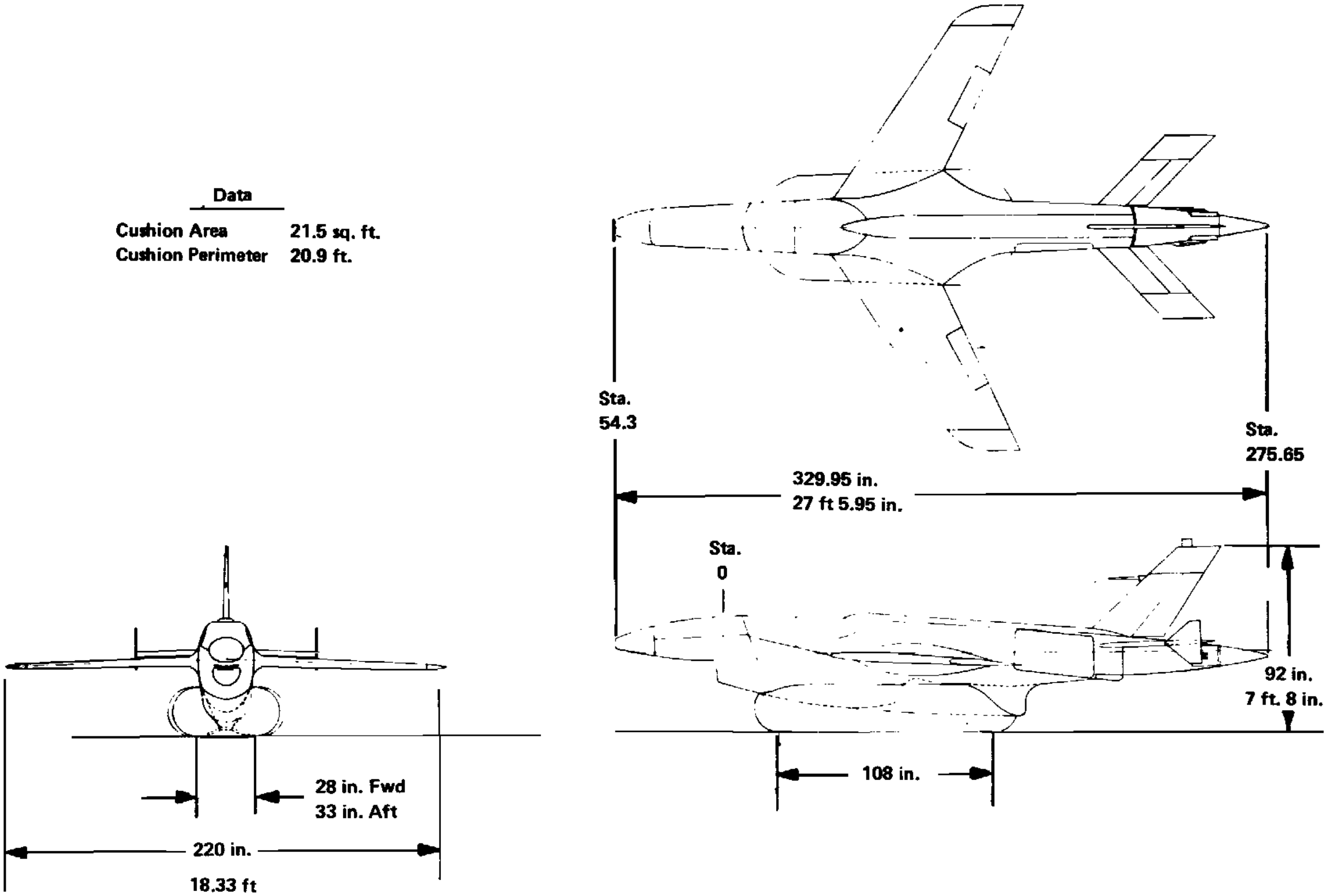


Figure 12. Ryan Model 147G "REPEX" Drone with ACLS

SECTION II
ACLS DESIGN AND ANALYSIS

1. SUMMARY

The ground rule that "it may be assumed that the vehicle is launched by an entirely separate system from the recovery system," made possible two major changes from previous ACLS concepts:

(a) A major reduction in the amount of air flow and consequently the elimination of ACLS engines and fans to provide the air flow.

(b) Stowage of the trunk prior to launch.

The ACLS concepts for the modified Ryan 147G take advantage of both of these simplifications. However, the studies have shown that a takeoff capability can be provided for only minor increases in cost and weight. Also for some applications a self stowing elastic trunk may be preferable to a trunk which is manually stowed.

Figures 13 and 14 show the trunk and cushion of the ACLS concept recommended for the modified "short fuselage" Ryan Model 147G. Figure 12 shows the same concept on the "long fuselage" REPEX version of the 147G. Significant features of the ACLS are:

(a) A trunk which can either form a low air flow cushion cavity, or act as an inflated skid with zero air flow during the slideout after landing. At landing, the trunk acts much like the decelerator bags used to attenuate landing shocks of cargos or drones landed by parachutes.

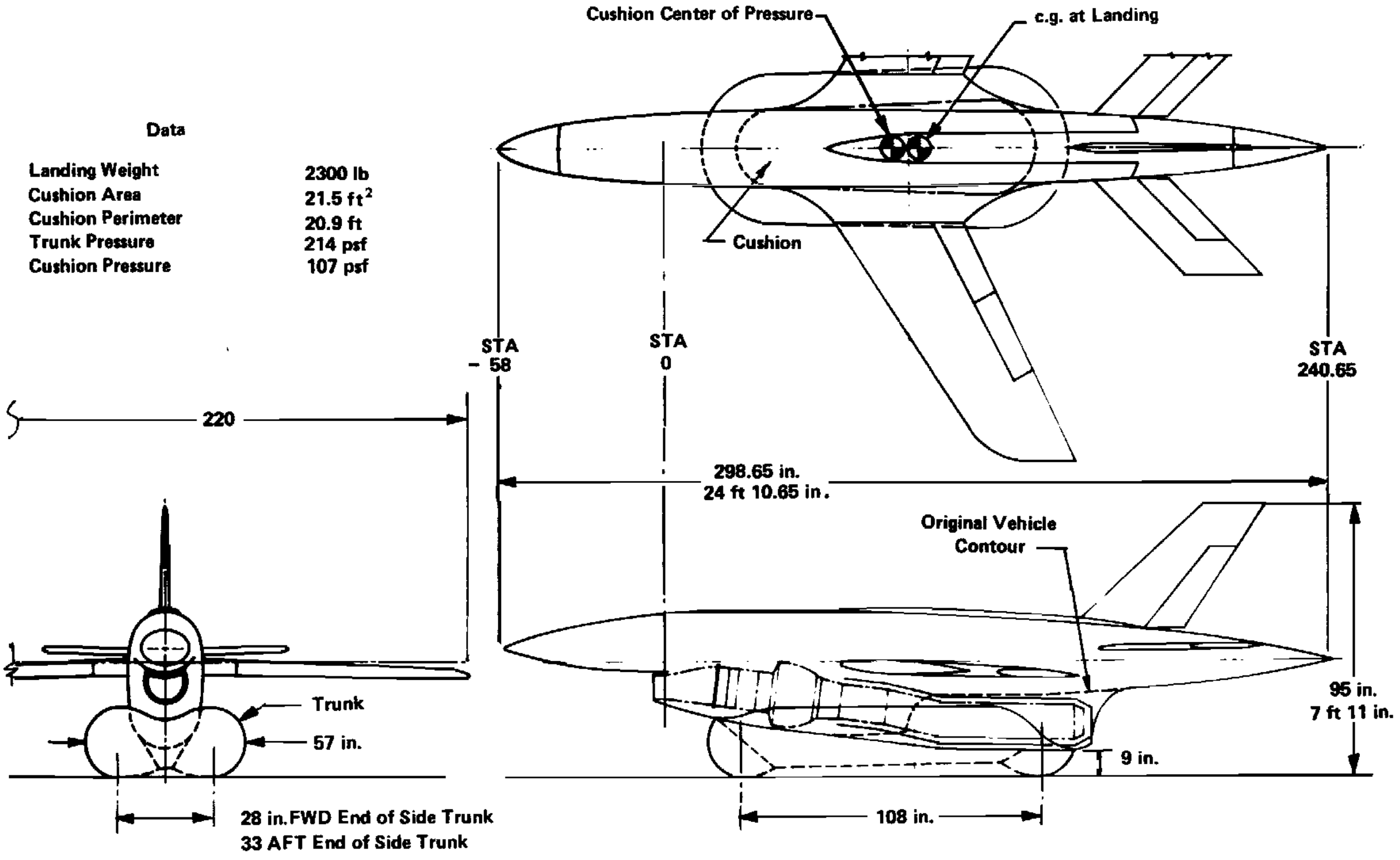
In either the low flow or zero flow mode, the air cushion formed beneath the vehicle also contributes to energy absorption. This air cushion significantly increases the allowable sink rate if landings are made at low attitudes.

For a system designed for landing only, the trunk can be constructed of an inelastic material that is stowed prior to launch. For a system with a takeoff capability the trunk will be of two-way stretch elastic material which retracts snugly against the fuselage when the air supply is shut off.

Replaceable elastomeric tread material on the areas of the trunk which contact the landing surface will provide a deceleration of 0.3 to 1.0 g on dry concrete. (Higher decelerations can also be provided; see (d), Suction Braking.) Tread life of 20 landings without replacement is projected.

It will be necessary to extend the engine pod and tail pipe of the Ryan 147G in order to provide support for the aft portion of the trunk, as shown in Figure 13. Even with these vehicle modifications, the estimated ACLS weight is less than that of the Mid Air Recovery System (MARS).

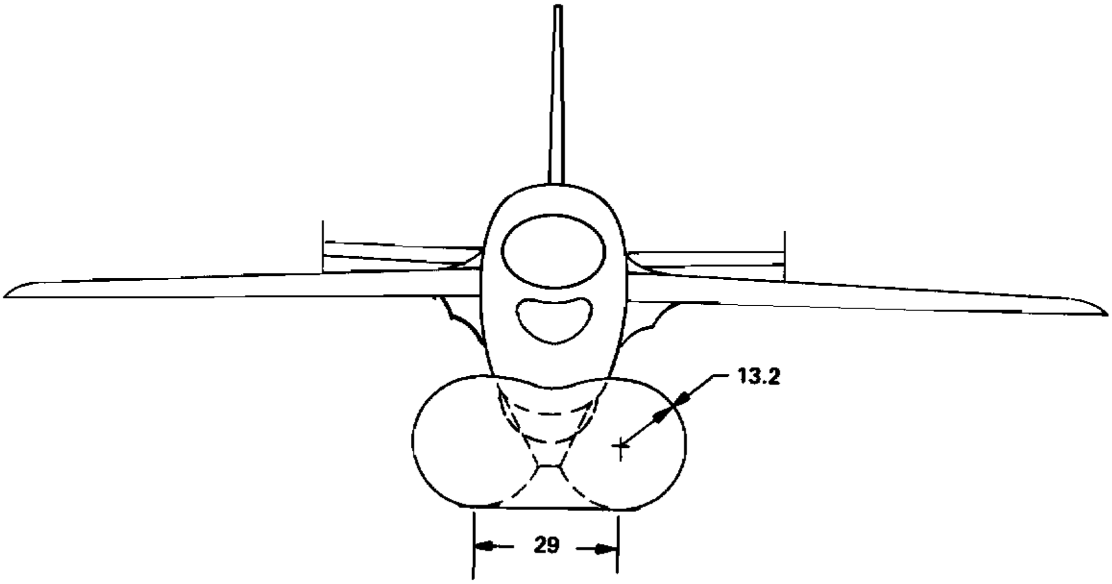
(b) An ejector, utilizing propulsion engine bleed air, inflates the trunk. The ejector can also provide a small amount of air flow (1.5 to 2.0 lb/sec or 15 to 20% of the LA-4 air flow) from trunk orifices located near the ground tangent. This flow will provide air lubrication to reduce friction forces and moments during the landing transient. The recommended configuration can easily be adapted for tests with and without this air flow.



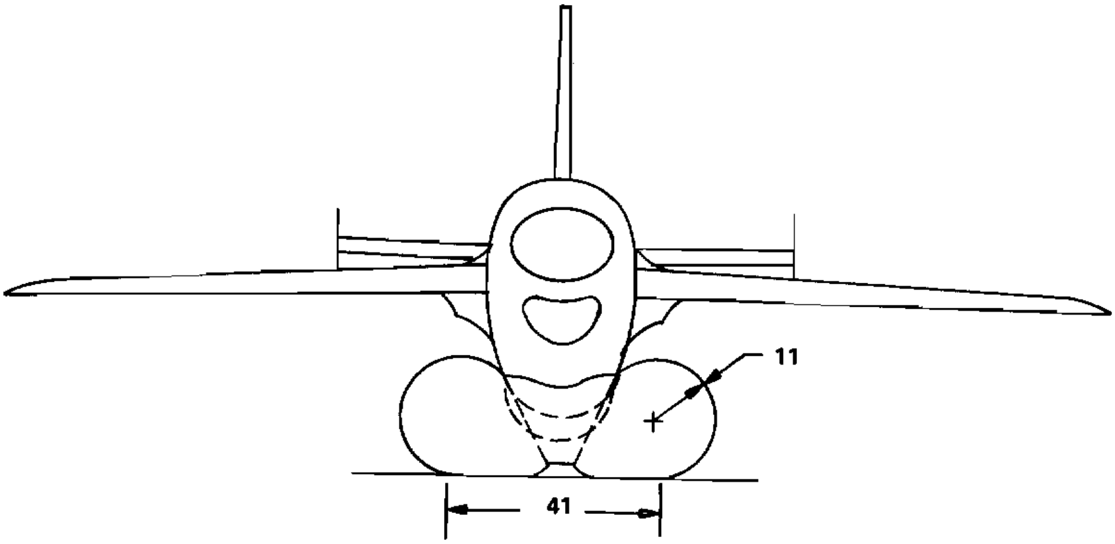
Data

Landing Weight	2300 lb
Cushion Area	21.5 ft^2
Cushion Perimeter	20.9 ft
Trunk Pressure	214 psf
Cushion Pressure	107 psf

Figure 13. Modified Ryan Model "147G" (Short Fuselage) with ACLS



Landing Approach
(No Vertical Load)



Suction Braking
(2g Vertical Load on Trunk)

Figure 14. Front Views of 147G with ACLS

A later section (Air Supply) discusses use of a stored gas system plus an ejector as an alternate or backup air source for a zero flow ACLS.

(c) A simple relief port to vent air from the trunk and limit the vertical acceleration during hard landings, (may not be required, see Section II.4, Energy Absorbtion).

(d) An optional suction braking system which utilizes a second ejector to reduce pressure in the cushion cavity to less than atmospheric pressure. This increases the down load on the trunk and increases the deceleration during roll out by approximately 50% over that attainable without the suction. On dry concrete runways, maximum decelerations of 1.5 to 2.0 g can be achieved. If touchdown is at 136 knots, a 2g deceleration will result in a slide out of less than 500 ft. Suction braking is also expected to be of great benefit on low friction surfaces (wet runways, etc.).

(e) An optional differential braking capability to improve directional control during slideout and taxiing. This would be provided by inflatable valves or seals to cover trunk orifices on the left or right side of the trunk and thus to vary the friction between the trunk and the ground.

(f) An optional takeoff capability in which a third ejector provides additional flow into the trunk and/or the cushion so the vehicle is supported on the low friction air cushion.

To provide an early and low cost demonstration of a very simple and reliable ACLS, the ACLS could be initially designed for landing only and without suction braking or differential braking. Such a system can be provided for flight testing within 8 months from go-ahead. The optional features (suction braking, differential braking, and a takeoff capability) can be phased into the program with relatively little impact on flight test schedules.

An ACLS incorporating all of the optional features could be ready for flight testing within 12 months from go-ahead.

It is estimated that weight of an ACLS (excluding engine pod and tail pipe extensions) for landing only could be as low as 60 lb (approximately 2.1% of the vehicle gross weight). An ACLS with all of the optional features should weigh less than 100 lb. These weights compare to 180 lb for the Mid-Air Retrieval System (MARS). The required fuselage and tail pipe extensions (estimated weight = 67 lb) will negate a significant portion of the ACLS weight benefit for the 147G vehicle. However, such penalties associated with vehicle modifications can be avoided in new vehicles designed for use with an ACLS.

Benefits expected from an ACLS include:

(a) Reduced operational costs relative to MARS recovery.

(b) Reduced damage relative to parachute recovery.

(c) Ability to operate from unprepared sites having very low bearing strengths with negligible effect on the landing surface due to repeated landings.

(d) High decelerations and short landing slideouts.

(e) A large tolerance on conditions at landing; with resulting simplification of landing guidance and control systems.

(f) A takeoff capability (optional).

(g) Removal of sortie rate limits of the MARS system (determined by Helicopter availability).

(h) Removal of vehicle weight limitations of the MARS system (determined by Helicopter load capability).

(i) Recovery is possible in bad weather and at night.

2. TRUNK AND CUSHION

a. Requirements

In landing, the primary function of the trunk and cushion is to reduce the vehicles vertical velocity to zero and to dissipate the associated energy. The vertical velocity at touchdown depends upon the vehicle flight characteristics, the sophistication of the guidance and control systems provided for landing, and operator skill. In this study a capability for landing without a flare was established as an objective in order to minimize guidance and control requirements and/or operator training. Figure 15 shows estimated modified Ryan Model 147G equilibrium sink rates at landing as a function of vehicle attitude, velocity, and thrust. A nominal sink rate of 6 ft/sec at a pitch angle of 6 degrees and a velocity of 136 knots was selected. A relatively high velocity was selected (α below L/D max) to give control of the flight path angle as well as short term control of sink rate without varying thrust. This was done because of the very slow response of the present throttle control system. The relatively low landing attitude associated with this nominal condition also results in more efficient operation of the ACLS and greater tolerance for variations in touchdown conditions than would be available at higher attitudes.

For ACLS design, an objective of providing a system that would permit a sink rate of at least 6 ±6 ft/sec through a pitch attitude range of at least 6 ±3 degrees, was established. The estimated capability of the recommended concept exceeds this objective.

Based on information provided by the USAF Flight Dynamics Laboratory, a maximum of 9 g vertical deceleration could be permitted. A maximum vertical deceleration of 8 g due to the ACLS was established as a requirement. With the recommended ACLS design, decelerations will be below this limit unless landings are made at sink rates higher than the "allowables" of Figure 15. At the nominal sink rate of 6 ft/sec, at $\theta = 6$ degrees, the deceleration due to the ACLS will be 3g.

If the approach is at the nominal touchdown condition, the flight path angle will be only −1.5 degrees. However the equilibrium flight path angle can be increased to −3 degrees without exceeding the allowable sink rates at touchdown or even steeper approaches can be made if a flare is used to reduce the sink rate at touchdown.

The trunk and cushion, supplemented by aerodynamic moments, must also provide sufficient stability to keep pitch and roll attitudes within acceptable limits during landing and braking. The primary requirement is to prevent contact of hard structure with the landing surface and thus to eliminate possible damage. However, it is desirable to further limit pitch and roll to provide a margin of safety and to reduce possible effects of large attitude excursions on the slideout ground track. An objective of preventing wing tip contact when landing in a 30 ft/sec crosswind with $\beta = 0$ with the "allowable sink rates" of Figure 15 and limiting roll to 10 degrees after the initial landing transient, was established. It is estimated that this objective can be met with the ACLS having 1.5 to 2.0 lb/sec air flow to lubricate the trunk. With a zero air flow ACLS it would be necessary to further limit yaw and/or the sink rates at touchdown. As an alternative or a safety precaution, wing skids could be provided to limit roll and prevent damage to wing tips; these could be small inflated elastic air bags which retract snugly against the wings or inelastic bags that are stored internally.

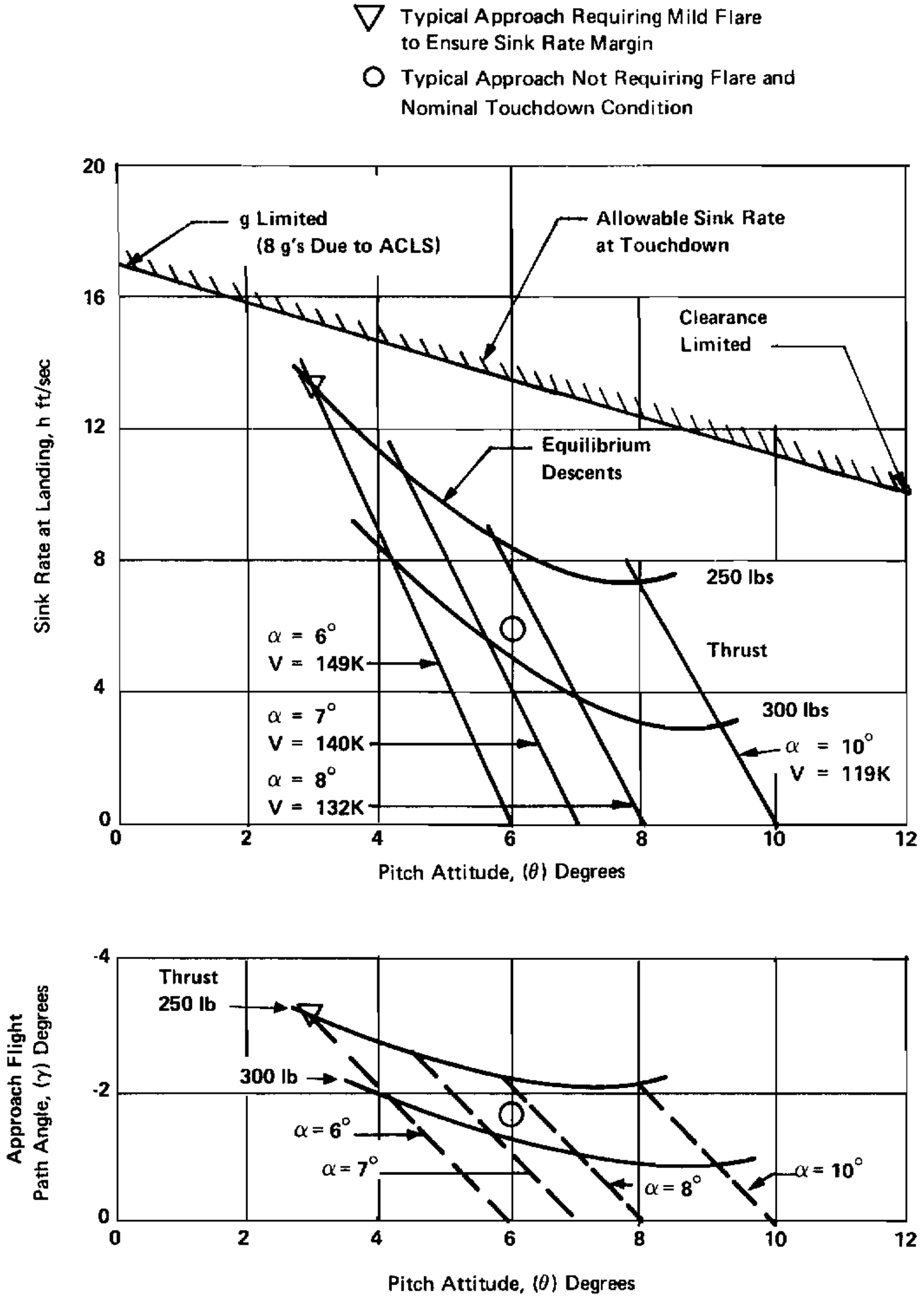


Figure 15. Maximum Allowable Sink Rates Compared to Equilibrium Descent Conditions

An objective of limiting vehicle pitch to a nose-down attitude no greater than 5 degrees during the landing transient and during subsequent 1.5 g braking was rather arbitrarily established; considerably larger nose-down attitudes could be tolerated but it is estimated that the maximum nose-down angle will be within this limit.

b. Configuration

Several trunk, cushion, and inflatable skid configurations, including single and double skids and partial and full cushions were considered in this study. (Figure 16.) Each of these could be provided with or without air flow.

A single inflated skid would be a somewhat simpler configuration than the others shown in Figure 16. The single inflatable skid is essentially a decelerator bag, similar to those used for landing shock attenuation of cargos or drone aircraft landed by parachute, but with the possibility of airflow to lubricate the bag to landing surface interface.

Landings on a passive inflated rubber air bag restrained by an external net were made in 1942 by the English Hengist troop glider, build by the Slingsby Sailplane Co., Ltd. The bag was not retractable, but formed a well faired shape beneath the fuselage in its hammock-shaped net. Five of these aircraft were built and the skid performed very well through many takeoffs and landings without mishap.

The principal objection to a single inflatable skid for unmanned vehicles is its poor roll stability. Although such a concept was successfully used for the Hengist glider, it is likely to be unsuitable for the 147G, with its narrow fuselage and high c.g., unless landings are made with near zero crosswinds and near zero yaw. This would impose unnecessary operational limitations as well as additional requirements on the landing guidance and control equipment and/or operator.

A dual inflated skid configuration will provide improved roll stability, especially if some air lubrication is provided. For the same trunk or skid weight it will have somewhat less energy absorption capability than either the single inflated skid, the partial cushion, or the full cushion configuration because of the absence of the cushion and the rear trunk. In addition, the cushion configurations provide improved vertical and pitch damping. This is particularly true of the full cushion configuration. The front and rear trunks of the full cushion configuration also give lateral restraint to the side trunks with resulting improvement in roll stability.

The full cushion configuration offers the above benefits with little or no weight, cost, or complexity penalties. In addition it has a potential for taxiing and for takeoff. Therefore, it is recommended for a program to demonstrate an ACLS on unmanned vehicles.

The trunk and cushion configuration recommended is shown in Figures 13 and 17. It is similar to the configuration used on the LA-4 and the one being designed for the CC-115.

There are some features of this trunk that differ from trunks for the LA-4, CC-115, and most previous ACLS design concepts. For example, Figures 13 and 17 show that the trunk is not attached directly to the fuselage near its longitudinal centerline. Instead Figure 17 shows a web (Item 2) which drops the center attachment to a point below the fuselage when the trunk is inflated. One can also visualize the function of this web as a pulling up of the bottom centerline of a single air bag or trunk to create a cushion cavity and to transform it into the more conventional elongated toroidal trunk shape. This concept has been incorporated in an ACLS design for the F-8 aircraft. A dynamic model of this F-8 ACLS is scheduled for testing at NASA, Langley Research Center late in 1972.

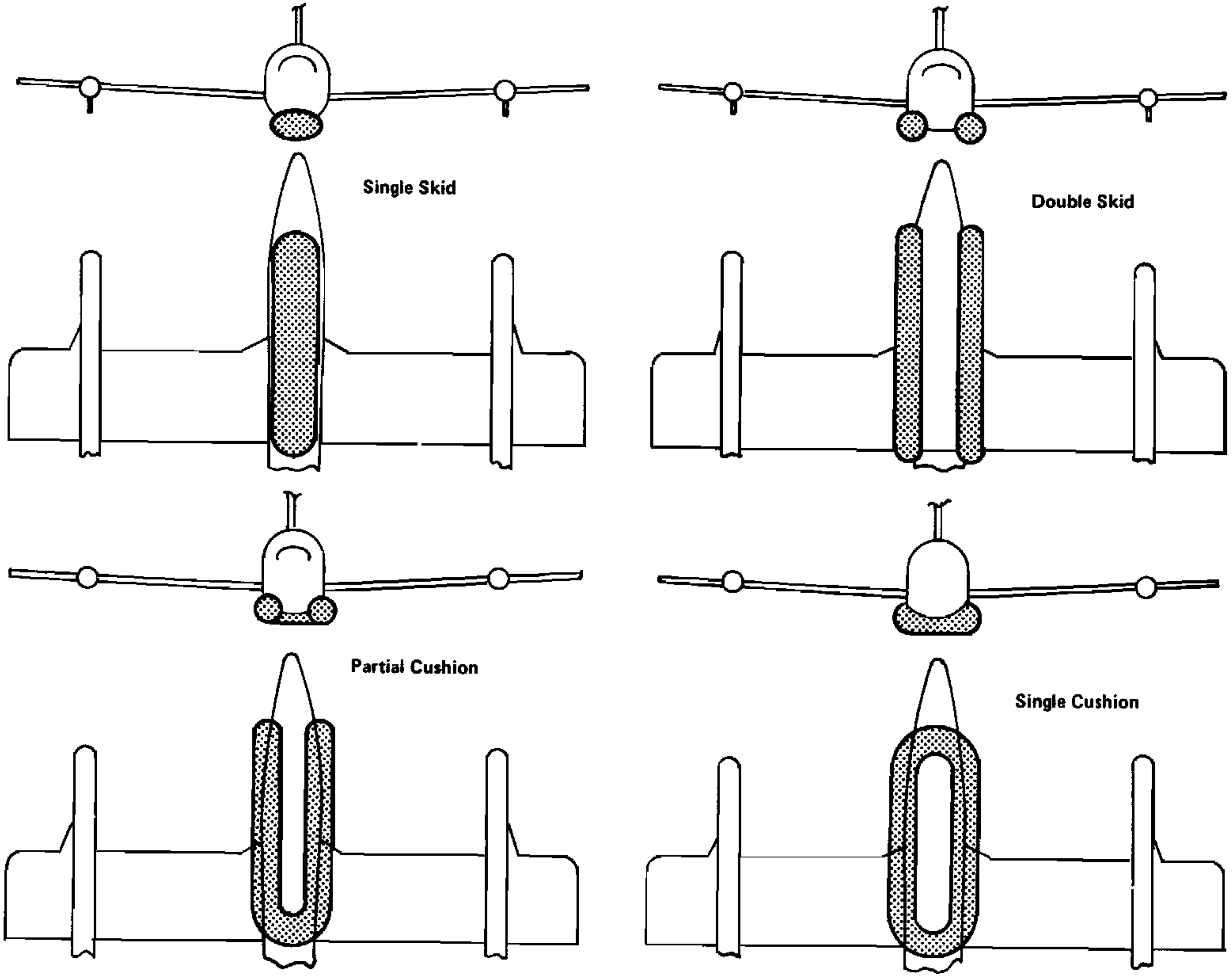


Figure 16. Inflated Skid and Trunk Cushion Configurations

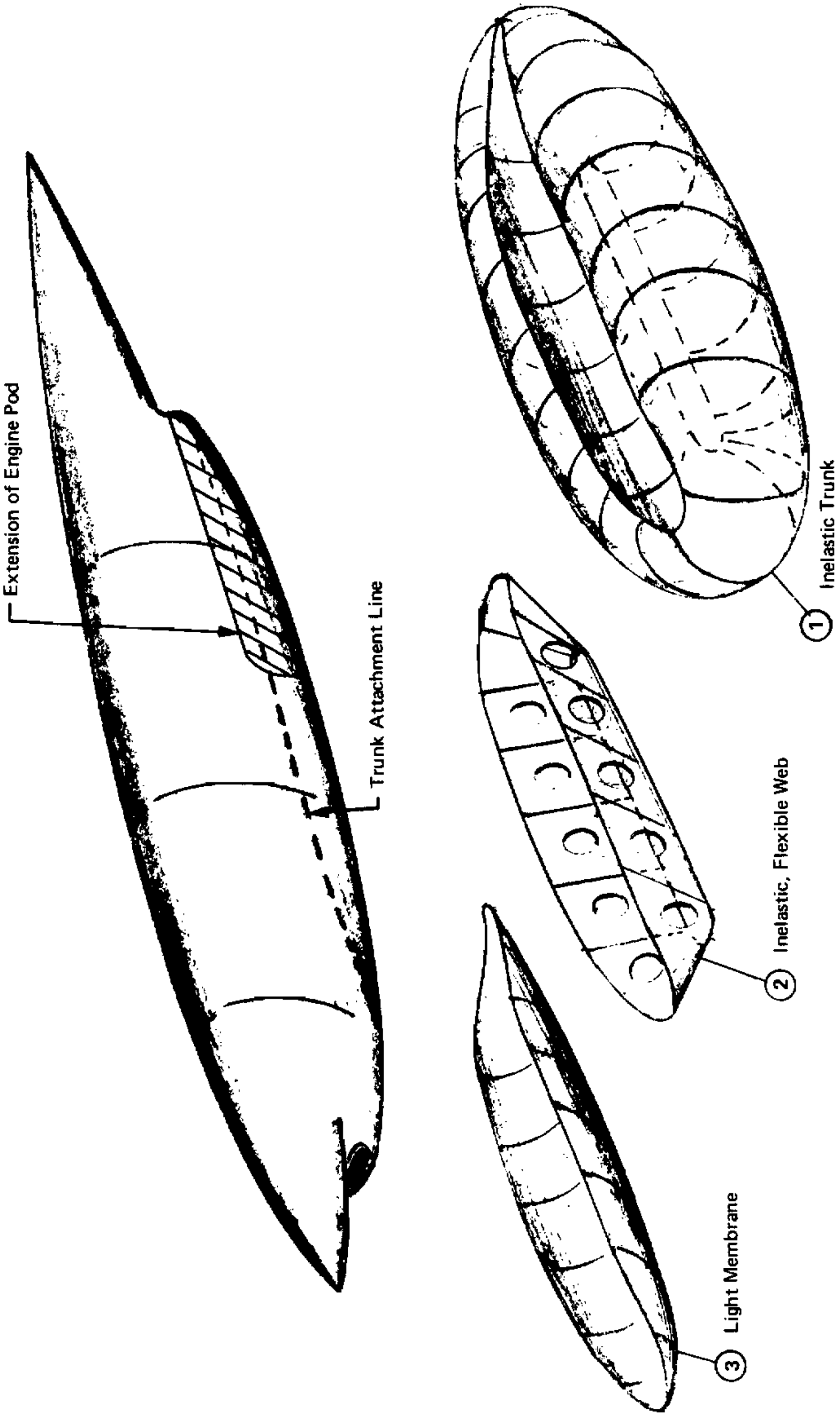


Figure 17. Trunk Elements

This dropped trunk centerline was made necessary because two side trunks of sufficient width and depth would overlap in the front view if they were attached directly to the fuselage at both the side and bottom of the fuselage. In addition there are two very significant benefits from this arrangement: 1) a significant improvement in load stroke efficiency (see Energy Absorption Section, II.4), and 2) improved accessibility to equipment, doors, etc. on the bottom of the fuselage via an access slit at the bottom centerline of the trunk (see Service and Maintenance Section III.3).

Item 3 of Figure 17 is a very light membrane (less than 4 oz. per square yard), which approximately matches the lower fuselage contour. A completely closed trunk volume is formed by attaching Items 1, 2, and 3 to each other along their upper edges during trunk manufacture. Thus, the joining of Item 3 membrane to the Item 1 outer trunk, prevents leakage along the fuselage attachment (dotted line on fuselage sketch) and leakage into the fuselage at structural joints, access doors, etc.. Local flaps, retained by velcro will permit rapid access to doors, etc. on the lower fuselage.

The external tab formed by joining the three elements of the trunk will be folded over a light cord as shown in Figure 18. At trunk installation the tab will be secured to the fuselage with a light metal strip running all along the fuselage attachment line. The cord will prevent the trunk from being pulled from between the fuselage and the attachment strip. Stiffeners internal to the fuselage, transmit loads to the fuselage frames.

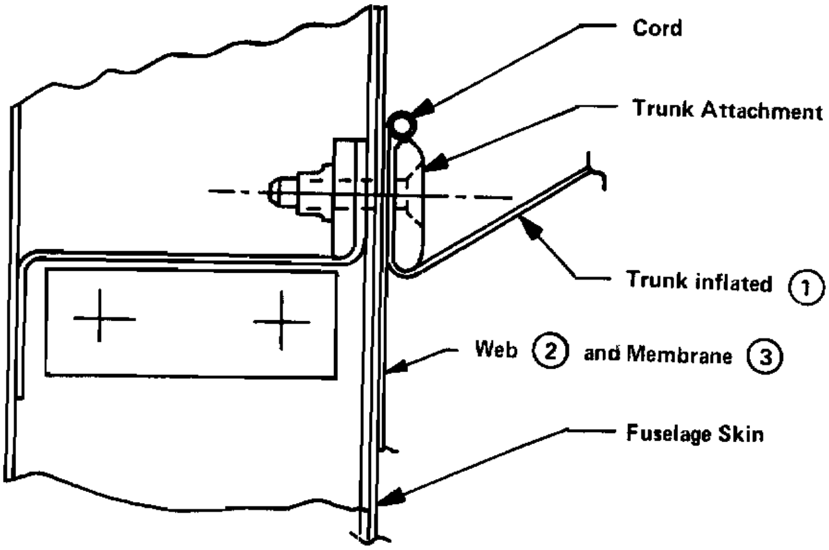
This method of attachment is similar to those used successfully on ACLS models. It is simpler and aerodynamically much cleaner than attachments used on either the LA-4 or CC-115. On a vehicle designed for an ACLS, the attachment strips could be inset into the side of the fuselage to completely eliminate any projection from the side of the fuselage.

With this configuration, trunk orifices in a horseshoe shaped area at the bottom of the rear and aft side portions of the trunk near the ground tangent are recommended (at least for initial flights) to air lubricate this region and reduce moments due to the landing transients. The amount of airflow (15 to 20% of LA-4 flow) and the distribution of the orifices will be such that during slideout, cushion pressure will be only a small percent of that required to support the weight of the vehicle. After pitch down to a small negative attitude, most of the vertical load will be transferred to the front unlubricated portion of the trunk. This will result in a high deceleration and a short slideout.

This trunk configuration, made of inelastic material, will be provided with tread material over the entire trunk area which contacts the ground. This results in a low tread bearing pressure and a low tread wear. This is discussed further in the section on braking.

An alternate trunk/cushion design, using elastic material, is shown in Figure 19. Dual cylindrical inflated skids are enclosed by an outer cover. The cover is attached to the cylinders along lines 1 and 2. When,air flow is provided to the region inside of the cover and between the two cylinders, the cover balloons out to form a seal with the ground between the front and rear ends of the cylinders. Orifices permit flow into the cushion volume which is formed by the two cylinders and the two end seals. This gives a full cushion configuration for landing, taxi, or takeoff.

If the airflow to the space between the dual side trunks or skids is cut off after touchdown, the elasticity of the cover sheet causes the cover to retract away from the ground between the front and rear ends of the side trunks. This vents the cushion and places the full weight on the side trunks to decelerate the vehicle. Thus, during slideout this concept is essentially a dual skid, but with lateral restraint by the outer cover.



Detail B

Figure 18. Cross Section of Trunk Attachment

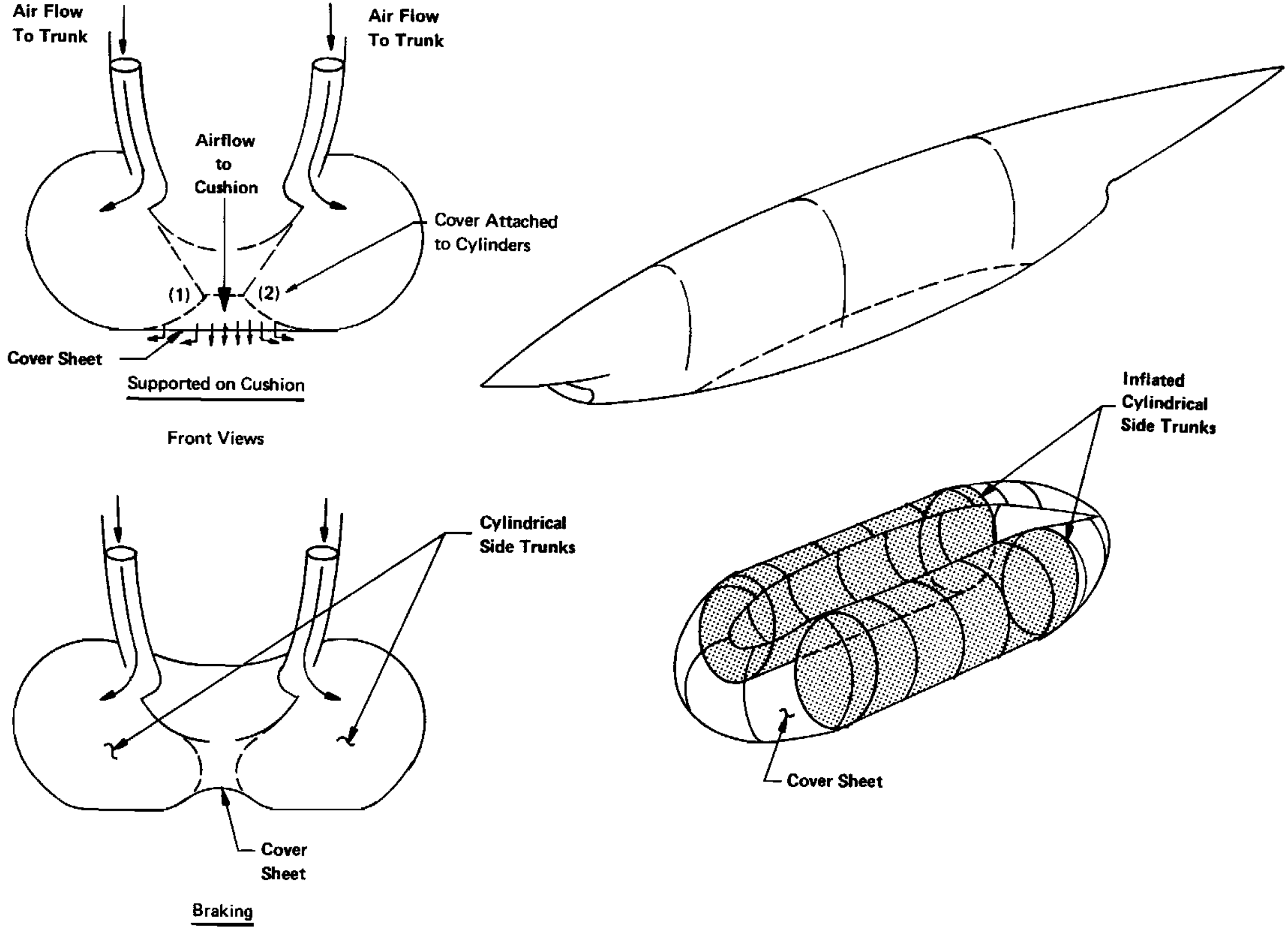


Figure 19. Alternate Trunk and Cushion Configuration

With this concept, air lubrication will be provided through the cover sheet at the front and rear of the cushion. These are the areas that experience the greatest vertical loads during the initial landing impact and during the subsequent pitch down. Therefore, it is in these areas that air lubrication is of most benefit for minimizing pitch and roll moments and trunk wear.

This concept simplifies installation of tread material on an elastic trunk because most of the wear will be on the side trunks where only one-way stretch is required. This is discussed in a later section on braking.

The dual side trunks should give improved roll damping if a relief port is provided on each side. During landing it retains the energy absorption and heave damping due to a cushion.

c. Pressures

Figure 20 shows the cushion pressures required to support the weight of the modified Ryan Model 147G, with the cushion design of Figure 13. At the design landing weight of 2300 lb, a cushion pressure of 107 lb/ft^2 would be required; at a 2800 lb gross weight this increases to 130 lb/ft^2. These pressures are considerably higher than the nominal 60 lb/ft^2 cushion pressure for the LA-4, which has a comparable weight and size (Figure 13 versus 21). The pressures for the Model 147G are higher because the 147G is a high density vehicle with a narrow fuselage. Also the geometry of the bottom of the 147G fuselage limits cushion length. Therefore, it is not practical to provide a cushion as large as the one on the LA-4. Figure 22 compares the cushion plan forms for the LA-4 and the 147G.

Figure 20 also shows the trunk pressures for the 147G and the LA-4. A nominal trunk pressure of 200 lb/ft^2 prior to touchdown, was selected for the 147G. This will increase to near 250 lb/ft^2 during slideout. Trunk pressure during the landing transient will be limited to a maximum of 500 lb/ft^2 by a relief port (see Energy Absorption, Section II.4). The trunk pressure was kept relatively low to minimize the air supply power requirement, which is proportional to trunk pressure times air flow. Also a low trunk pressure reduces tread wear. Preliminary estimates have indicated that a 200 lb/ft^2 trunk pressure prior to touchdown will provide adequate energy absorption and stability and acceptable tread wear. However, with the recommended inelastic trunk and the ejector air supply, variations in trunk pressure and air flow can easily be investigated during ground and/or flight tests (see Air Supply, Section II.3).

d. Trunk Materials

Trunks for the LA-4 and the CC-115 ACLS utilized elastic one and two-way stretch elastic materials made of a composite of nylon cords and rubber. Figure 23 illustrates this type of construction. Figure 24 illustrates a typical load versus elongation characteristic for this type of material. The low initial slope of the load versus elongation curve permits initial inflation with low pressure; the stiffening, at the knee of the curve, prevents inflation beyond the desired shape.

When the trunk is fully inflated, the helically wound nylon cords are fully extended and carry most of the tension load. When the air supply is shut off, the rubber matrix causes the material to retract snugly against the fuselage like a deicer boot. Thus, elastic material provides a very simple means of trunk retraction.

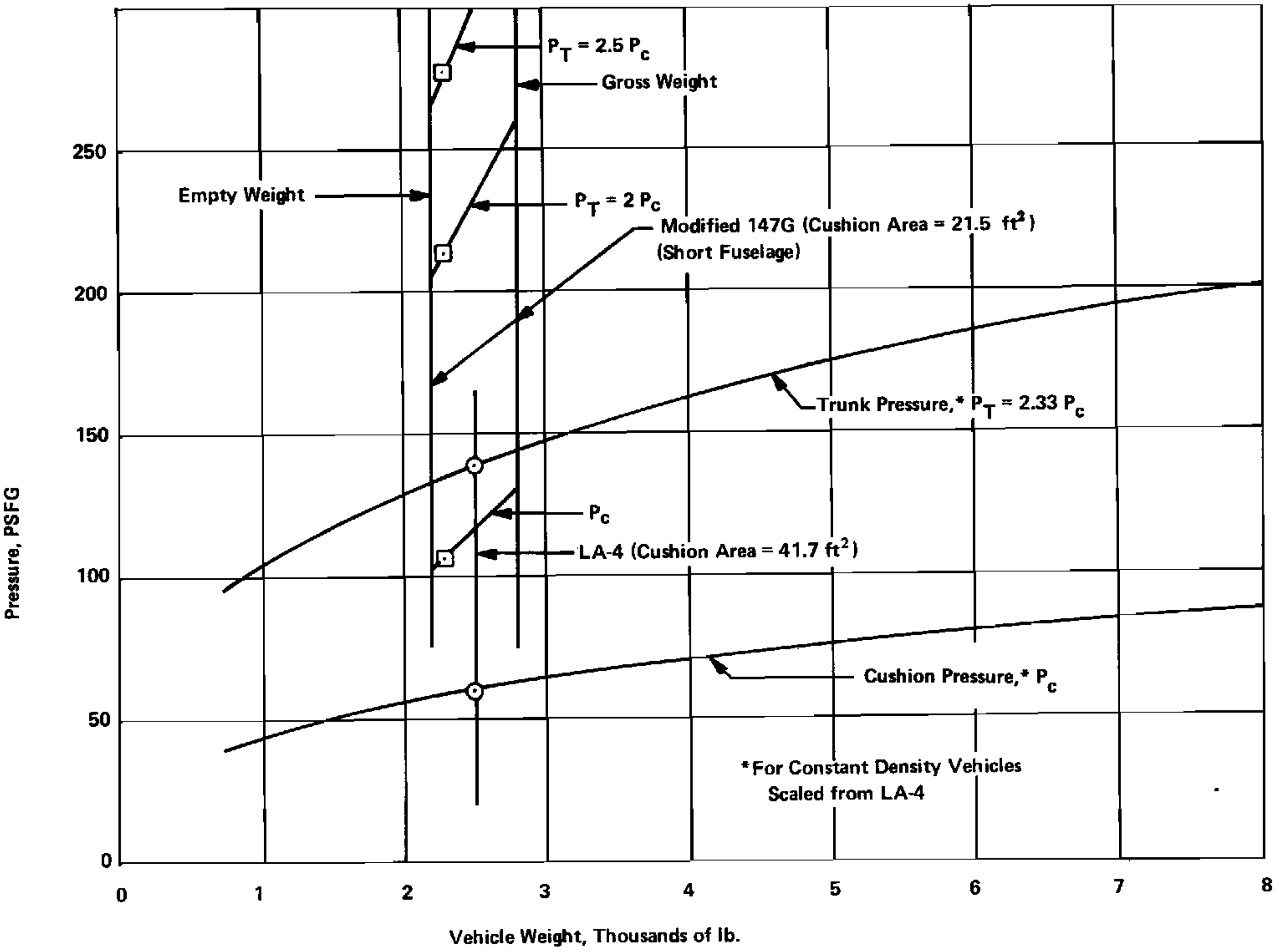


Figure 20. Trunk and Cushion Pressure versus Vehicle Weight

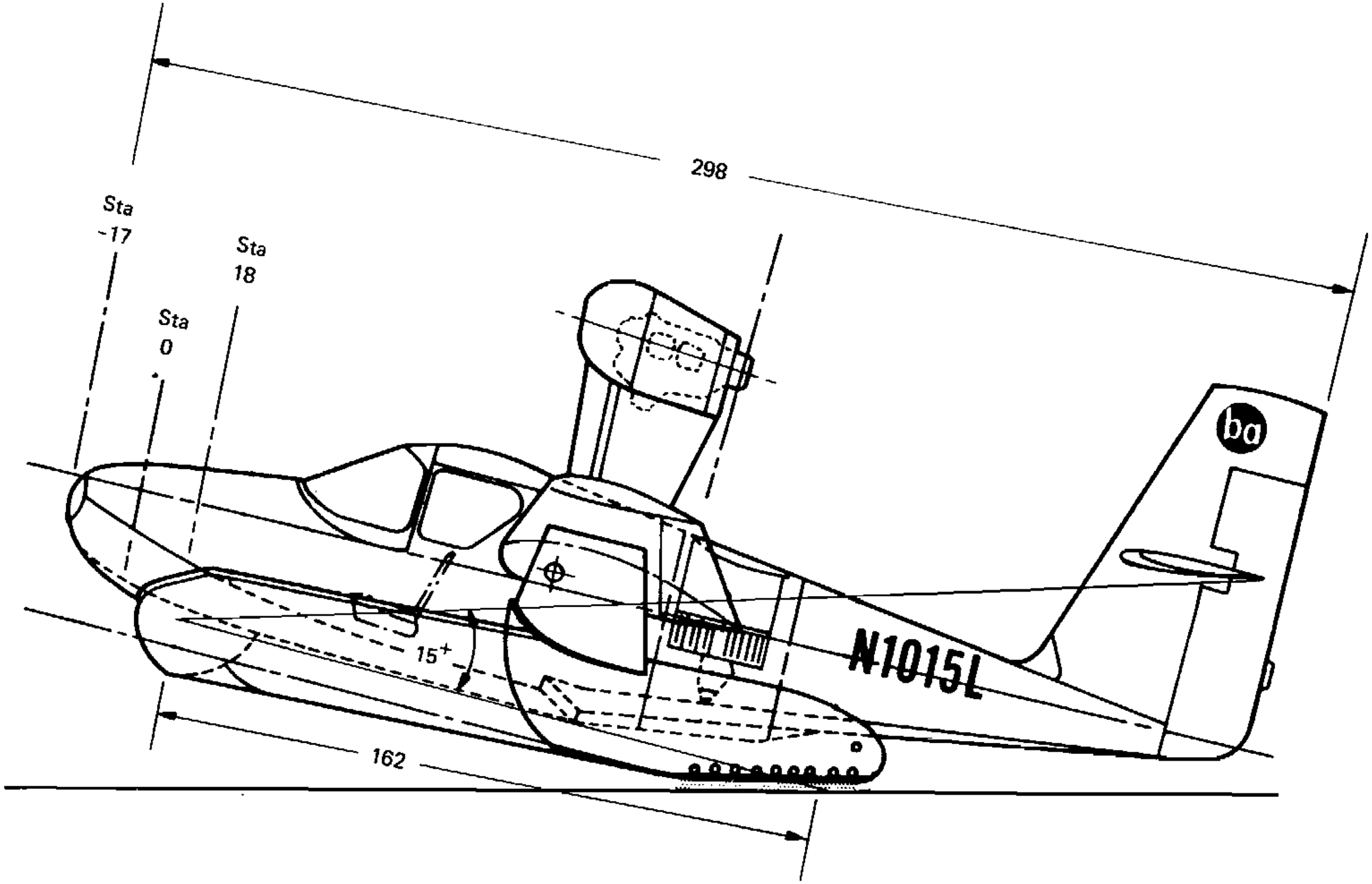


Figure 21. LA-4 with ACLS

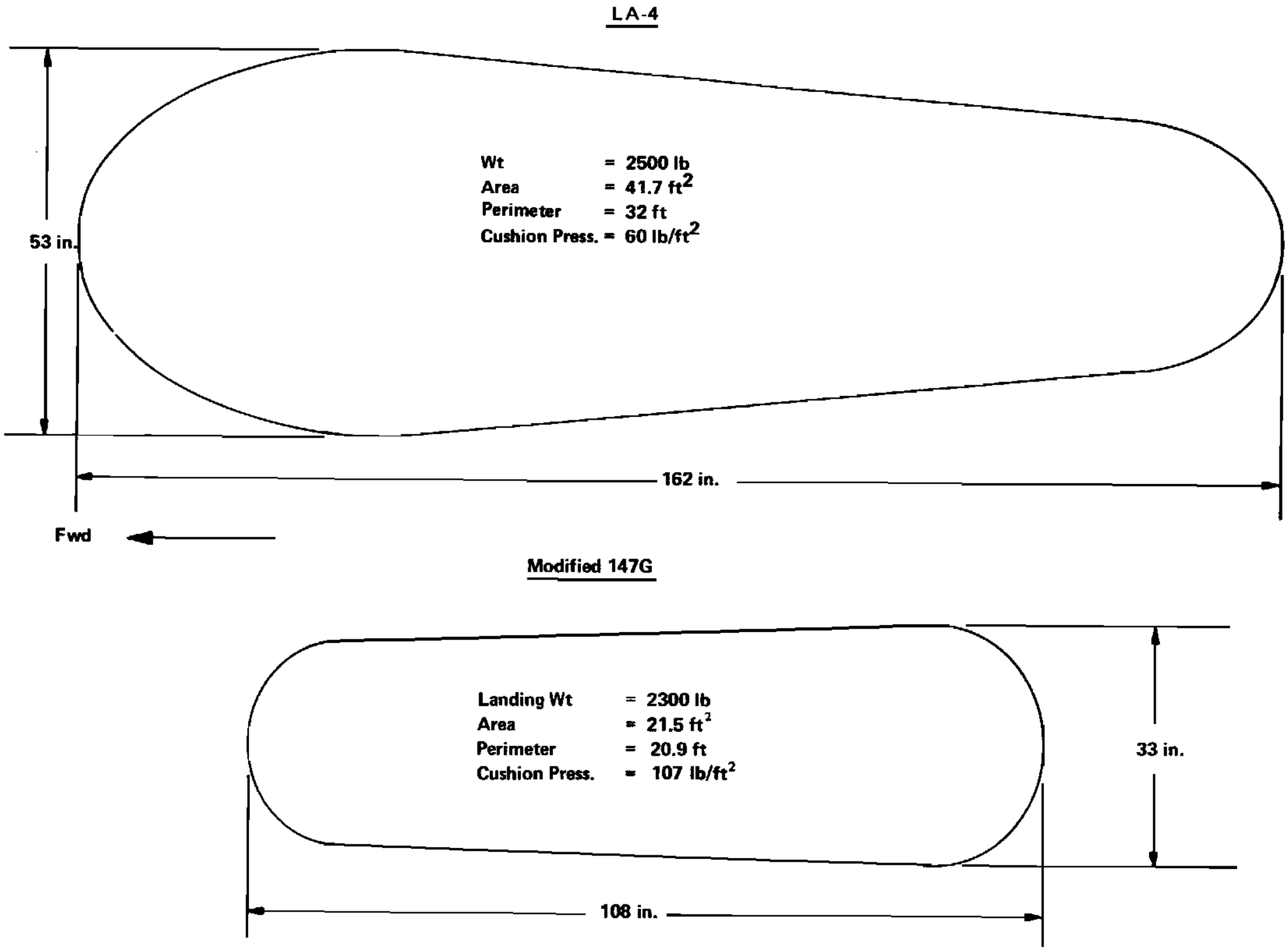
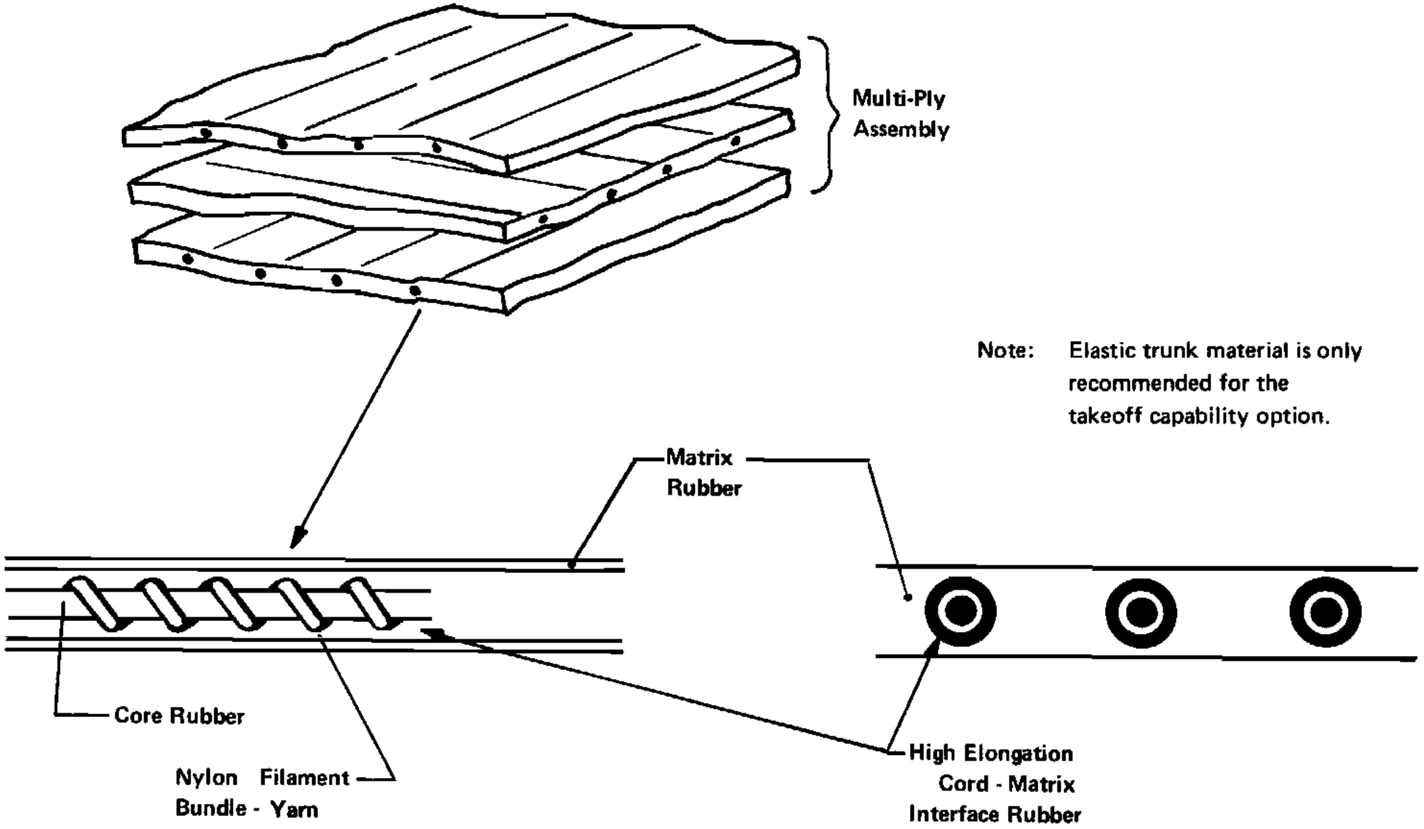
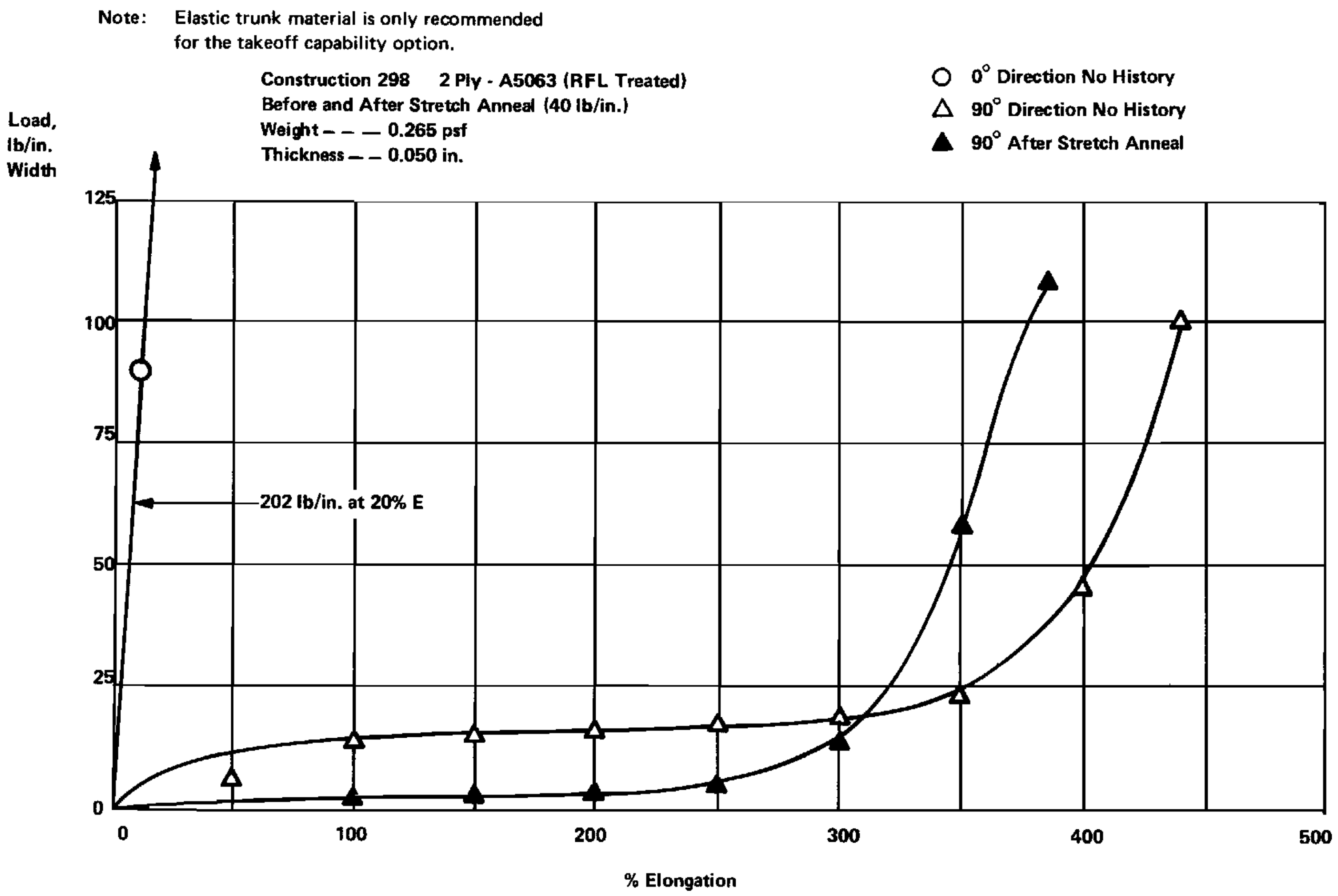


Figure 22. LA-4 and 147G Cushion Geometries



Note: Elastic trunk material is only recommended for the takeoff capability option.

Figure 23. Typical Reinforced Elastic Trunk Composite



Note: Elastic trunk material is only recommended for the takeoff capability option.

Construction 298 2 Ply - A5063 (RFL Treated)
Before and After Stretch Anneal (40 lb/in.)
Weight — — — 0.265 psf
Thickness — — 0.050 in.

Figure 24. Typical Elastic Trunk Material Load versus Elongation

Because of the ground rule that "it can be assumed that launch is by means other than the ACLS," inelastic trunks which are manually stowed prior to launch can also be used for this application. Figure 25 shows weights of a number of coated fabrics that could be used for this application. This figure also shows that these coated fabrics generally weigh 3.6 oz/yd^2 = 0.025 lb/ft^2 or less, per 100 lb ultimate tensile per inch of width.

In order to compare weights of elastic and inelastic trunk materials, one must account for the reduction of the weight per ft^2 of the elastic materials as they are stretched. Figure 26 shows how the wt/ft^2 per 100 lb/in. ultimate strength of three typical elastic cord constructions decreases as the materials are stretched. When the trunk is inflated, these materials will be near the knees of their load elongation curves.

Thus, their weight in the inflated condition will be of the order of 0.06 to 0.08 lb/ft^2 per 100 lb/in. of ultimate strength versus 0.025 or less for the inelastic materials.

The trunk material area of the inflated trunk of Figure 13 is approximately 13 yd^2 = 117 ft^2. The above data indicates that if the trunk is designed with an average ultimate tension of 200 lb/in, an elastic trunk would exceed the weight of the inelastic trunk by 9 to 14 lb.

If allowance is made for differences in test methods used to obtain the above weight to strength ratios for the elastic and inelastic materials and for an estimated 5 lb weight penalty for stowage of the inelastic trunk, the net penalty for the elastic trunk can probably be reduced to 5 lb or less. Thus, trunk weight is not a major consideration in selecting an elastic versus inelastic trunk, at least for a demonstration vehicle.

Figure 27 shows elongations required for a two-way stretch elastic trunk, and estimated maximum tensions for either elastic or inelastic trunks. The tensions are based on a maximum pressure of 500 lb/ft^2 during the landing and on the in flight (cushion pressure = 0 and zero flattening) trunk shape. This is a very conservative assumption, as non-zero cushion pressure and trunk flattening both decrease tensions for a given trunk pressure. A material ultimate tension four times these conservatively estimated maximum tensions has been used for estimating material requirements and trunk weights.

One and two way stretch trunk materials have demonstrated characteristics meeting or exceeding these requirements; a number of suitable inelastic trunk materials are commercially available.

It is estimated that in production quantities, the cost of an elastic trunk will not be significantly greater than an inelastic trunk. Initial design and development costs will be somewhat higher for an elastic trunk even though many elastic trunk materials, in the strength and elongation ranges required for this application, have already been fabricated and tested. This trunk development cost delta must be weighed against the elastic trunk's self stowage feature which eliminates the need for manual stowage and offers a potential for takeoff as well as landing.

Other factors to be considered are the difficulties of installing a large area of tread material to maintain low tread pressures, on an elastic trunk which must elongate 200 to 350%, (see Tread/Braking Section), and the beneficial stiffening effect of a tread material which can also serve as a cover for a manually stowed inelastic trunk (see Stowage, Section II.2.e). This stiffening effect should be of benefit in avoiding flapping or flutter of an externally stowed trunk. Internal stowage and disposable covers for the trunk have been dismissed because of weight penalties, potential deployment and ejection problems, and logistic and cost penalties.

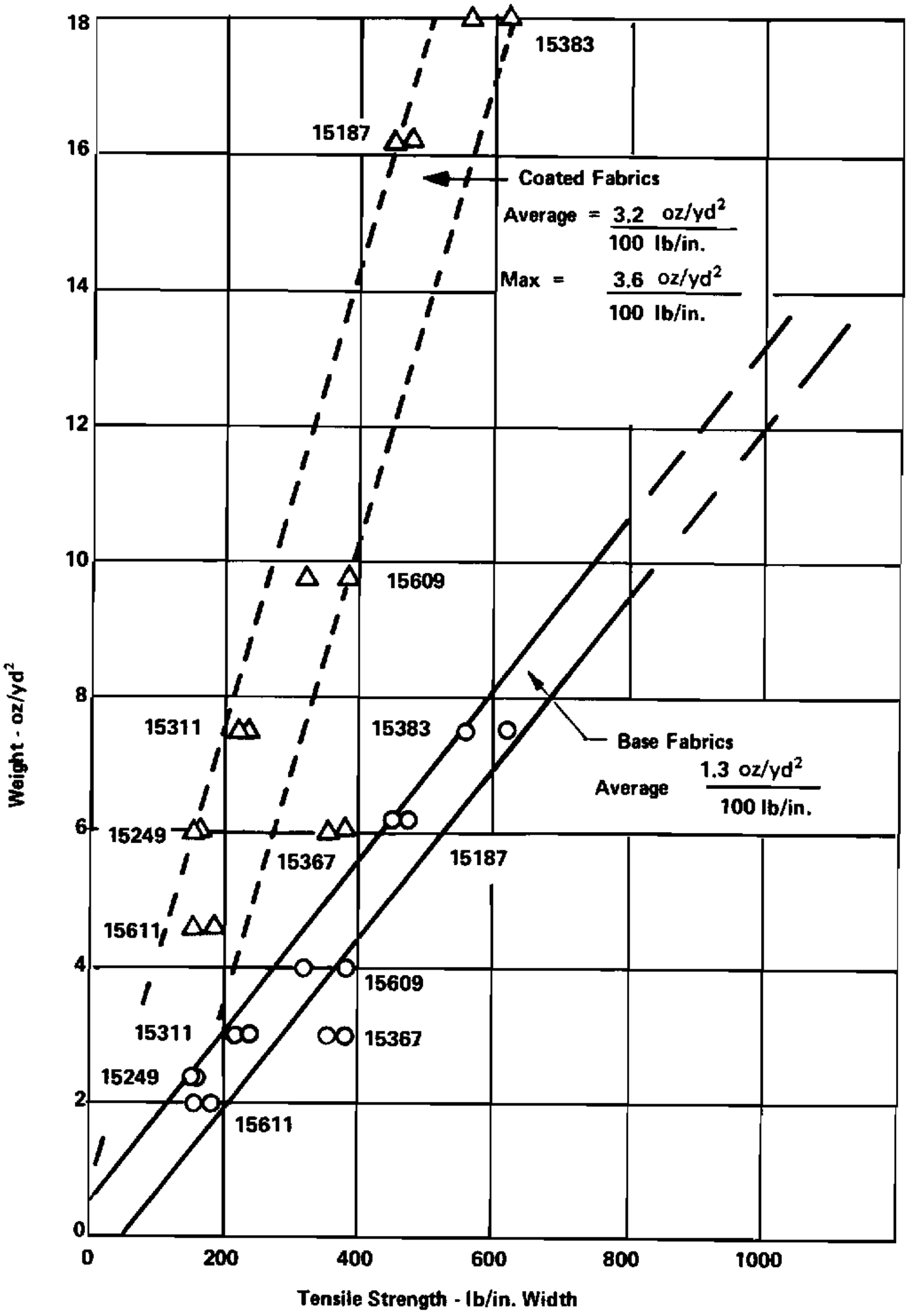
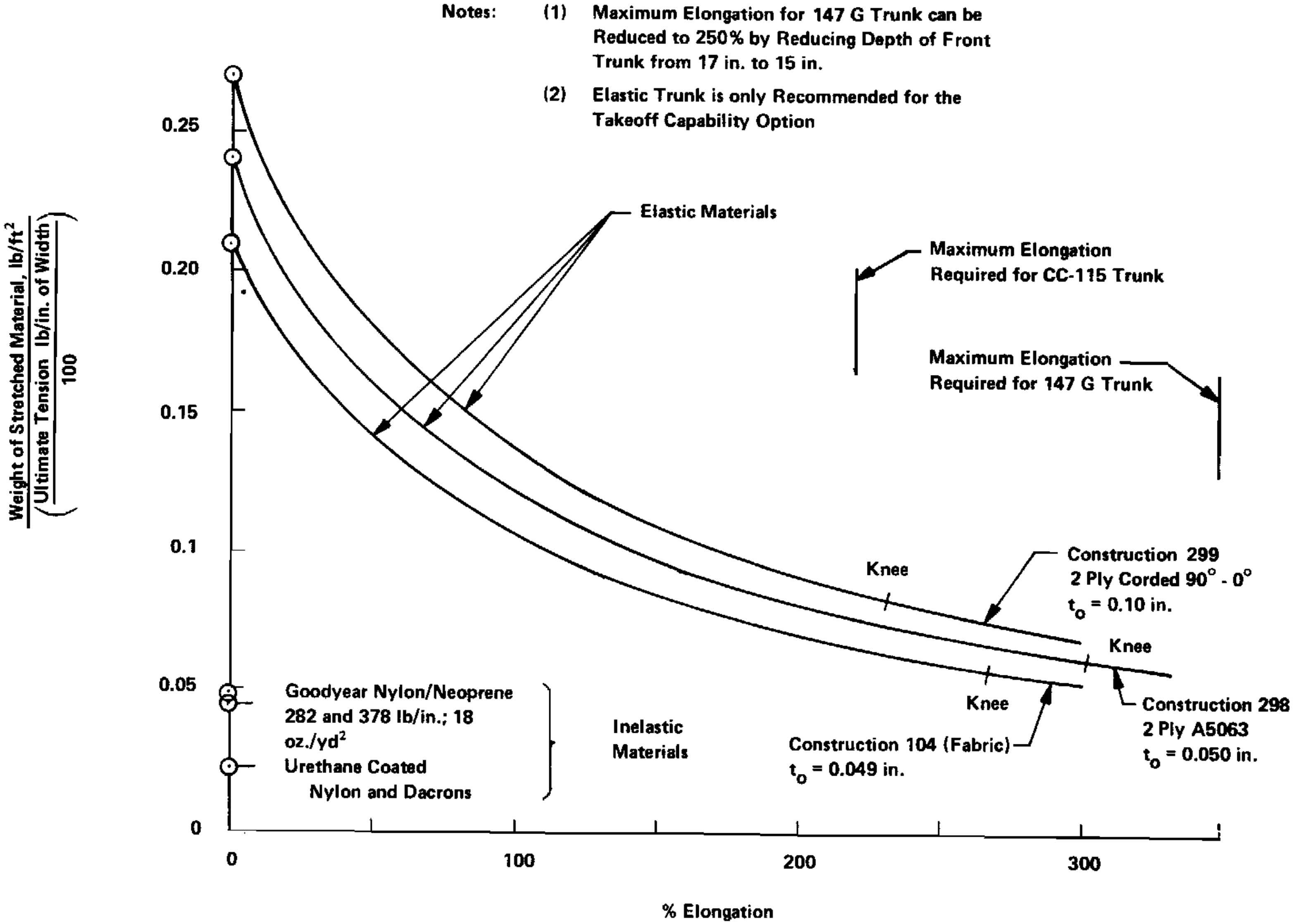


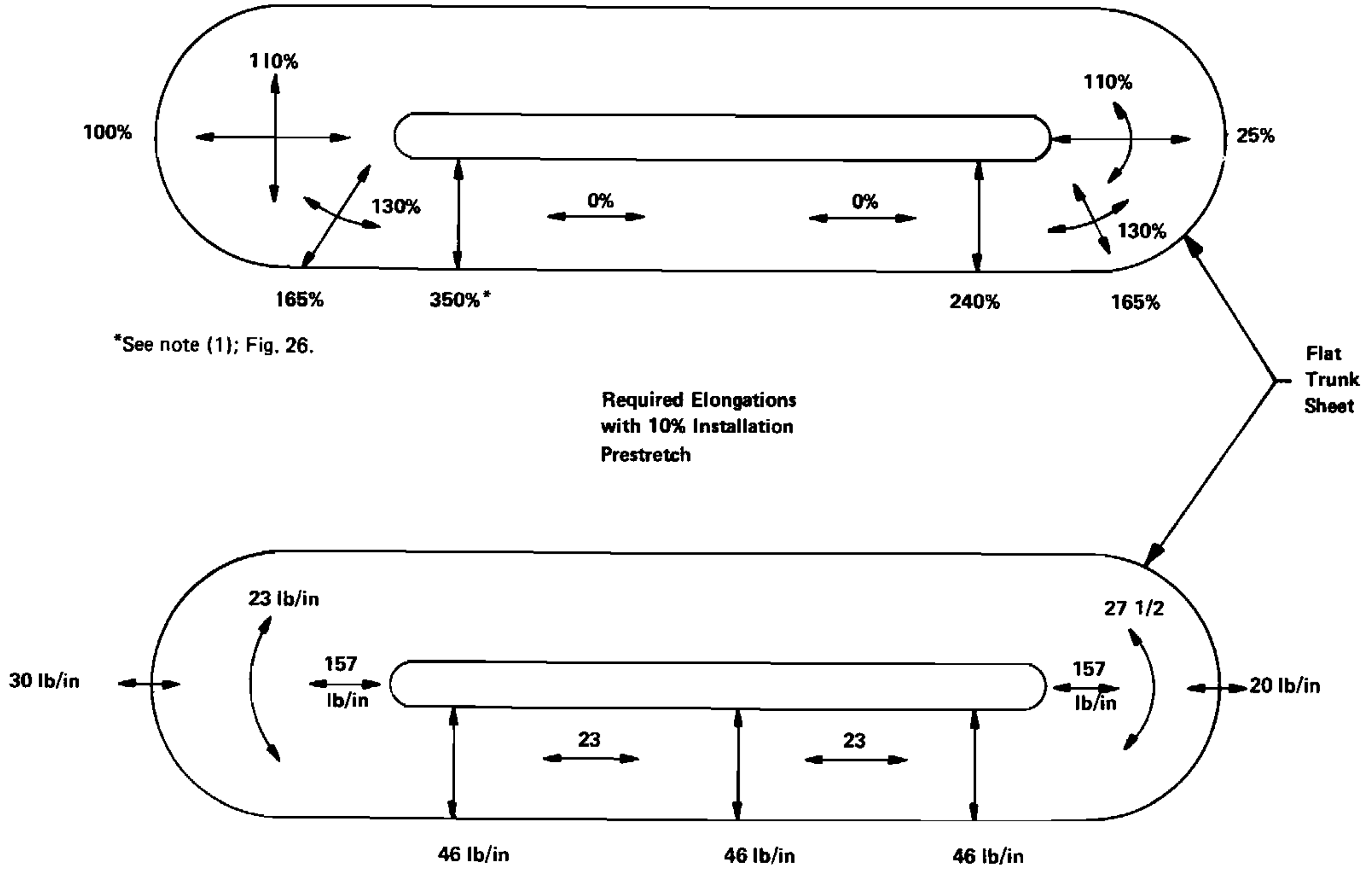
Figure 25. Weight versus Strength - Urethane Coated Nylon and Dacron Fabrics for Inelastic Trunks



Notes:
(1) Maximum Elongation for 147 G Trunk can be Reduced to 250% by Reducing Depth of Front Trunk from 17 in. to 15 in.
(2) Elastic Trunk is only Recommended for the Takeoff Capability Option

Figure 26. Weight/Strength versus Elongation of Elastic Trunk Materials

Note: Elastic trunk is only recommended for the takeoff capability option.



*See note (1); Fig. 26.

Required Elongations with 10% Installation Prestretch

Maximum Applied Tension due to Trunk Pressure*

* $P_T = 500$ lb/ft^2, $P_c = 0$; No Flattening

Figure 27. Elongations and Maximum Tensions for Elastic Trunk

After considering the preceding factors, an inelastic manually stowed trunk is recommended for an early and low cost demonstration of an ACLS for landing only. If a takeoff capability is desired, a retrofitted elastic trunk is recommended as the simplest, most reliable and probably the least expensive means of accomplishing retraction after takeoff.

e. Trunk Stowage and Deployment

Retraction and inflation of elastic trunks, when the air supply is turned off and on, has been demonstrated on the LA-4 and in many laboratory tests. This is certainly the simplest and most reliable method of trunk stowage and deployment and is recommended for an ACLS designed for takeoff as well as landing.

As mentioned in the preceding section, inelastic trunks have some advantages if a takeoff (and hence, in flight retraction) is not required. However, even with manual stowage before launch, the stowage and deployment of such trunks poses some problems.

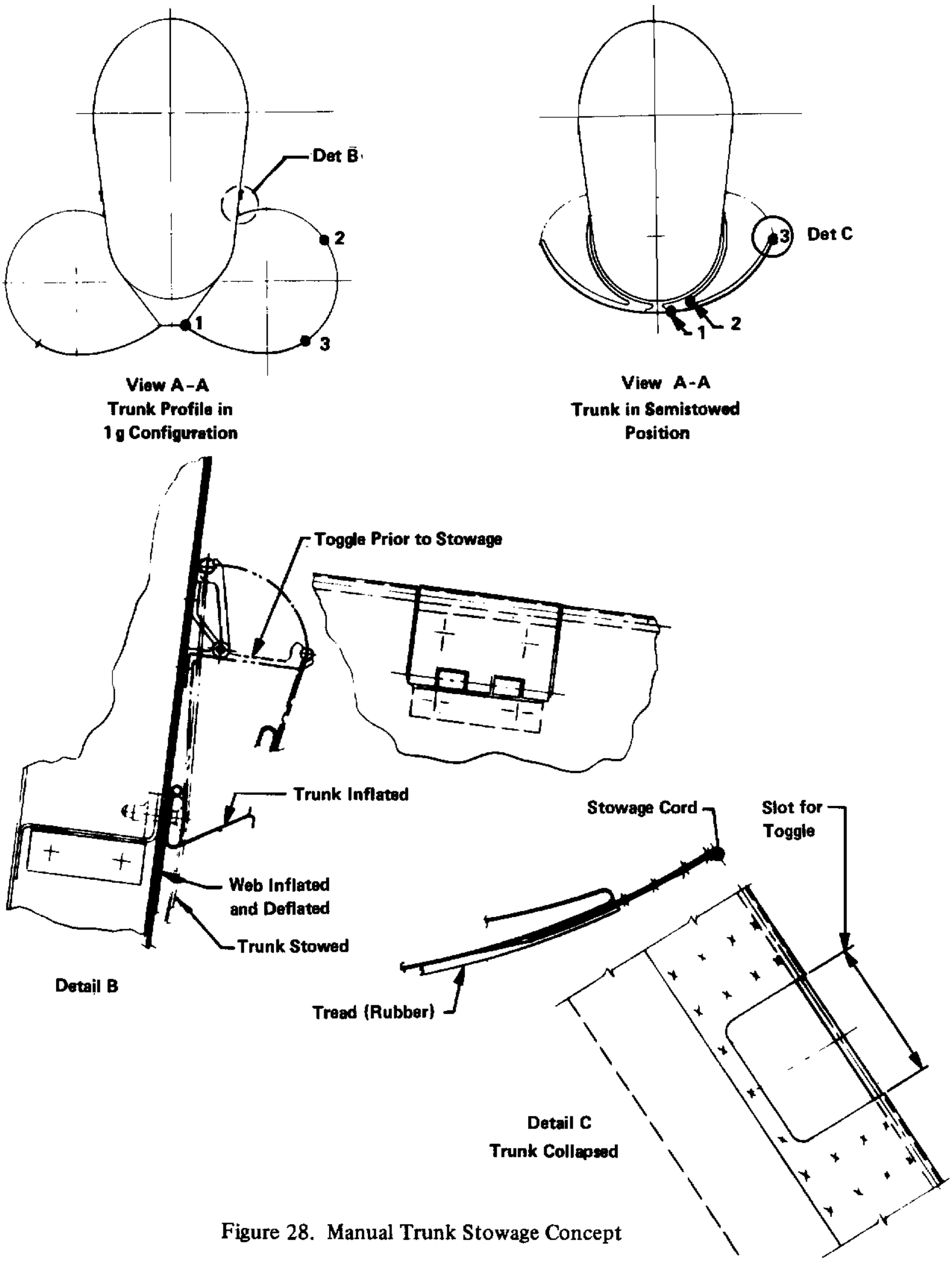
Stowage in one or more small compartments, similar to stowage of a life raft or impact attenuator bag, was considered but discarded. (The impact attenuator bag for the 3,000 lb F-111 escape capsule is stowed in a 30 inch square by 2 inch compartment and inflates to a 63 cubic foot volume; this bag compares to a 70 cubic ft inflated volume for the ACLS trunk for the Model 147G.) Folding of an ACLS trunk in a small compartment is complicated by the need for tread material at least 0.2 inch thick to allow for trunk wear and to limit trunk temperatures during slideout. Deployment is complicated by the need for attachment of the trunk to the fuselage in order to transfer drag and side loads and to provide adequate roll stiffness. Qualitative tests of a simple model of the 147G ACLS showed that without trunk attachments along the side of the fuselage, the vehicle rolled excessively relative to the trunk.

An inelastic trunk could be manually stowed beneath a disposable cover fitted to the bottom of the fuselage and extending from one outer trunk attachment to the other. Ejection of the cover could be accomplished by inflating the trunk. Release could be from spring clips or by tearing of a "dotted line" at the attachment to the fuselage. This method has been discarded because of potential problems with ejecting such a cover and the need for resupply of the covers.

The recommended method of inelastic trunk stowage and deployment (Figure 28) is an outgrowth of the ejectable cover concept. The tread provided for trunk protection and braking also serves as the cover when the trunk is stowed. A series of toggles are engaged with cords or cables sewn to the trunk near the outer edges of the tread. Prior to launch the portion of the trunk between the tread and the outer trunk attachment is manually folded beneath the tread; the toggles are then pushed over center to pull the tread and trunk snugly against the fuselage. The required inelastic trunk material is less than 0.02 inch thick and sufficiently flexible to permit this folding.

Deployment is accomplished by turning on the air supply. The rear portion of the trunk will inflate first, because a small inflation here will produce a downward and overcenter component of trunk tension at the toggles. As the trunk fills, more forward toggles will be pulled over center. This progressive front to rear inflation avoids having the entire trunk free while inflation is occurring.

A rubber strip which is attached to the fuselage and is folded over the toggles and the edge of the stowed trunk/tread will prevent in flight dynamic pressure from causing unwanted deployment in flight. This will probably only be required along the front portions of the trunk.



View A-A
Trunk Profile in
1 g Configuration

View A-A
Trunk in Semistowed
Position

Detail B

Detail C
Trunk Collapsed

Figure 28. Manual Trunk Stowage Concept

3. AIR SUPPLY

A major objective of this study has been to estimate the minimum air flow required for ACLS recovery of a modified Ryan Model 147G drone and then to conceptually design an air supply system which is simple, light, and small.

a. Requirements

Figure 20 compares trunk and cushion pressures for the ACLS of the modified Model 147G with those for the LA-4. This figure indicates that the air supply for the 147G with a design landing weight of 2300 lb must provide a trunk pressure of approximately 200 lb/ft^2 (1.4 psig). Section 2.4 "Energy Absorption" shows that a pressure of 200 lb/ft^2 prior to touchdown will give good energy absorbtion. Stability and tread wear considerations allow trunk pressures of 200 to 400 lb/ft^2 during the slideout.

Figure 29 uses LA-4 experience as a basis for estimating air flow requirements for the ACLS for the modified Ryan 147G. The LA-4 had an average gap of 0.24 inch beneath the trunk. Curves of Figure 29 also show the flow required for vehicles of other weights if performance comparable to that of the LA-4 is desired. References 4 and 5 report on operations of the LA-4 on runways; various unprepared sites including mud, snow, silt; over obstacles and on water.

The air flow requirement depends primarily on the vehicle weight, whether or not a takeoff capability is required, and the character of the takeoff surface. It is insensitive to cushion planform geometry as shown by the curves for cushion length to beam (L/B) ratios of 3 and 4. For a given vehicle weight, it is practically independent of whether a small high pressure cushion or a large low pressure cushion is used.

If an ACLS takeoff capability is provided for the 147G, performance comparable to the LA-4 should be the most that should be required. If such a takeoff performance is desired, an air flow of approximately 10 lb/sec (140 scfs) should be provided.

If a landing only capability is desired, the air flow to the trunk and/or cushion can be drastically reduced. In fact, a system with zero air flow from the trunk and cushion (after initial filling of the trunk) has the advantages of reduced slideout distance after touchdown, and an ability to land if the air supply fails after trunk inflation. It would also permit incorporation of a small and lightweight backup system for trunk inflation if the primary air supply fails prior to trunk inflation. In addition, if propulsion engine bleed is used to supply the air for trunk inflation, the requirement for no air flow after trunk inflation, limits the time that engine bleed is required and permits a freedom to vary engine thrust after inflation without affecting ACLS characteristics. This could include the ability to make power off landings.

Low speed slideout tests of ACLS models conducted by Bell without air flow have demonstrated that a zero air flow ACLS is neutrally stable in yaw, even with decelerations in excess of 1g. In addition the 1/10 scale CC-115 dynamic model has been successfully landed on a plywood surface and on water without air flow. Section II.6 analyzes 147G ACLS pitch and roll stiffness and estimates that landings could be made with zero air flow if yaw angles are less than about 5 degrees or crosswinds are less than 15 knots. However, analyses including flight control systems dynamics, dynamic simulations and/or additional tests are required to determine whether or not a zero air flow ACLS for the 147G will result in excessive roll motions if landings are made in higher crosswinds or with yaw greater than 5 degrees.

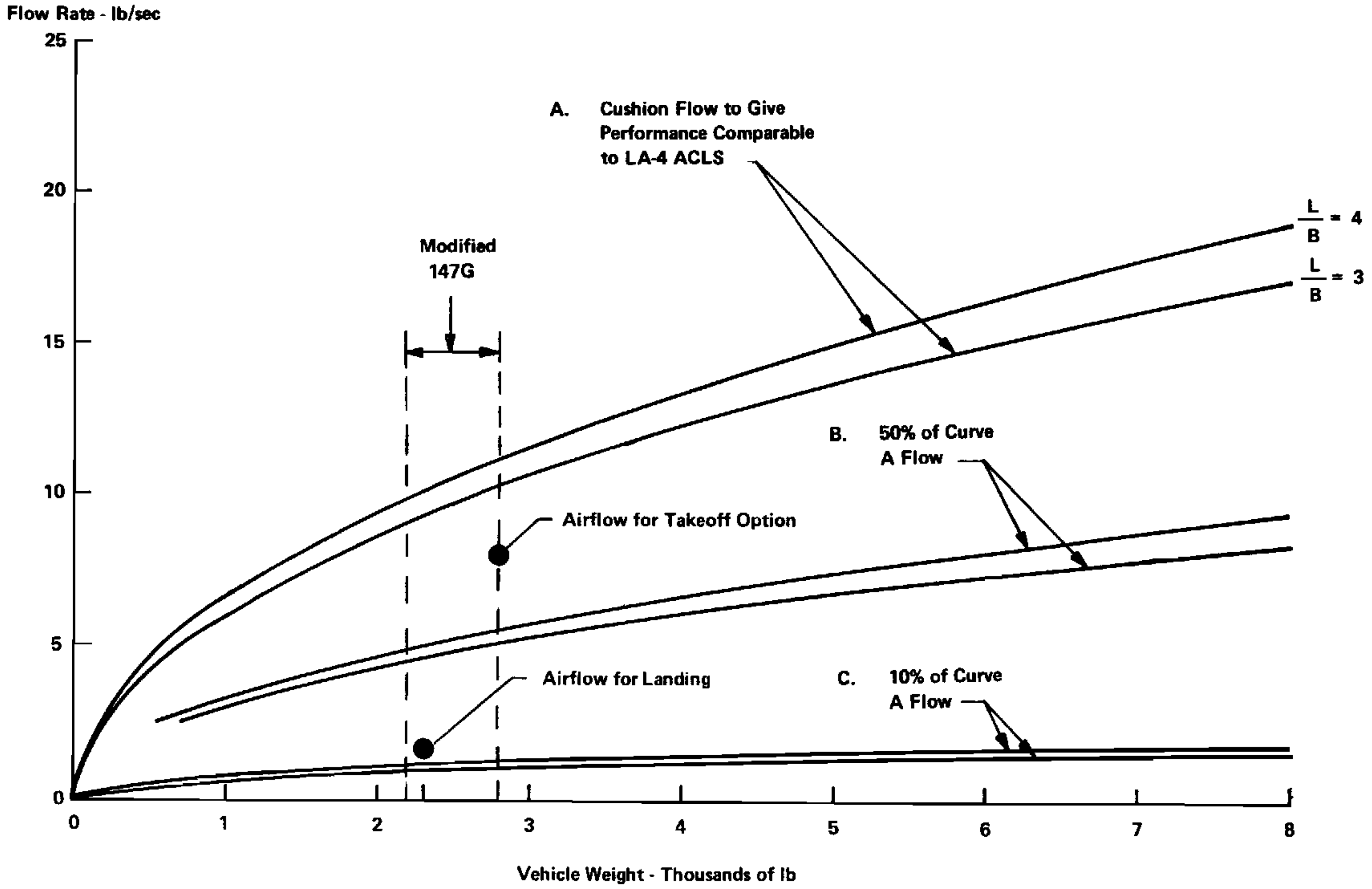


Figure 29. Air Flow Rate versus Vehicle Weight

Air flow lubricating the trunk to landing surface interface can be used to reduce tread wear. To be fully effective in reducing wear such lubrication must ensure that no portion of tread contacts the landing surface. Unless very large air flow can be provided to ensure a large gap beneath trunk, it is difficult to achieve zero trunk contact in practice. For an RPV application of an ACLS for landing only, it seems preferable to have a large area of trunk/tread purposely contact the landing surface. This will result in a short slideout distance and less tread thickness loss than will result from unintentional contact of a small portion of tread during a long slideout.

Because of the ground rule that it could be assumed that the vehicle will be launched by an entirely different system from the recovery system, air supply studies have emphasized the landing only requirement with low air flow or no air flow. However, it has also been shown that an air supply system utilizing propulsion engine bleed air as a power source could be designed to provide sufficient air flow for takeoff from either runways or other relatively smooth surfaces.

For the landing only system, it is concluded that it would be desirable to provide the maximum amount of air flow that can be obtained without incorporating a separate air supply power system specifically for the ACLS. An objective for providing a flow of the order of 2 lb/sec or more (20% of LA-4 flow) was established. This should provide adequate trunk lubrication during the landing transient without requiring a braking system to limit the slideout distance. The recommended air supply and trunk concept permits investigation of landings with lower flow and/or zero flow by covering some or all of the trunk orifices and making minor adjustments to the air supply.

A system to provide the optional suction braking capability (Section II.5, Braking) should be capable of producing a suction of about 100 lb/ft^2 in the cushion cavity when flow into the cushion approaches zero. If suction braking is used with a zero air flow (landing only) trunk/cushion system, an air flow of 2 lb/sec (27 scfs) at zero cushion pressure should be sufficient to initiate and maintain suction on a runway or other even surface. If suction braking is used with a system designed with continuous air flow to the cushion (i.e., takeoff capability), the suction system must exhaust an air flow slightly in excess of the air flow being provided to the cushion. However, this does not mean that the suction system air flow (from the cushion) must exceed the nominal flow to the cushion. The air flow to the cushion can be reduced when suction braking system is activated. Tests of Bell Aerospace Company's braking model have demonstrated good suction braking by using the air supply designed to provide the nominal flow into the trunk and cushion to also evacuate air from the cushion (see Section II.5). Thus, the requirements for a suction system depend upon the nominal air flow to the cushion, and upon how the suction system is integrated into the total system.

b. Air Supply Concepts

The following methods of supplying ACLS air were investigated:

(a) Propulsion engine compressor bleed fed directly to the trunk.

(b) Propulsion engine compressor bleed supplied to the trunk via a simple regulator.

(c) An ejector (jet pump) utilizing propulsion engine compressor bleed and air from the atmosphere.

(d) A small blower with a partial admittance tip turbine driven by propulsion engine compressor bleed air.

(e) A small blower driven by electrical power.

(f) Stored gas (air or nitrogen) with or without an ejector.

(g) A cool gas generator with an ejector.

All of these would be feasible for a very low or zero air flow system for landing only. (c) or (d) will be required if a takeoff capability is desired, unless a very short duration rocket or JATO assisted takeoff is used.

Figures 30 and 31 present estimated weights and order of magnitude cost estimates for development of each of these air supply concepts for the Ryan Model 147G. Systems for landing only and for landing plus takeoff are shown. The systems for landing only are further divided into a group which does not use propulsion engine compressor bleed and a group which does use propulsion bleed.

The no bleed systems are practical only for zero flow or very low flow systems. An air or nitrogen bottle to inflate the 70 ft^3 trunk is heavy and requires a volume of at least 1 ft^3.

By using an ejector to supplement an air or nitrogen bottle, the volume could be reduced to as low as 300 $in.^3$ and the total air supply weight to 20 lbs or less. However, such a system is still vulnerable to any leakage because of the limited amount of air available.

The systems using bleed air directly or via a regulator are also only useable in zero or very low flow systems. Bleed air temperatures are of the order of 300°F at landing thrust and trunk material long term temperature limits are 200 to 300°F. Estimates of the trunk material heat sink capacity and short duration tolerance to higher temperatures show that direct use of bleed air would be feasible in no-flow systems.

A small blower with a partial admittance tip turbine blower driven by propulsion engine bleed air has the advantage of providing more air flow than an ejector for a given system weight. It is estimated that an 8 inch dia by 3 inch thick unit could provide 3 lb/sec of air with only 0.5 lb/sec bleed at landing. It's weight would be about 4 lbs. Such a device would be more expensive to develop and produce than would an ejector system. Because an ejector will provide sufficient air flow, there is no need to provide a tip turbine blower for a landing only system. If a capability to take off from short or rough fields is desired, the greater efficiency and increased air flow of a tip turbine blower may be required.

Similar conclusions apply to electrically driven blowers, except that the weight will be significantly higher than for a tip turbine drive.

Rocket Research Corporation has developed ejectors and cool gas generators employing solid propellants and liquids such as freon to inflate aircraft escape slides,impact attenuation bags, etc. These systems are lighter than stored gas/ejector systems for inflation of zero flow trunks having volumes greater than 150 to 200 ft^3 and require less space than the stored gas systems even for smaller trunk volumes. Such systems appear attractive as backup air supplies for air cushion landing systems, especially for larger aircraft and for ACLS which have a zero flow backup mode. However, some development would be required to provide even a small flow (i.e. 2 lb/sec or 25 scfs) for durations of the order of 30 seconds or more. The weight of such a system would be much greater than that of an engine bleed/ejector system which is not duration limited.

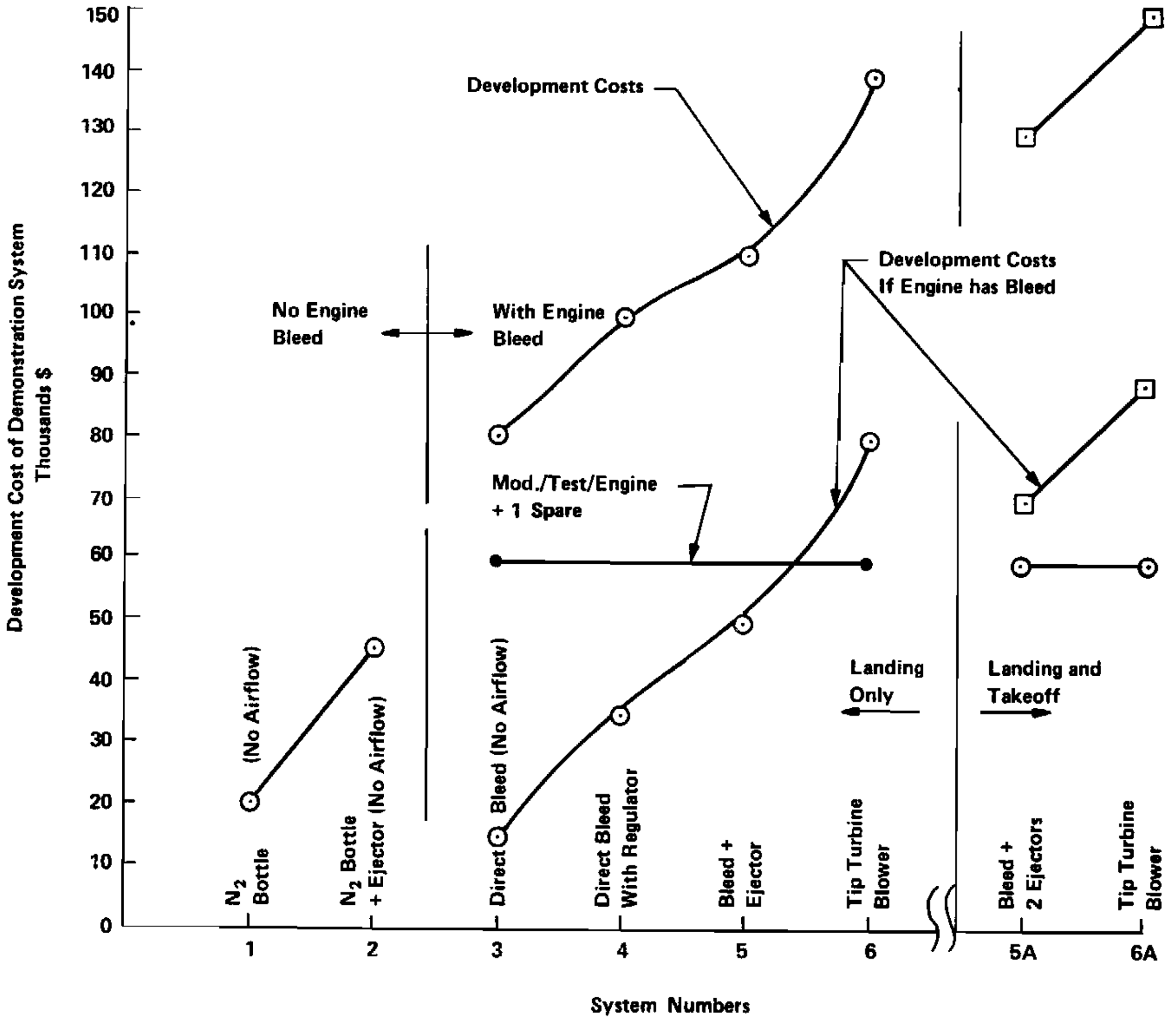


Figure 30. Development Costs of Several Air Supply Concepts

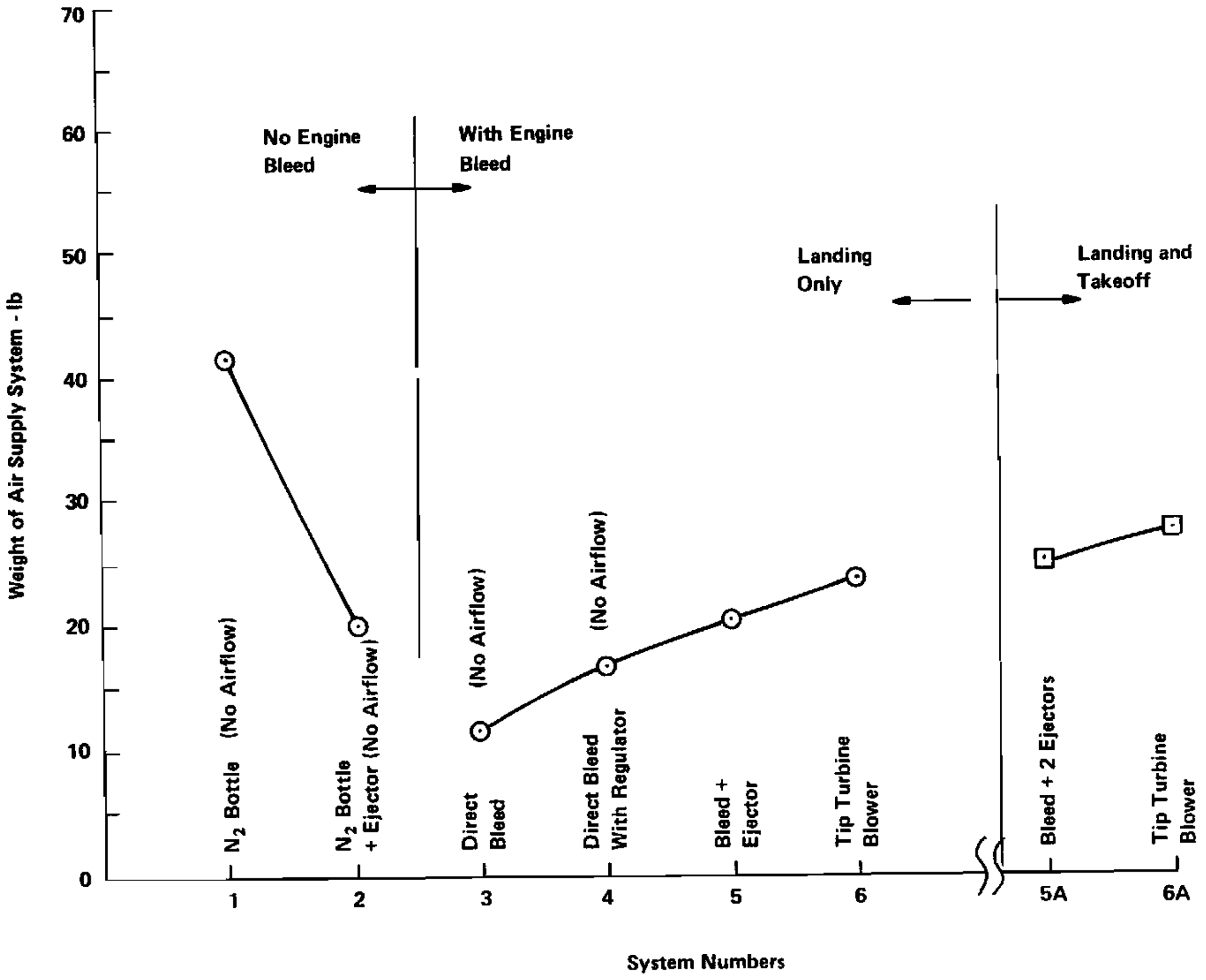


Figure 31. Weights of Several Air Supply Concepts

Costs of developing the systems using bleed air for the 147G are significantly greater than those using stored gas. However, this is only because the propulsion engine for the 147G does not now have bleed provisions. Figure 30 also shows how development costs of bleed and no-bleed systems would compare if the engine already had adequate bleed provisions. Based on an estimate provided by the engine manufacturer, an allowance of $60K was made for design and installation of bleed ports in a GFE flight engine and a GFE spare engine and test runs to verify engine characteristics at low thrusts with and without bleed.

Costs of quantity production of the various air supply concepts, with the possible exception of the tip turbine blower, should not differ by more than ±$1000. Even the cost of the tip turbine might be brought within this band, if design simplicity rather than efficiency is emphasized. Thus, with the limited cost estimating that was possible in the concept study, air supply production cost does not appear to be a primary factor in selection of one of these systems.

c. Recommended Air Supply

Despite the additional cost associated with providing bleed air from the 147G propulsion engine and the necessity of maintaining a thrust of the order of 300 lb during slideout, an air supply utilizing engine bleed plus an ejector to augment the air flow is recommended for ACLS demonstration flights. This will permit evaluation of systems with or without flow. The 300 lb thrust need not result in unacceptable slideout distances and can be of benefit in controlling the ground trajectory (see Section II.5).

The second choice for a demonstration program is a system utilizing stored gas plus an ejector. However, this should be considered only after extensive dynamic model or full scale ground tests to determine limitations of zero flow systems. A stored gas system has operational disadvantages because of the necessity of replacing or repressurizing the gas bottle before each flight, but would be acceptable for an ACLS demonstration program. However, such a system is also more susceptible to trunk leakage because of the limited supply of gas.

Figure 15 (Trunk Section) shows that a propulsion engine thrust of 250 to 350 lb will permit landings without flares. The J69-T-41A engine used in the Ryan Model 147G does not now have a compressor bleed. However, the engine manufacturer has stated that bleed ports could be added to provide up to 1.0 lb/sec of bleed air at the above landing conditions. For ACLS design studies a maximum bleed of 0.8 lb/sec has been used. Figure 32 presents estimates of total engine air flow, bleed temperature, and bleed pressure versus thrust for maximum and minimum velocities during the approach and landing slideout.

From Figure 32, a 0.8 lb/sec bleed at a thrust of 300 lb is equivalent to approximately 4.5% of the total air flow at 150 knots and 6.2% at V = 0.

The engine manufacturer was not able to provide estimates of the effect of bleed on thrust in this low thrust range. However, Figure 33 shows Bell's estimate of thrust changes due to bleed. The engine is not RPM governed below approximately 75% of normal RPM. If it is desired to maintain the same thrust before and after initiation of bleed, it will be necessary to advance the throttle to cause an RPM increase of about 500 RPM when bleed is initiated. Although engine response is very slow in the low thrust range, this is not expected to create any problem. In fact, the drag increment due to trunk inflation and thrust decrease due to bleed might be compensated by an attitude decrease to initiate descent while maintaining a near constant flight speed.

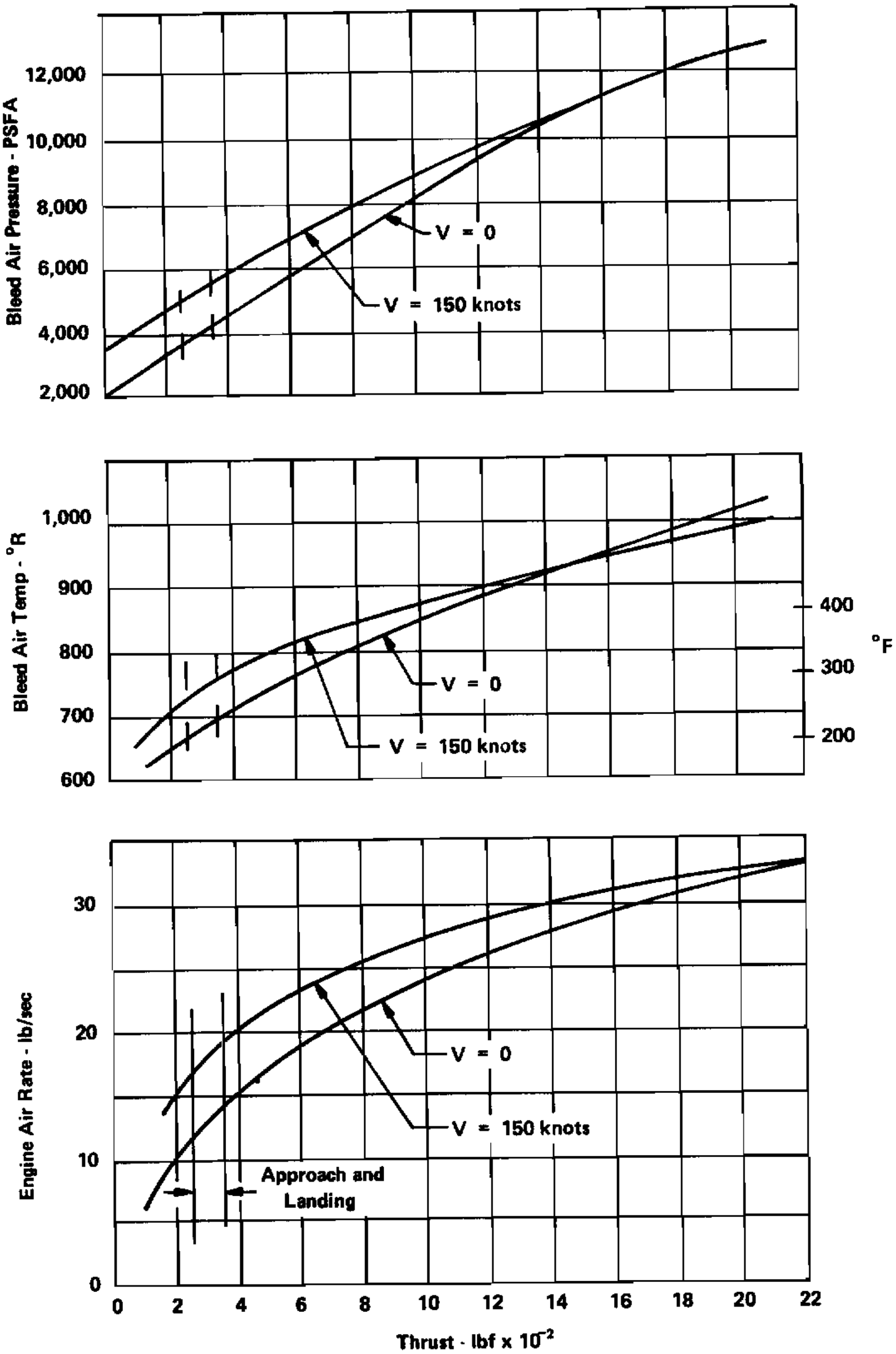


Figure 32. Propulsion Engine Bleed Characteristics versus Thrust

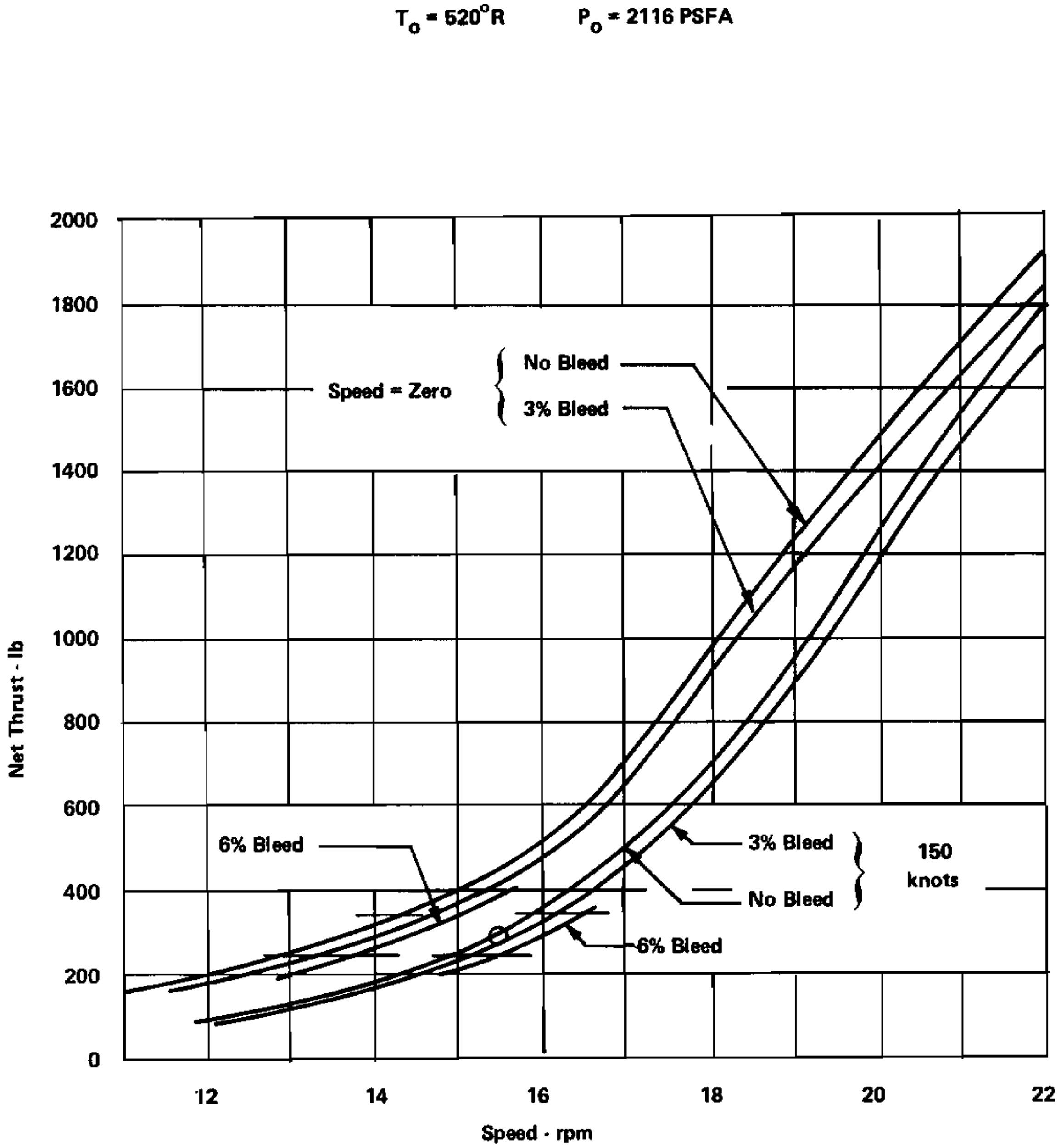


Figure 33. J69-T-41A Estimated Effect of Bleed on Thrust

The recommended ACLS air supply concept utilizes an ejector to supplement the amount of air that can be bled from the propulsion engine and to reduce the pressure and temperature of the delivered air to acceptable levels. Figure 34 illustrates the ejector principle. An ejector is a very simple device with no moving parts, hence its reliability is near 100%. It consists of a duct into which one or more nozzles inject a stream of high velocity air. This primary stream induces a flow of secondary air in the duct. The two streams mix so the delivered air has pressures and temperatures between those of the primary and secondary flows.

Curves A and B of Figure 35 show flow versus pressure characteristics of an ejector design optimized to give maximum flow into the trunk at 200 lb/ft^2 pressure at a velocity of 150 knots with engine thrust of 300 lb and a bleed of 0.8 lb/sec. Also shown is the pressure versus flow characteristic of this ejector at $V = 0$ with thrust = 300 lb. The reduced pressure and flow at $V = 0$ are due to a 74 psfg decrease in ram pressure (after inlet losses) and to the reduced bleed flow at $V = 0$ if thrust is kept constant as velocity decreases. If RPM were kept constant, instead of thrust, the bleed flow would be nearly constant but net thrust would increase by 100 to 150 lb as the velocity decreased from 150 K to zero. After touchdown it will be desirable to maintain constant thrust or to decrease thrust. Although the variation in ejector characteristics from curve A to curve B of Figure 35 would be acceptable, a reduction in this variation would be desirable.

Figure 35 also shows curves giving the flow from the trunk to the atmosphere and from the trunk to the cushion if trunk orifices having an effective area, $C_d A_t$, are provided. Intersections of the ejector to trunk with the trunk to atmosphere and trunk to cushion flow lines establish trunk pressures and corresponding flows.

The curves C and D of Figure 35 give estimated characteristics of an ejector designed for an inlet on the side of the fuselage. This inlet location sacrifices the additional flow due to ram pressure in order to reduce sensitivity to air speed. It also avoids the additional complexity of an ejector inlet door to prevent trunk inflation at flight conditions with high dynamic pressures.

Figure 35 shows that the inlet on the side of the vehicle reduces the spread in ejector characteristics between the $V = 0$ and $V = 150$ knot cases. The remaining spread is due to the change in bleed air characteristics as the velocity decreases with thrust constant (Figure 32) and the resulting decrease of bleed flow to 0.6 lb/sec, with a fixed ejector design.

If the discharge coefficient C_d, is 0.8, the 9 $in.^2$ effective orifice area of the design without ram is equivalent to over 1300 orifices with a 0.1 inch diameter spaced at 1 x 1 inch intervals over an area of 8.3 ft^2 on the bottom of the trunk. At a trunk pressure of 200 lb/ft^2, less than 12 ft^2, of trunk must flatten to the ground to support the vehicle at 2300 lb landing weight, when cushion pressure is zero. Therefore, such orifices could provide good air lubrication of the trunk, if the cushion supports 1/3 or more of the vehicle weight. It is planned to place all of the orifices in a horseshoe shaped area around the rear curved portion of the ground tangent. This will give good air lubrication for high attitude landings, where cushion oressure is low. Also, if thrust is increased to extend slideout or to taxi, this rear area will tend to contact the surface while the front of the trunk is lifted by the additional thrust acting below the c.g.

With an ejector inlet parallel to the air stream, and a trunk orifice effective area, $C_d A_t = 9$ $in.^2$, point 1 of Figure 35 represents the trunk pressure and flow during an approach at 150 knots. During the landing transient, trunk pressure will build up to a maximum of 500 lb/ft^2 (see Section II.4 - Energy Absorption). Flow from the ejector will then approach zero as indicated by point 2. As the vehicle settles onto the cushion, conditions will be between points 1 and 3. If velocity decayed to zero with the vehicle supported on the cushion, final conditions would be represented by point 4.

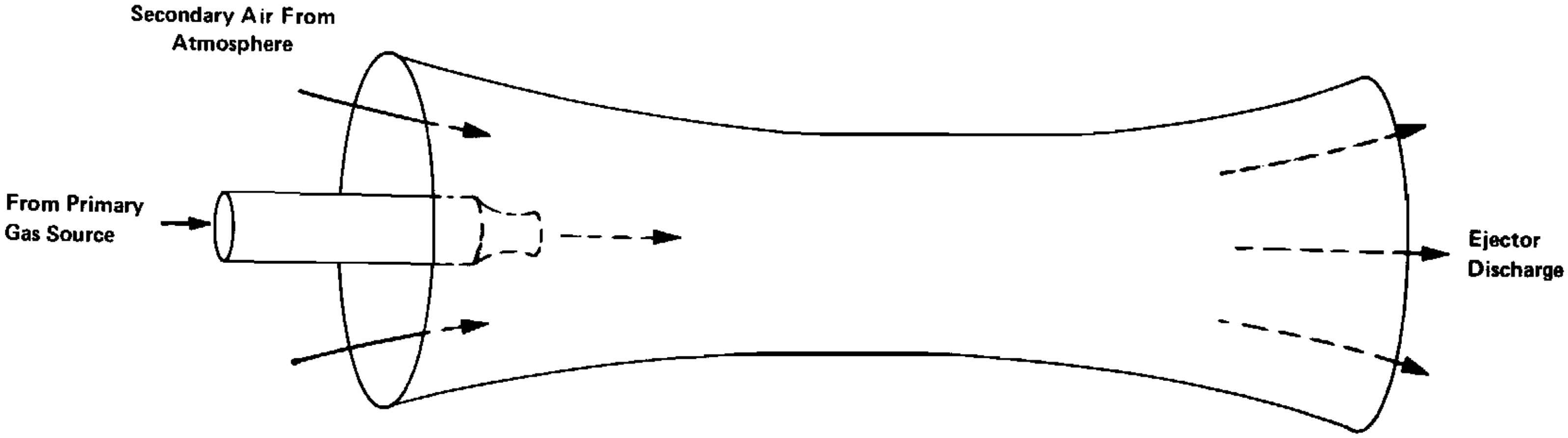
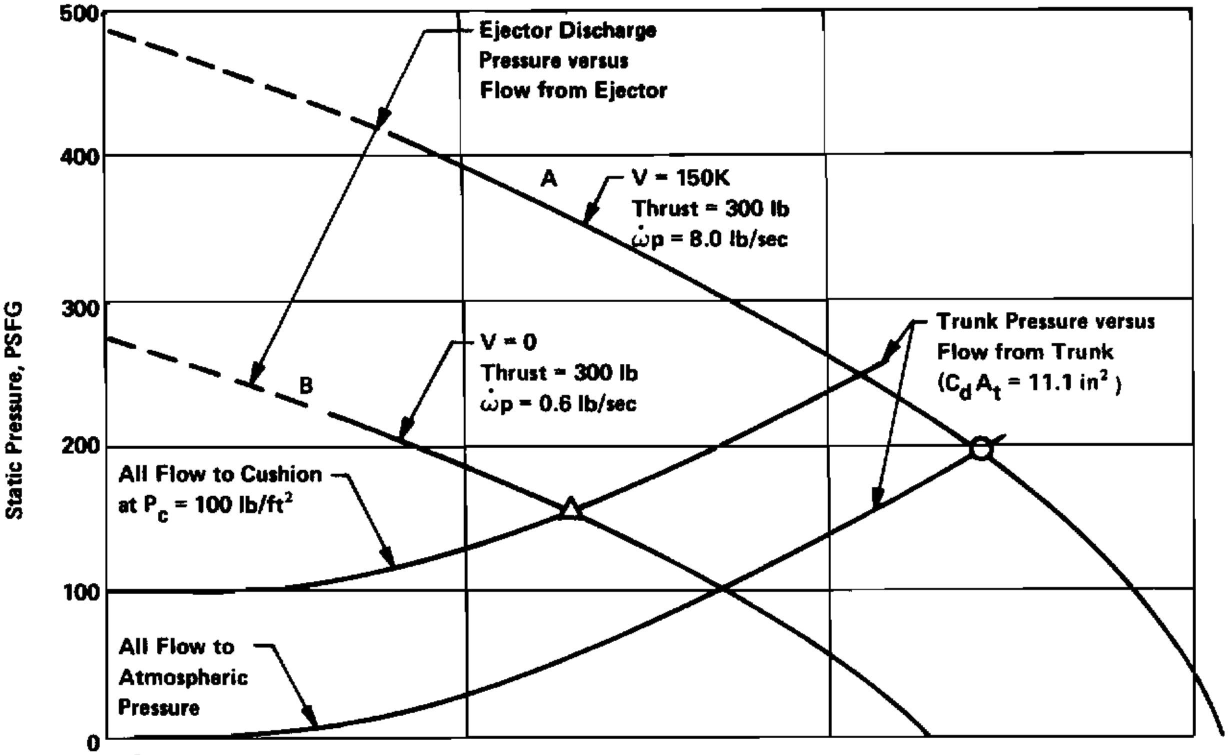


Figure 34. Ejector Schematic

(a) Initial Design with Ram



○ Trunk Pressure and Flow with P_c = 0 at 150 Knots
△ Trunk Pressure and Flow when Cushionborne at V = 0

(b) Final Design without Ram

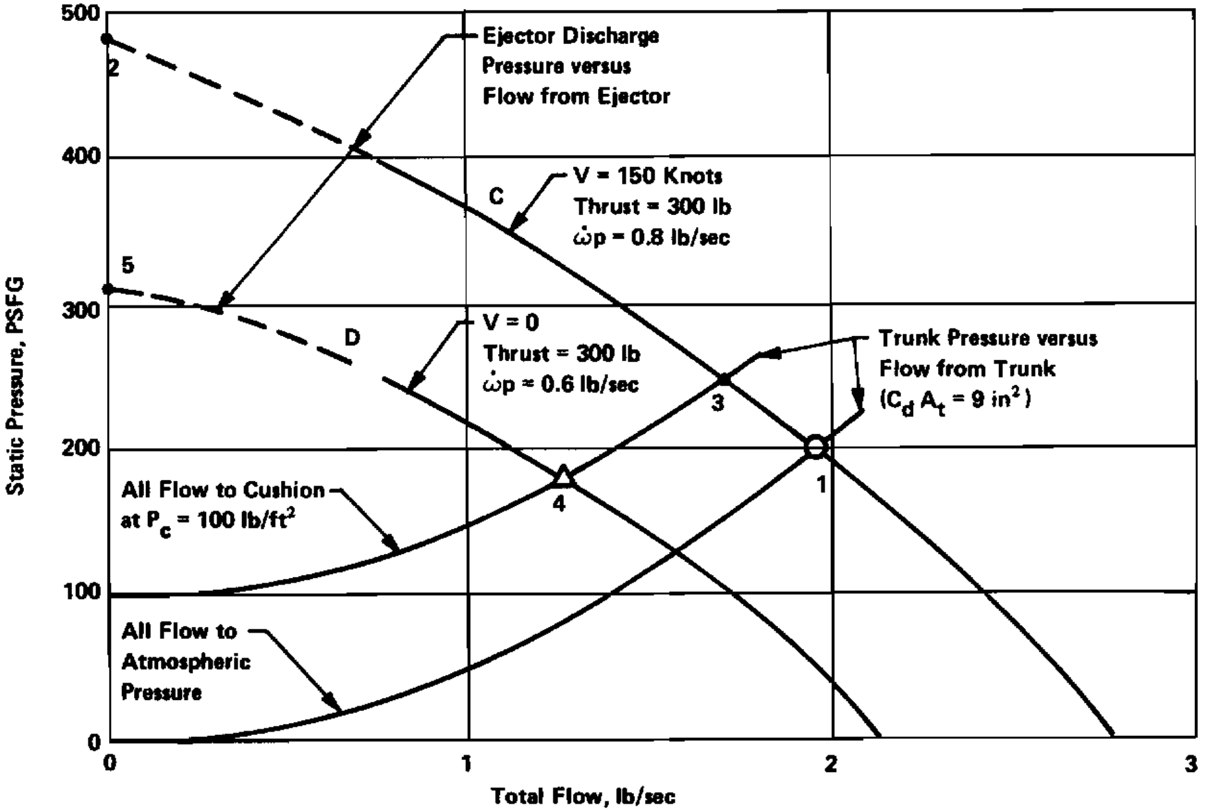


Figure 35. Ejector and Trunk Pressure versus Flow at Landing

At point 3, (on cushion at high speed) the average gap beneath the trunk will be at least 0.05 inch, or about 20% of the average gap of the LA-4 ACLS. Although this is a very small gap, it in combination with trunk air lubrication should reduce friction forces to a level equivalent to about 0.4 g during the landing slideout on a runway or other smooth surface such as the Edwards lake bed (Figure 36).

If suction braking is used, the trunk will be flattened to the ground and flow from the trunk orifices will become small. The decrease of effective orifice area will more than compensate for the decrease of cushion pressure, and operating conditions will lie within region 2,3,4,5 of Figure 35.

If the ejector of Figure 35(b) is used in a zero flow system (no trunk orifices), its operating points will lie along line 2, 5. Point 2 lies rather close to the maximum desired trunk pressure of 500 lb/ft^2. With a trunk pressure relief valve to limit the pressure, this should result in a high load stroke efficiency, but flow would be continuously dumped via the relief valve. As an alternate one or more of the ejector primary nozzles could be closed. This would reduce the ejector zero flow pressure to a value further below the cracking pressure of the relief port. Thus, a single basic ejector air supply concept offers an ability to investigate various pressure and flow combinations.

Figure 35 also illustrates one of the advantages of ultimately going to a zero flow system. If the system were designed for zero flow with trunk inflation air from engine bleed, trunk damage resulting in an effective leakage area of 9 in.^{2} could be tolerated without reducing pretouchdown trunk pressure below 200 lb/ft^2 or the landing energy absorption below that shown in Figure 15.

Figure 37 shows a possible installation of an ejector and a trunk relief valve. The ejector shown has a mixing duct approximately 4 inches in diameter x 20 inches long. It will have the characteristic shown by curves C and D of Figure 35. The length of the ejector could be reduced to 10 or 12 inches, without significantly changing its characteristics, by providing additional primary nozzles. This may permit a near vertical installation with a very short ejector to trunk duct.

d. Air Supply for Taxi and Takeoff

The curves of Figure 38 show the characteristics of the ejector optimized for landing but operated with the propulsion engine at 1650 lb thrust. The normal static sea level thrust case was investigated because it is understood that engine limitations may prevent use of maximum thrust at V = 0. The bleed flow for the case shown would be 1.14 lb/sec, well below the estimated allowable of 2 lb/sec or more at this thrust.

If the trunk effective orifice area is 9 in.^{2}, as for the landing case, the trunk pressure would be over 500 lb/ft^2 and the total flow (if there were no relief valve) would be about 3.0 lb/sec or 30% of the LA-4 ACLS cushion flow. The average gap beneath the trunk would be at least 0.085 inch. Although this flow and gap are less than will be required if a short takeoff run is required, it would permit taxiing, exploratory tests of simulated takeoffs, and possibly even takeoff from a long runway or lake bed. Figure 35 estimates a deceleration of 0.2 g (equivalent to 600 lb friction at a 3000 lb takeoff weight) with this flow. This ACLS friction will approach zero as aerodynamic lift is developed to support the vehicle. Aerodynamic drag at the end of the takeoff run will be 350 lb to 400 lb. Thus, if ACLS friction estimates are valid, a thrust margin of about 1000 lb will exist throughout the takeoff run even with this low flow.

Because it is planned to provide a trunk relief port set to crack at 400 lb/ft^2, it will be necessary to either accept the corresponding lower flow (approximately 2.2 lb/sec) through the trunk orifices, to reset the relief port to crack at 500 or more lb/ft^2, or to provide additional trunk orifices (or trunk to cushion ports) for such taxi and simulated takeoff operations. The latter would

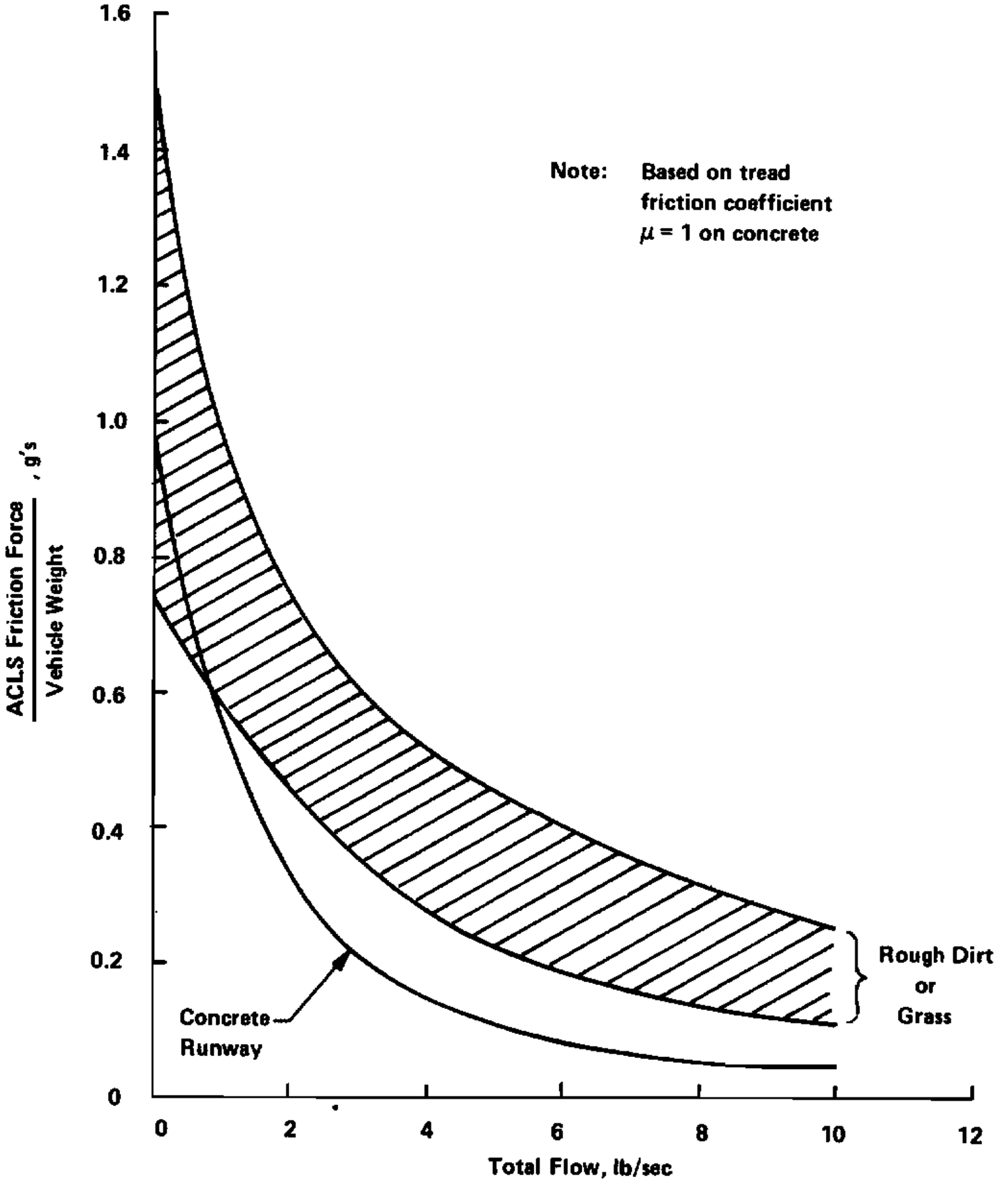


Figure 36. ACLS Friction Force versus Air Flow

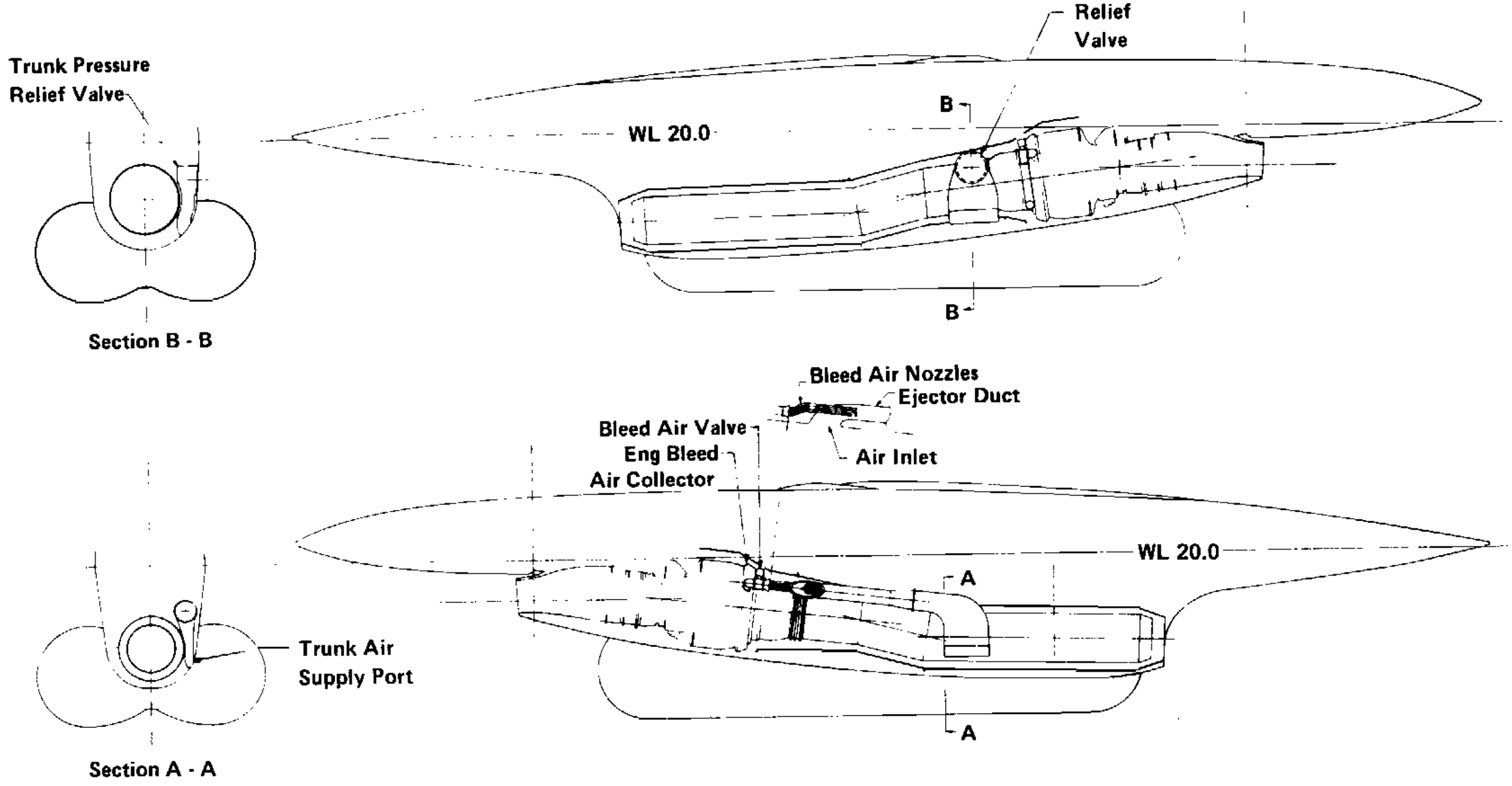


Figure 37. Ejector and Relief Valve Installation

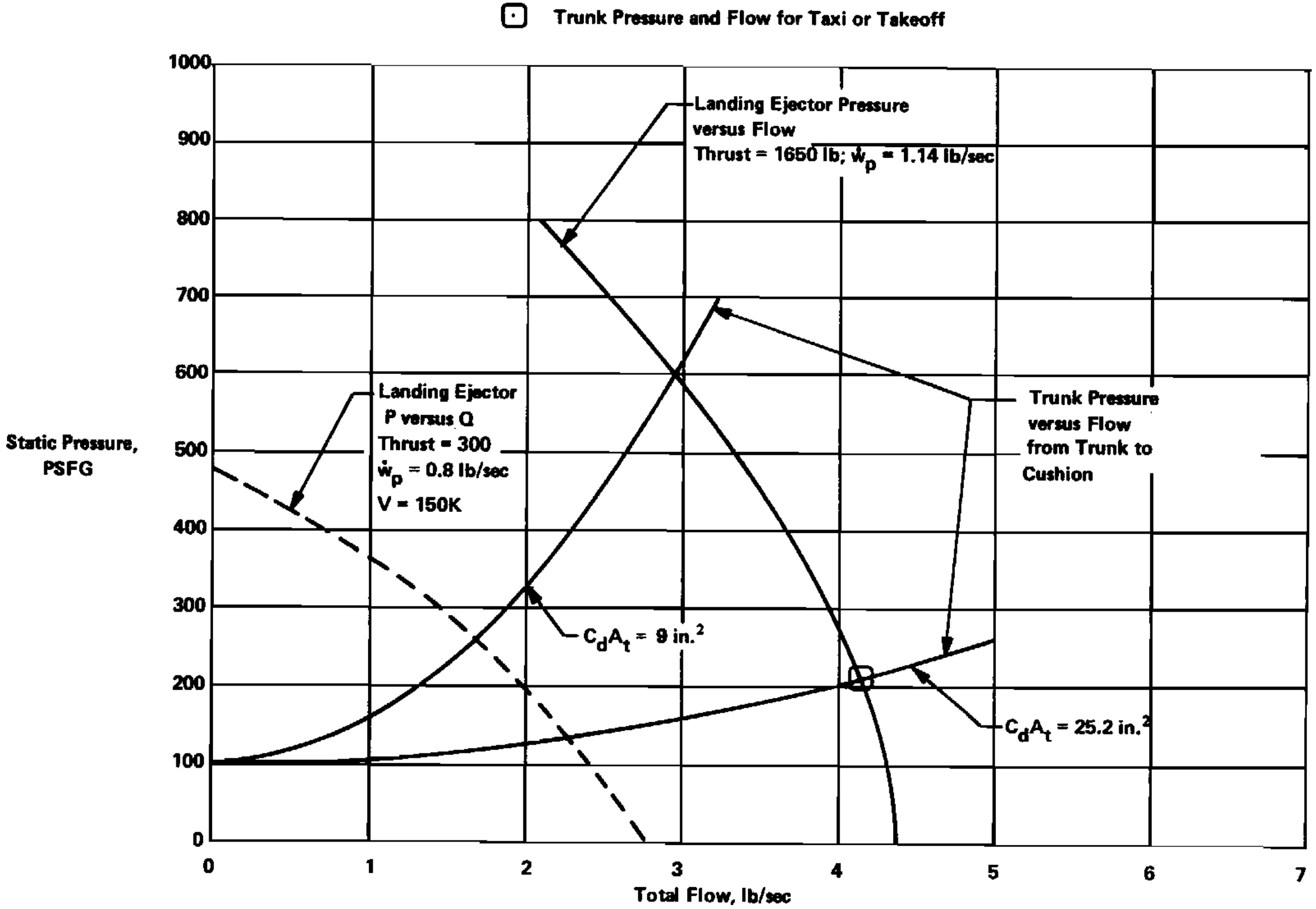


Figure 38. Use of Landing Ejector for Taxi or Takeoff

be the preferred approach. The lower curve of Figure 38 shows the effect of providing an effective trunk orifice area of 25.2 in.^{2}. This will result in a trunk pressure near 200 lb/ft^2 and a flow over 4 lb/sec (40% of LA-4 flow).

Figure 36 indicates that on a concrete runway, a flow of 4 lb/sec would result in an ACLS friction equivalent to about 0.15 g (or 420 lb at a vehicle weight of 2800 lb). This would leave a net force (thrust minus ACLS friction) of over 1200 lb at low speeds for taxiing, extending landing roll, or takeoff from long runways.

If an actual takeoff followed by an ACLS landing is desired, it will be necessary to close some or all of the additional trunk orifices or ports prior to landing so the required trunk pressure is achieved at the lower flow available for landing.

This could be accomplished by inflated valves of lightweight rubberized fabric, shown in Figure 39. Engine bleed is used to inflate the cylindrical valves. This uncovers the trunk orifices for taxi or takeoff. For landing they are deflated; trunk pressure then flattens them against the trunk to seal the orifices. This concept is similar to the one being used to open and close trunk to cushion ports on the CC-115 ACLS. Air flow requirements for the valves are almost zero, since actuation is required only prior to takeoff or landings; hence actuation time is of little importance.

The above orifice valve concept could also be incorporated in a landing only concept to provide differential braking during taxiing and/or the slideout after landing. Separate valves would then be provided for the left and right sides. Tests of Bell's braking model, extrapolated to the higher tread friction coefficients planned for the Model 147G, indicate that such a system could provide yaw moments of the order of 1500 ft-lb. In the absence of yaw moments due to friction or aerodynamics, such a moment could produce a yaw acceleration of 43 deg/sec^2. This value could be decreased by only covering and uncovering some of the trunk orifices. An on-off or proportional system could be provided, depending on the type of valve used to inflate the inflated orifice covers.

Figure 40 shows characteristics of an ejector designed specifically for takeoff. It gives maximum flow to the trunk at 200 lb/ft^2 pressure, at a propulsion engine thrust of 1650 lb. At this condition, a bleed of at least 2 lb/sec should be allowable. The curve shows a total ejector flow near 8 lb/sec at a trunk pressure of 200 lb/ft^2. This is approximately 80% of the LA-4 flow and twice the flow that could be achieved by using the ejector optimized for landing (Figure 38). Figure 36 indicates that with this flow, ACLS friction will be of the order of (0.05) (2800) = 140 lb on a concrete runway. This is only 8½% of the 1650 lb sea level static thrust at normal RPM and should permit takeoffs from runways or other smooth surfaces.

If takeoff from rough surfaces or grass is desired, additional flow may be required. This could be achieved by using one ejector to provide flow to the trunk, for trunk inflation and lubrication via trunk orifices, and using a second ejector to provide flow directly to the cushion. Because a takeoff capability was a secondary consideration for this study, such a concept was not designed. However, with this dual ejector concept, it is believed that ACLS performance equal to or better than that of the LA-4 ACLS could be achieved.

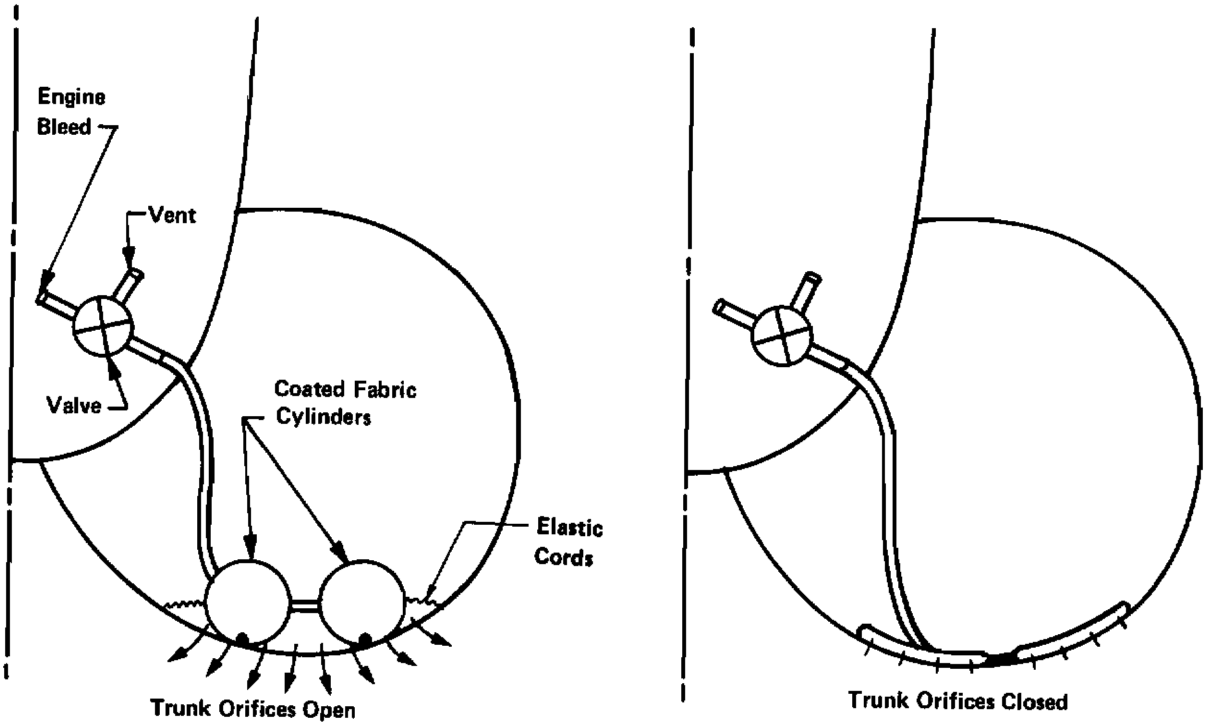


Figure 39. Inflatable Trunk Orifice Valve Concept

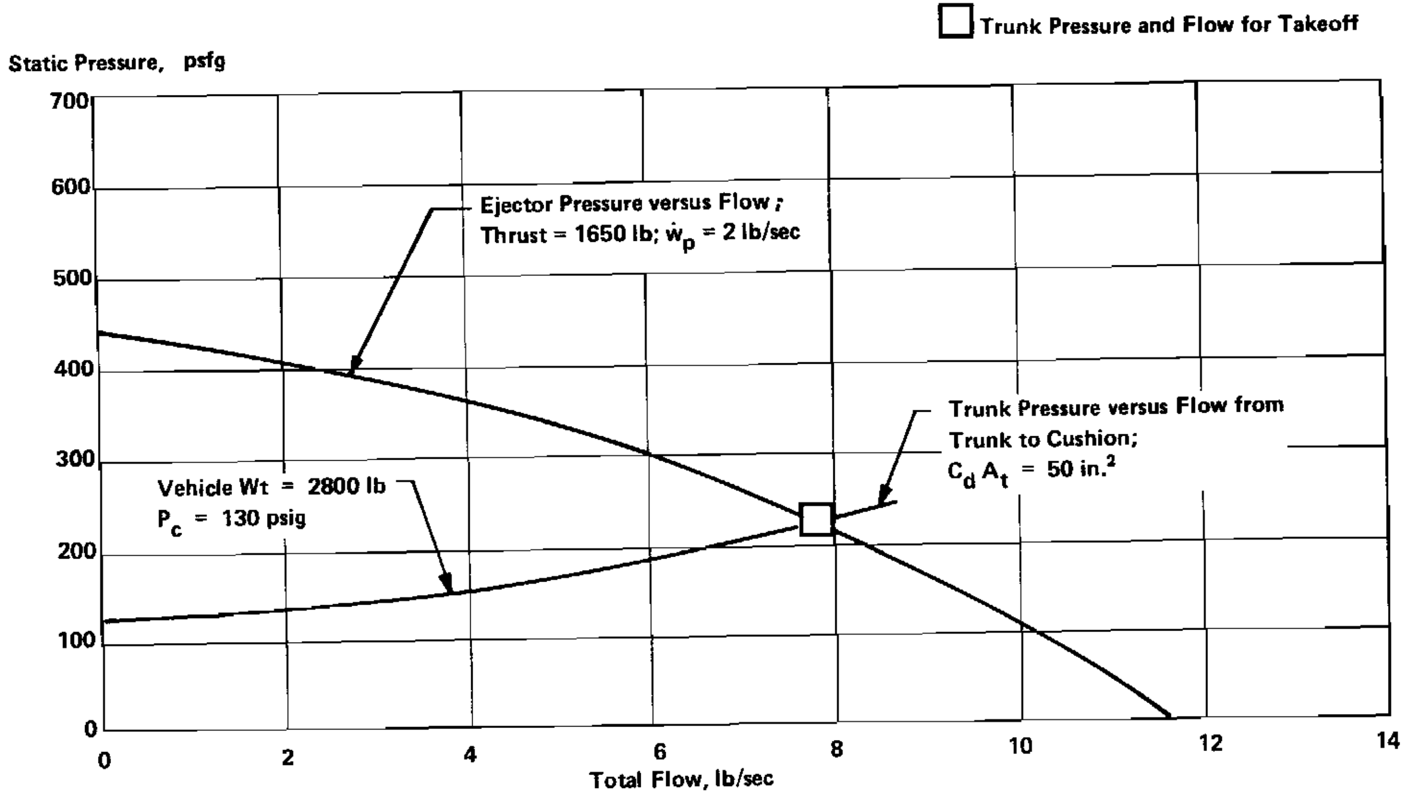


Figure 40. Ejector Pressure versus Flow for Takeoff

4. ENERGY ABSORPTION

a. Requirements

The ACLS must reduce the vehicles vertical velocity at landing to zero without exceeding allowable decelerations or damaging the structure. It must also dissipate a major portion of the associated kinetic energy so the vehicle does not bounce back into the air.

The vertical velocity at landing depends upon the vehicle aerodynamic characteristics, the sophistication of the guidance and control systems provided for landing, and pilot/operator skill. In order to minimize guidance and control system requirements and the need for operator skills, the ability to perform landings without a flare was established as an objective. After an initial investigation of vehicle characteristics, a goal of an ACLS permitting landings with lift equal to weight at pitch attitudes of 0 to 12 degrees and sink rates up to 12 ft/sec was established. Vertical decelerations due to the ACLS should not exceed 8 g. (Maximum allowable vertical deceleration for the vehicle is 9g).

b. Capability

Figure 15 shows estimated allowable sink rates versus pitch attitude for the ACLS design of Figure 13. Also shown are equilibrium rates of descent, velocities, angles of attack and flight path angles. The allowable sink rates vary from 10 ft/sec at $\theta = 12°$ to 17 ft/sec at $\theta = 0$. The equilibrium conditions for $\alpha = 7$ to $8°$ and thrust = 250 to 300 lb are well within the envelope of allowable sink rates; therefore, from these conditions no flare should be required. The initial portion of the descent could be made at steeper glide path (i.e.; $\gamma = -3°$, $\alpha = 6°$, $T = 250$ lb, $V = 149$ knots) to reduce touchdown dispersion. However, for a low cost demonstration of the ACLS at Edwards AFB, shallow descents could be used until pilot experience is developed.

Figure 41 shows estimated vertical g at landing versus vertical sink rate at landing. Figure 42 shows corresponding fuselage clearances. Figure 41 shows curves with and without a simple relief valve to limit trunk pressures to 500 lb/ft^2 when landings are made at low pitch attitudes. Without such a relief valve, the allowable sink rate at $\theta = 0$ would be approximately 10 ft/sec if vertical deceleration due to the ACLS is to be kept below 8 g. Air flow requirements for such a relief valve have been estimated and it has been conceptually designed (Figure 43). A possible installation was shown in Figure 37. It is likely that a combination of reducing the allowable sink rates at low attitudes and/or refining the ACLS design would make such a relief port unnecessary. This is discussed further in a later paragraph.

Figures 41 and 42 also show results of drop tests of a 1/4 scale model of the CC-115 ACLS. Although the CC-115 model test results were not used in estimating the energy absorption capability for the Model 147G, Figures 41 and 42 show a striking similarity between the CC-115 model test results and the 147G predictions for vertical velocities of 0 to 6 ft/sec.

Figures 44 and 45 compare weights, cushion areas, trunk cross section geometries, ACLS pressures and trunk tensions for the CC-115 model and full scale 147G.

The relatively large radii and high side attachment of the 147G trunk were selected to improve roll stability and vertical energy absorption characteristics relative to those of the CC-115. As the radii are decreased, the outer attachment moves lower on the fuselage and the vehicle tends to roll relative to the trunk. Also as the radii are decreased, there is less flattening of the trunk for a given vertical compression of the trunk. This decreases both roll stability and vertical energy absorption.

Figures 41 and 42 show that at $\theta = 0$, the 1/4 scale CC-115 met its design vertical velocity requirement of 6.25 ft/sec (12½ ft/sec full scale) with less than 1/2 of the available stroke. The bending over of the acceleration versus vertical velocity curve was due to fan stall and reverse flow from the trunk to the atmosphere via the fan.

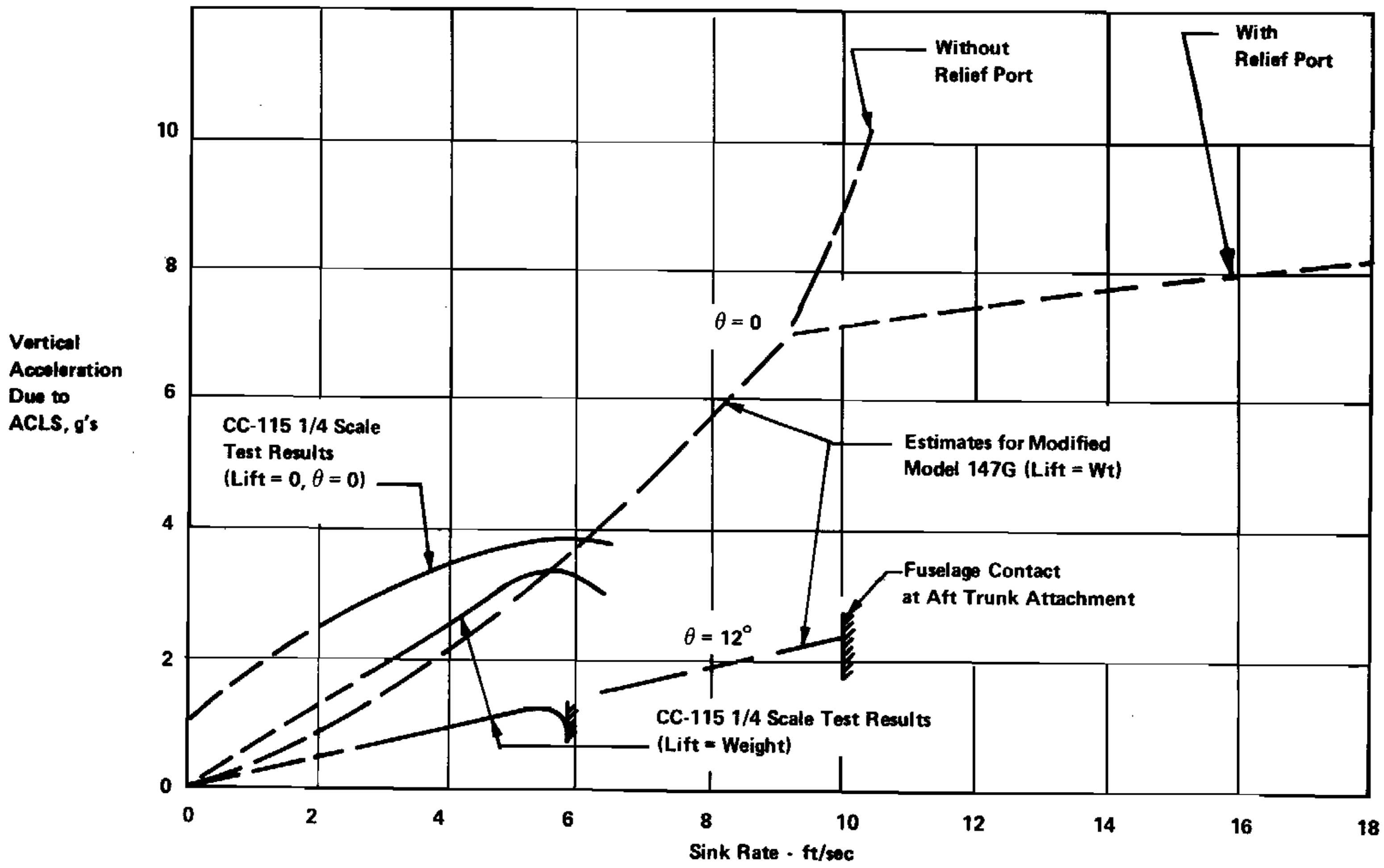


Figure 41. Vertical Accleration versus Sink Rate at Touchdown

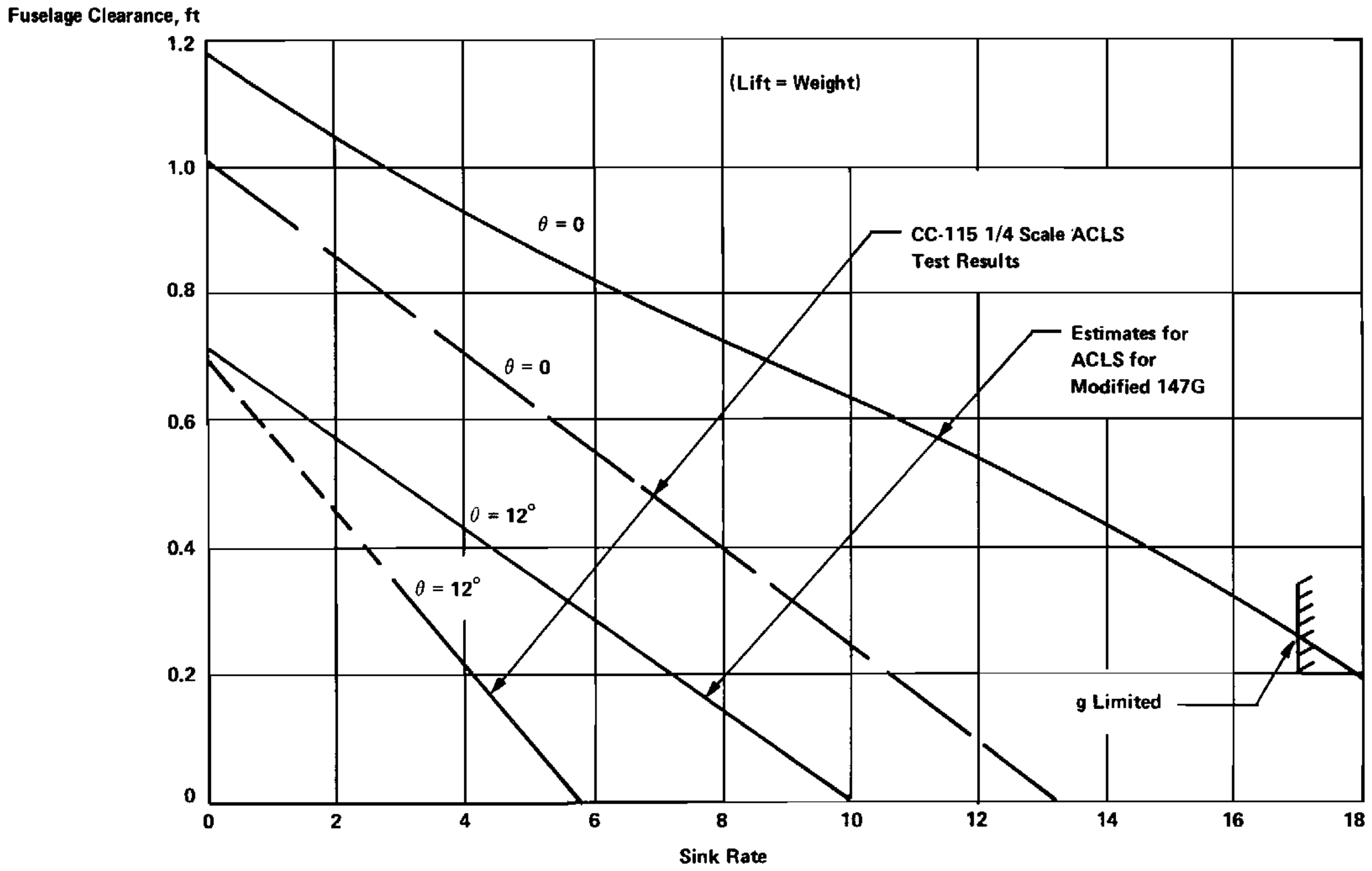


Figure 42. Fuselage Clearance versus Sink Rate at Touchdown

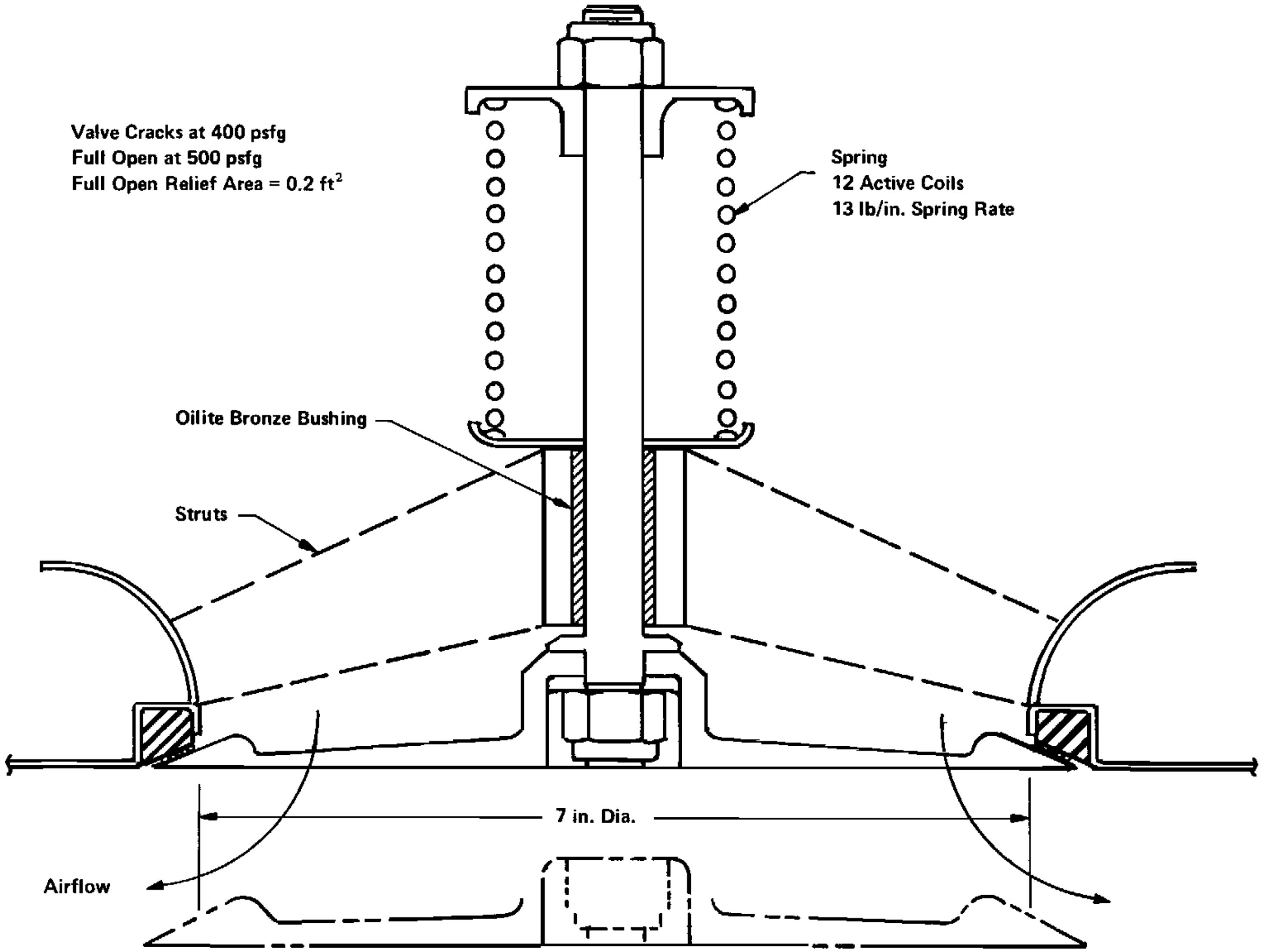
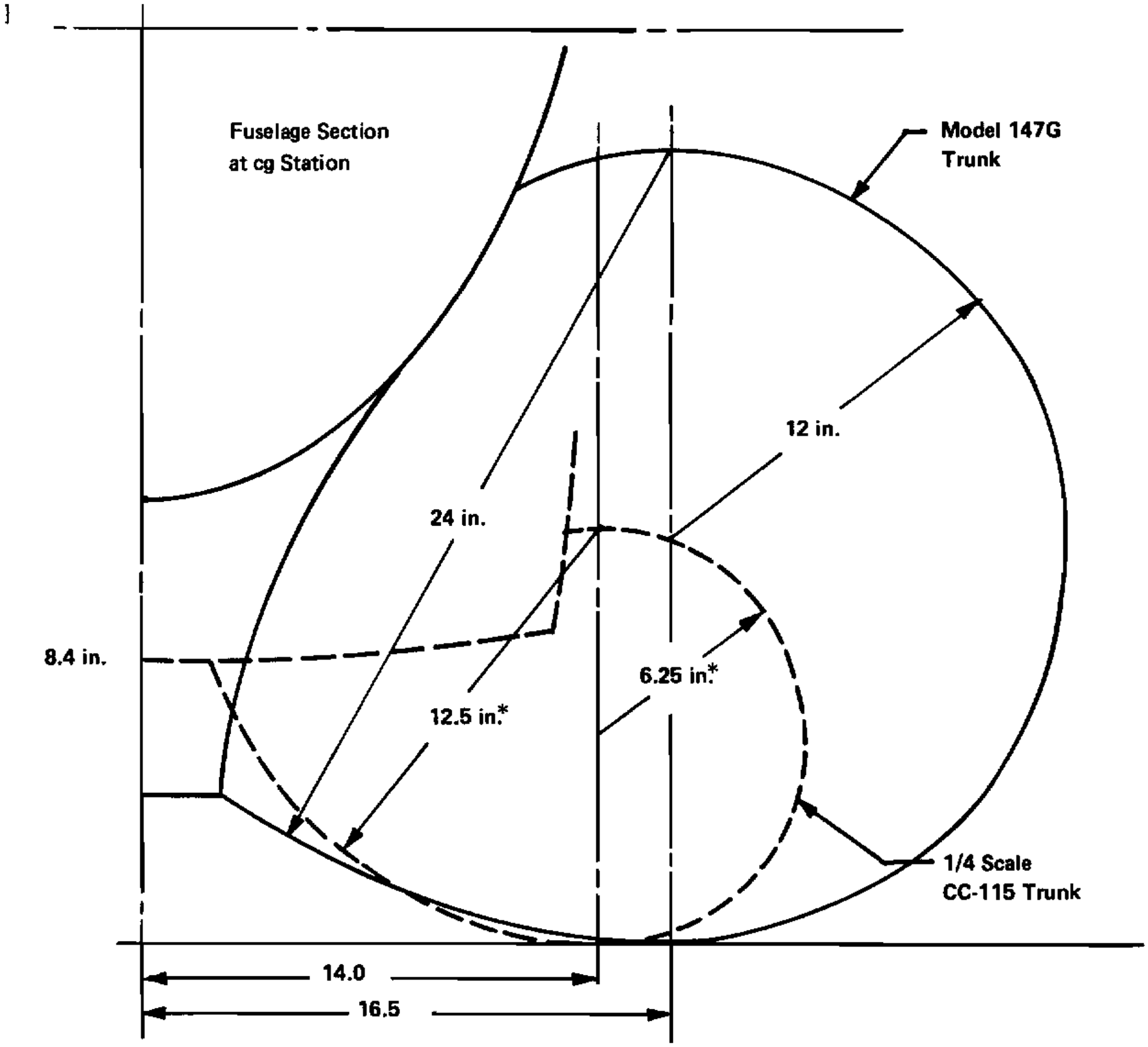


Figure 43. Trunk Relief Valve Concept

*Note: If the CC-115 were scaled to 147G landing weight (2300 lb.), its trunk radii would be 9.6 and 19.1 inches.



		CC-115 Full Scale	CC-115 1/4 Scale	147G Full Scale
Weight	lb	41,000	640	2300
P_T	lb/ft^2	342	85.5	214
P_c	lb/ft^2	171	42.75	107
Tension	lb/in.	60	3.7	17

Figure 44. Full Scale 147G and 1/4 Scale CC-115 Trunk Cross Sections

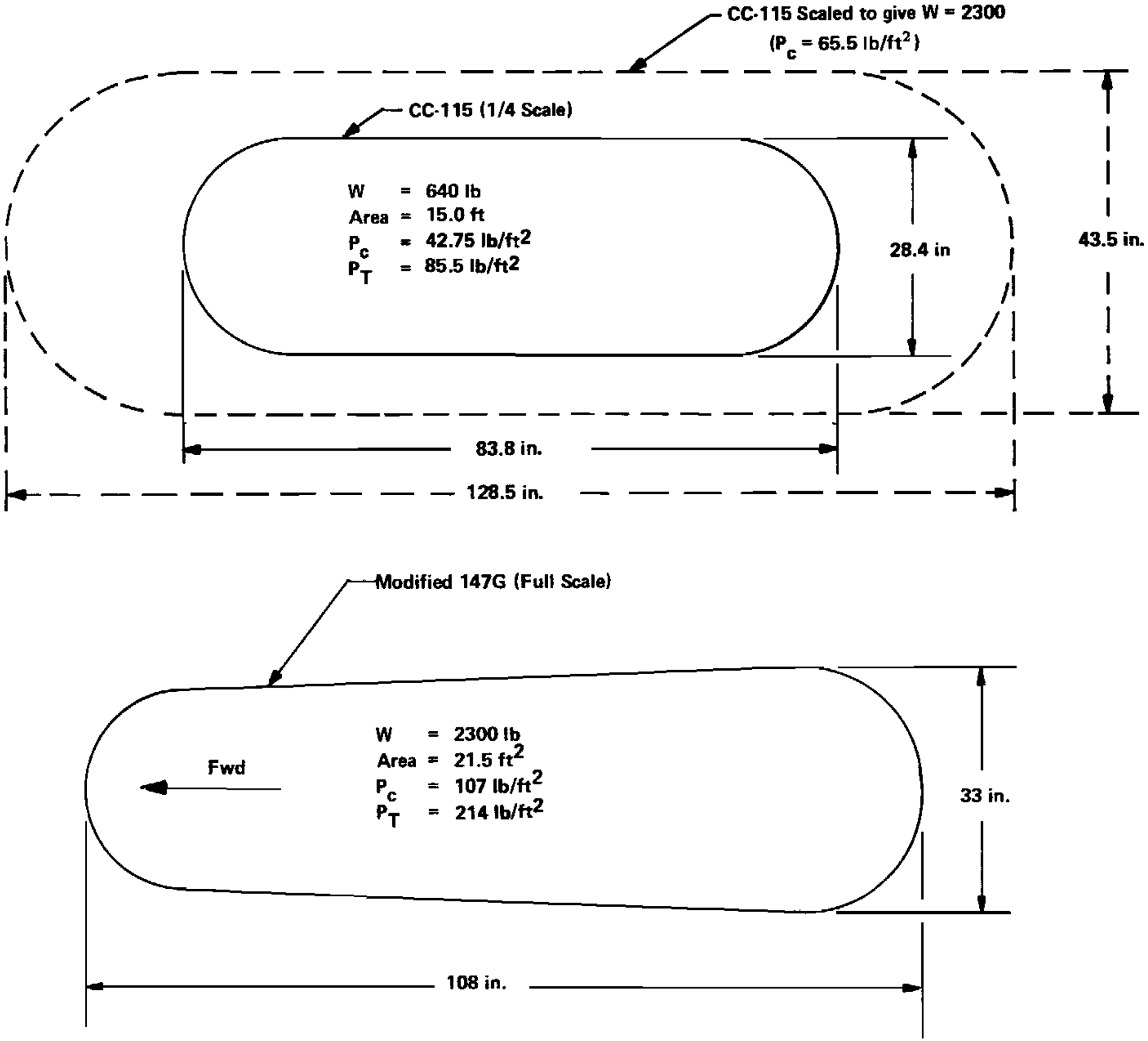


Figure 45. Full Scale 147G and 1/4 Scale CC-115 Cushion Planform

Figures 46 and 47 show load (g) versus stroke results from digital computer simulations of the CC-115 ACLS with $\theta = 0$ and 12°. Load stroke data were not obtained from CC-115 ACLS model drop tests. However, comparisons of other parameters indicated that the simulation was valid. As noted on the figures, stroke efficiencies were 62% for the $\theta = 0$ landing and 43% for the $\theta = 12°$ landing. These stroke efficiencies are based on a stroke measured from the in-flight depth of the trunk.

Figure 48 presents an estimated load versus stroke curve for the Model 147G ACLS with $\theta = 0$ and $\dot{h} = 17$ ft/sec. Its efficiency is 72%. There are two primary factors that contribute to the high efficiency of the ACLS for the Model 147G at high sink rates:

(1) The "dropped" center attachment of the trunk results in a nearly constant force versus deflection for deflections greater than 0.6 ft, if trunk pressure is held constant.

(2) The relief port limits maximum trunk pressure and hence maximum g.

Item (1) is illustrated by the family of force versus deflection curves for P_T = constant = 200 lb/ft² on Figure 48. Initial force buildup will occur within the family of curves labeled "Attachment at (0)." When the trunk is compressed to point (0), the webs from point (0) to the fuselage will go slack. Point (0) will then travel vertically to point (a) at the fuselage. During this transition the flattened area of the trunk remains nearly constant; and, if P_T could be held constant, a nearly constant force versus deflection would result as shown by line (0 - a) of Figure 48.

Figure 48 is for landings with $\theta = 0$. However, similar benefits will result from the large radius trunk and dropped center attachment at landing attitudes up to 12°. The relief port (if set to crack at 400 lb/ft²) will be of little or no benefit when θ is greater than approximately 5° because trunk pressures will not reach the relief pressure before the full stroke is utilized.

For low sink rates and hence small strokes, the 147G ACLS is expected to have stroke efficiencies comparable to those for the CC-115. This can be inferred from Figure 49. The solid curve for the 147G assumed no gap between the trunk and the ground and no flow from the cushion to the atmosphere. The curve labeled "Gap Height due to Cushion Dashpot Effect" accounts for a buildup of cushion pressure prior to the trunk contacting the ground, for a case with $\theta = 0$ and a sink rate of 17 ft/sec at touchdown. This will occur even with no flow into the cushion. Curves for $\dot{h}_O$ between 0 and 17 ft/sec would lie between the solid and dashed curves. A curve for $\dot{h} = 6.25$ ft/sec would be quite similar to the one for the 1/4 scale CC-115.

The stroke efficiencies at all landing attitudes could be further improved by landing with trunk pressure greater than 200 lb/ft². The present ejector design could provide trunk pressures in excess of 400 lb/ft² at low flows. However, as the pressure at landing is brought closer to the relief pressure, the requirements on relief port crack/reseat pressures, and frequency response become more stringent. In addition, a low trunk pressure during rollout is desired to keep tread temperatures and hence tread wear below the critical value.

Further study, simulations, and tests would be required to fully optimize the system. However, possible tradeoffs suggested above, give a high degree of confidence that the stroke efficiencies and energy absorption capabilities indicated for the ACLS for the Model 147G can be achieved or exceeded.

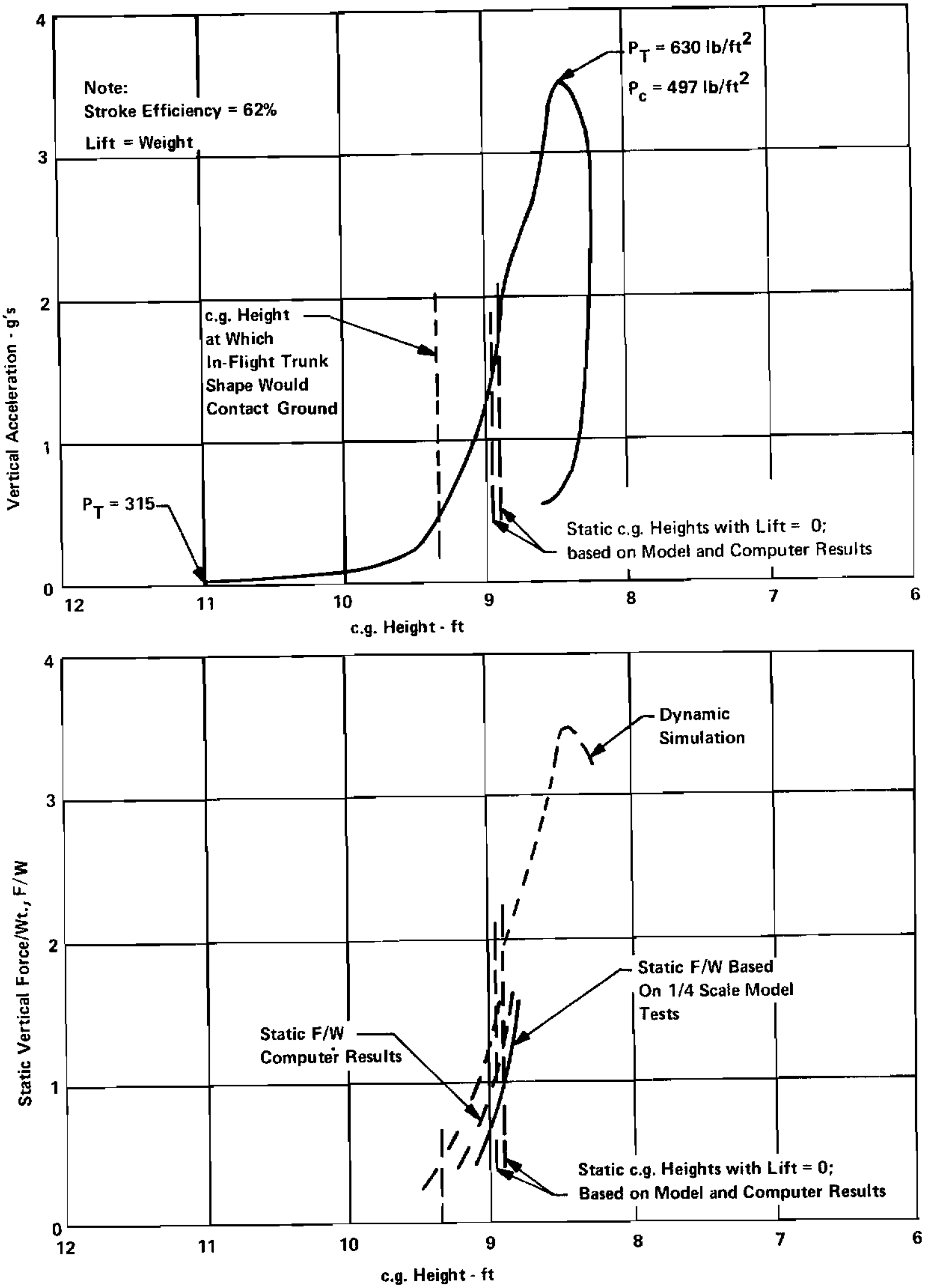


Figure 46. CC-115 Landing Simulation; θ = 0, $\dot{h}$ = 12½ ft/sec

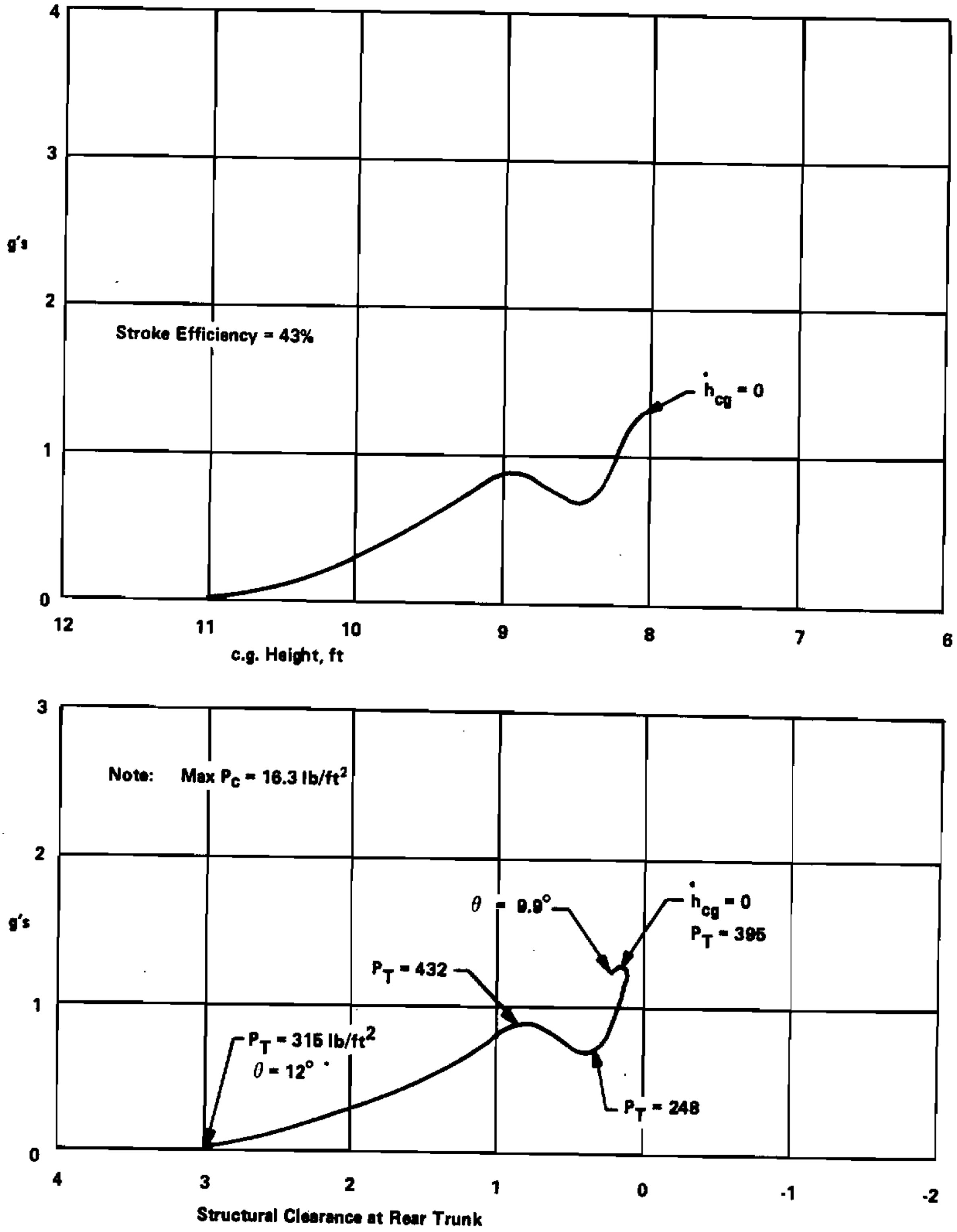


Figure 47. CC-115 Landing Simulation; θ = 12°; $\dot{h}$ = 10 ft/sec

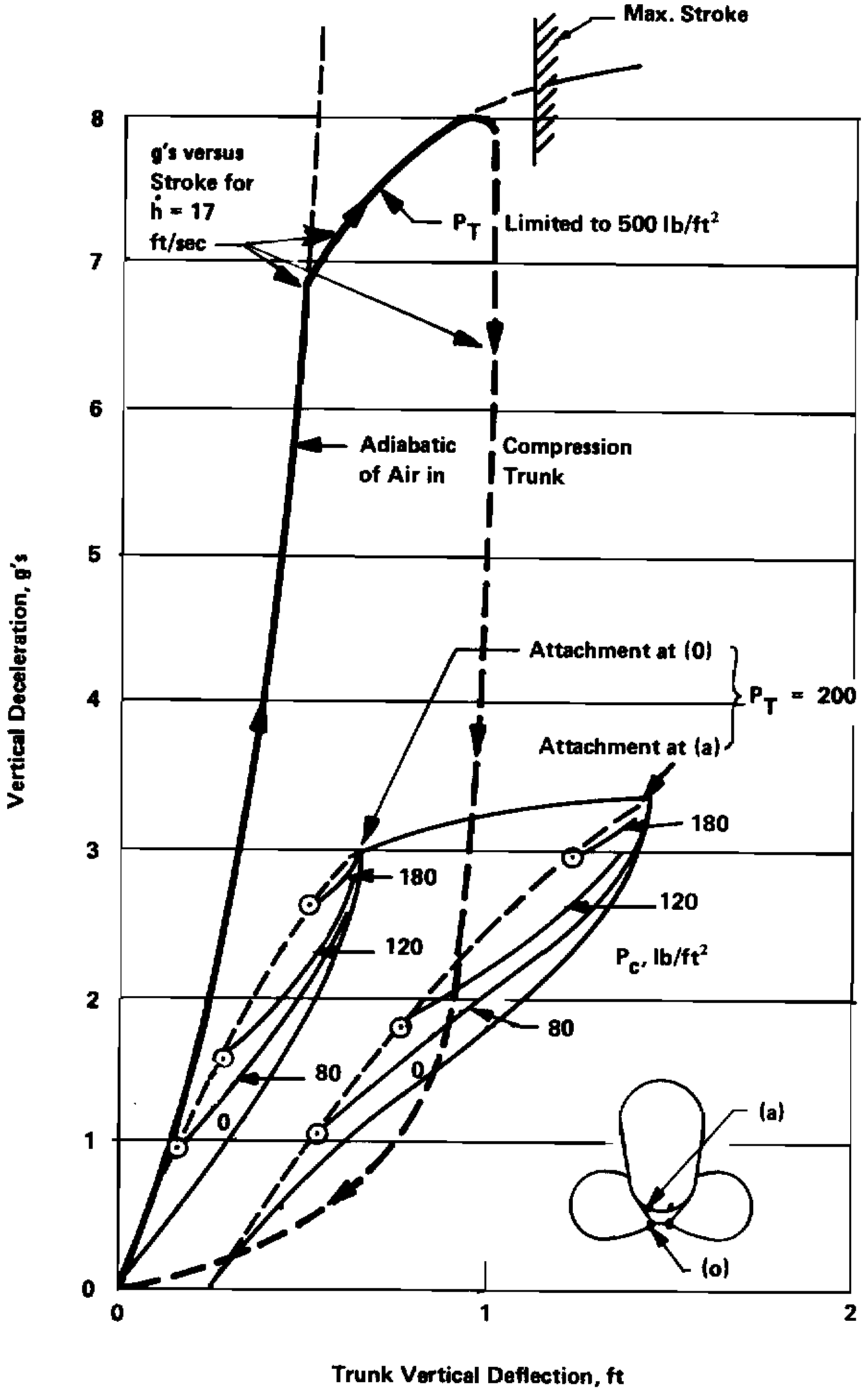


Figure 48. Vertical Deceleration versus Stroke for Landings at $\theta = 0$ with Lift = Weight

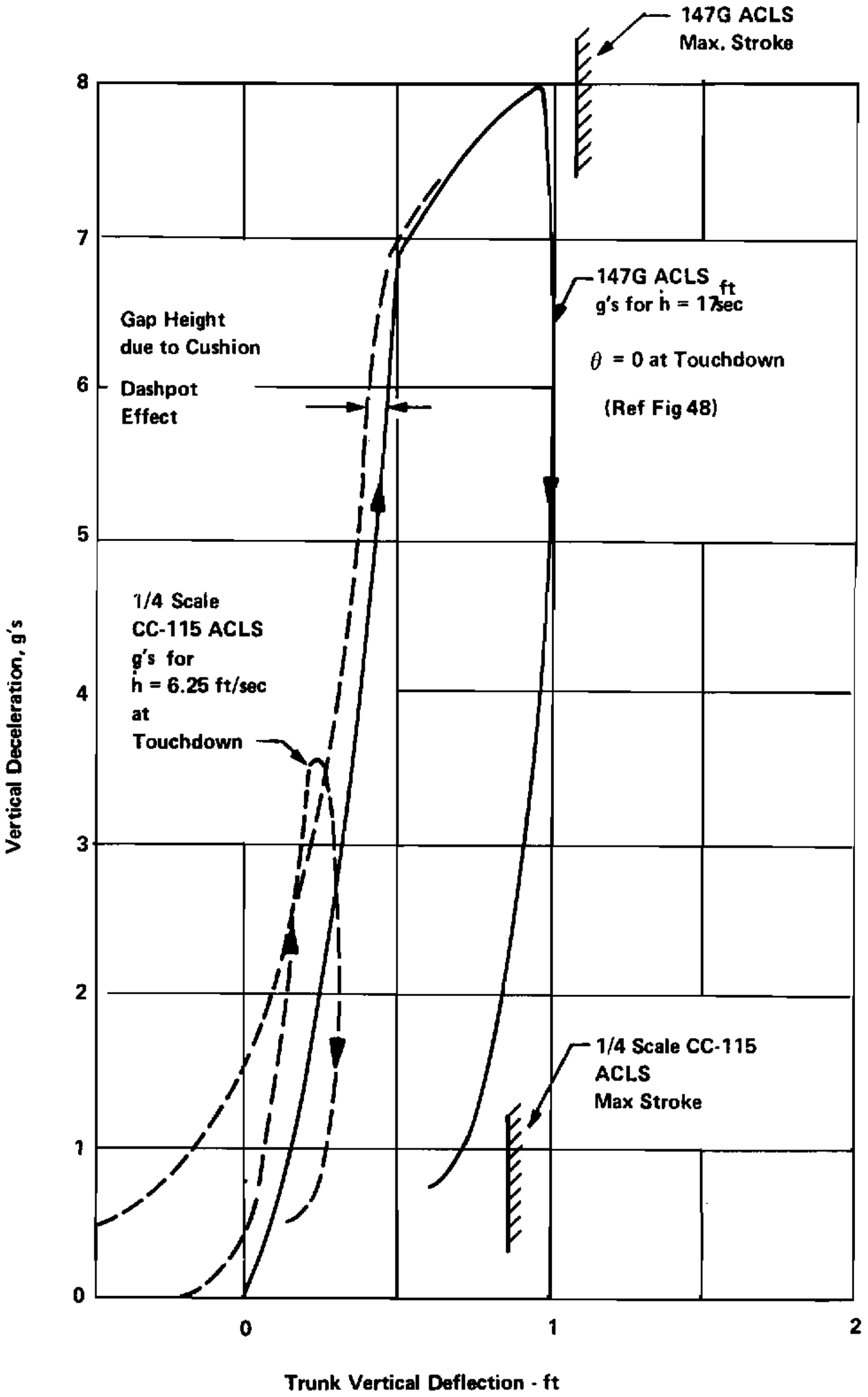


Figure 49. Additional Energy Absorption Due to Cushion Dashpot Effect

The maximum energy absorption capabilitiy of the Model 147G ACLS was estimated by utilizing the full available stroke with the limitation that the vertical deceleration due to the ACLS should not exceed 8 g. (The vehicle is designed for 9 g.) At $\theta = 0$, the 147G ACLS has a maximum stroke of 13 inches or 1.18 ft = distance from the bottom of the inflight trunk to the extended lower fuselage.

The Figure 41 curve labeled "Without Relief Port" shows that if there were no air flow out of the trunk, the 8 g limit would be reached with a touchdown vertical velocity of about 10 ft/sec at $\theta = 0$. This curve was based on adiabatic compression of the air in the trunk as the bottom of the trunk flattens and the trunk volume decreases during landings with $\theta = 0$. Although little is known of the reverse flow (trunk to atmosphere) characteristic of ejectors, it is quite apparent that the ejector mixing duct area of 9.7 in.^2 will not provide a significant percentage of the trunk to atmosphere reverse flow required to limit trunk pressure to 500 lb/ft^2 during hard landings at low attitudes. Therefore, the ejector will not provide a flattening of the g versus $\dot{h}$ curve comparable to that due to the CC-115 fan reverse flow.

It was estimated that an out flow of the order of 250 ft^3/sec would be required to limit trunk pressure to 500 lb/ft^2 if the vertical velocity at touchdown was 17 ft/sec, with $\theta = 0$, with a completely inelastic trunk, with no outflow through trunk orifices, and with no reverse flow through the ejector. This, therefore, provides an upper limit on the amount of flow required through a relief port in order to limit the trunk pressure.

The energy absorption capability of the ACLS at $\theta = 0$ was recomputed, with the assumption that a relief port limited trunk pressure to 500 lb/ft^2 (2½ times the prelanding pressure of 200 lb/ft^2). Results are shown in Figures 41, 42, 48 and 49.

Figure 43 shows a conceptual design for a relief port designed to limit trunk pressure to 500 lb/ft^2. It is designed to crack at 400 psfg and to give a maximum flow of 130 ft^3/sec at 500 psfg. This is only 50% of the very conservatively estimated maximum flow requirement for landings at $\theta = 0$ and 17 ft/sec. However, because of the very conservative nature of the estimate, this preliminary sizing is expected to be near that which will be required for this landing condition. If the sink rate at landing were reduced to 10 ft/sec, calculations indicate that the relief valve should not be required.

Qualitative (uninstrumented) drop tests of a simple 1/8 scale model of the ACLS for the Model 147G demonstrated good pitch and heave damping at sink rates equivalent to full scale sink rates over 17 ft/sec at $\theta = 0$ and 10 ft/sec at $\theta = 12°$. Roll damping, even without aerodynamic surfaces on the model, was acceptable unless roll angles at touchdown were of the order of 10 degrees or more. The model represented a near zero flow system, but exhibited damping comparable to that obtained on other designs with large air flows. It is theorized that the displacement of the air from the cushion provided a large pneumatic damping effect; also the rubbing of the tread on the landing surface as the trunk flattens and moves outward during the landing transient may have been a contributing factor.

The capability to land at $\theta = 0$ with a sink rate of 17 ft/sec may be an unnecessarily stringent requirement. Based on Figure 15, a nominal landing condition of $\theta = 6°$, with a sink rate of 6 ft/sec seems desirable. If, for example, the minimum attitude at landing is of the order of 3 degrees and the corresponding maximum sink rate is 12 ft/sec, the rate of change of trunk volume and hence the required out flow from the trunk will be greatly decreased. Then the relief port can be much smaller and there is a high probability that a relief port will not be required at all. Use of an ejector with a larger diameter mixing duct (greater reverse flow capability) could further reduce the need for the relief port. (A 40% increase in diameter would double the area; such an ejector could still produce the design trunk pressure of 200 $\mathrm{lb/ft^2}$ if leakage from the trunk is small - no relief port to produce leakage, no trunk orifices, trunk constructed as a closed volume.)

The following steps are recommended to firmly establish energy absorption requirements and associated ACLS design details:

(1) Simulator studies to define limits on design sink rates versus attitudes at landing, with a pilot/controller in the loop.

(2) Landing dynamics simulations with the Bell digital ACLS simulator, to refine estimates of the ACLS g versus $\dot{h}$ and θ at touchdown to determine effects of ejector characteristics, to determine whether or not a relief port is required, and to determine the mechanism of energy dissipation in low and zero flow ACLS systems.

(3) Ejector tests to determine pressure versus flow characteristics in the reverse flow region (trunk to atmosphere flow).

(4) Model and/or full scale drops tests to confirm the final design.

5. BRAKING, TREAD AND GROUND TRACK CONTROL

a. Requirements

A braking system can be used to dissipate horizontal kinetic energy after landing and/or for directional control on the ground. Deceleration and directional control requirements can vary widely with the vehicle and its operational concept. For example, if landings speeds are high and landings on short and/or narrow areas or runways are desired, requirements for energy dissipation and/or heading control can be severe. If landing speeds are low and/or landing areas are large, no separate braking system may be required.

Based on Figure 15, a nominal touchdown speed of 136 knots was established for the Ryan Model 147G with an ACLS. For brake system design, a maximum touchdown speed of 150 knots was used.

It was assumed that landings might be on concrete runways or on unprepared surfaces. A maximum runway or landing area width of 150 ft was assumed and a maximum slideout distance of 2500 ft was established. In addition, an objective of demonstrating decelerations in excess of 1g and slideout distances less than 1000 ft was established.

In addition to providing linear deceleration, a braking system can be used to supplement aerodynamic surfaces to provide heading control which may be needed to maintain the desired ground track. An ACLS has an inherent crosswind landing capability because it can land in a yawed attitude. However, the lack of side force that would be generated by wheels, results in a requirement to maintain a yawed attitude after touchdown so that aerodynamic side forces and/or thrust produce the desired ground track. The amount of required yaw depends on vehicle aerodynamic characteristics, the crosswind, the amount of thrust used after touchdown, and the linear deceleration or slideout distance. For these concept studies an ability to maintain ground track within ±50 ft with a 30 knot crosswind was established as an objective. The amount of required differential braking, if any, then depends on other design and operational factors cited above.

Differential braking can also be used during taxiing, including turns off the landing area at the end of the landing slideout. This can be important if a number of aircraft are using the same landing strip. It may not be required if there is only a single aircraft, or if a large area is available for landings.

An ACLS system with neither linear braking (other than ACLS tread friction) or differential braking is a very simple, reliable concept and should be considered for some applications. Demonstration of suction braking, with decelerations up to 1.5g, is also recommended because of the potential for landings on very short fields (< 1000 ft).

b. Braking Concepts

(1) No Braking Other than that Provided by Friction of the ACLS

The X-2 and X-15 aircraft have landed successfully at high velocities with no braking other than that resulting from friction of their metal skids. However, they landed only on the large dry lake at Edwards AFB, California. The Australian Jindivik drone lands with a single metal skid on runways or other hard smooth surfaces. After touchdown at a speed of approximately 120 knots, in response to steering commands it maintains a steady course and normally comes to a stop within

2500 ft after touchdown (Reference 7). It requires a 5000 x 150 ft runway for recovery. The British Hengist troop glider landed on grass on its inflated air bag with no braking system. Thus, there is considerable experience which shows that, for certain types of operations, brakes are not required.

Because of ACLS system simplicity, reliability, and ease of stowage without the additional elements required for braking, a no-brakes system should be considered for applications where landing areas permit slideouts of the order of 2500 ft and where operational considerations permit. The latter includes retrieval from the end of the landing run by towing or hoisting onto a dolly. Where space adjacent to the landing area permits, turns off the landing strip could be made while aerodynamic controls are still effective and retrieval could be accomplished after several vehicles have landed. Another possibility, for a small vehicle such as the Model 147G, would be for a ground crew to restrain one wing to effect a 90 degree turn off the runway after the vehicle comes to rest at the end of the slideout. High thrust could then be used to overcome ACLS friction and, thus, clear the runway for the next landing.

Figure 36, based on LA-4 model low speed friction force versus air flow tests and full scale LA-4 ACLS tests on various surfaces (Reference 4), indicates that if the ACLS for the Model 147G is provided with 1.5 to 2.0 lb/sec of air flow, a deceleration of the order of 0.3 to 0.4g can be expected on runways without a braking system. This is comparable to the braking capability of wheeled gear.

Even without a braking system, some variation in stopping distance can be achieved by varying thrust during the slideout. Associated with a decrease in thrust will be a decrease in ejector air flow, a resulting increase in ACLS friction, and an increased deceleration. For example, a 100-lb decrease in thrust is equivalent to a 0.044g increase in deceleration at a 2300-lb landing weight. In addition, this thrust reduction decreases ejector total flow by about 0.2 lb/sec. Figure 36 shows a 0.22g increase in deceleration (on concrete) per 1 lb/sec decrease in flow in the 1 to 2 lb/sec range of flows. Thus, the flow reduction contributes an additional 0.044g deceleration for a total change of 0.088g. This is a 25% increase relative to an initial deceleration of 0.35g. Figure 50 shows that this deceleration increment will shorten the slideout distance by 300 to 500 ft, if the thrust decrease is made immediately after touchdown.

A thrust decrease of the order of 100 lb during slideout is probably near the maximum that can be used with a bleed air/ejector system without reducing trunk pressure below the minimum value for good stability. However, there is no limit on the allowable thrust increase. Thus, the slideout could be extended indefinitely.

Figure 51 shows the effects of aerodynamic drag and a 300-lb thrust on net decelerations, for cases of 0, 1/2, and 1g decelerations due to brakes or ACLS friction. At 150 knots, with α near zero, the drag of the 147G with its ACLS, approximately cancels the 300-lb thrust. At $V = 0$, the 300-lb thrust decreases deceleration by 0.13g.

Figures 50, 52, and 53 further illustrate the effects of thrust, drag, and net deceleration on stopping distances and on the kinetic energy that must be dissipated by ACLS friction or brakes. The necessity to maintain thrust during slideout with a bleed air/ejector powered ACLS can significantly increase slideout distances and the energy to be dissipated by the ACLS if net deceleration is low. However, if net decelerations are of the order of 1g, these increments become insignificant.

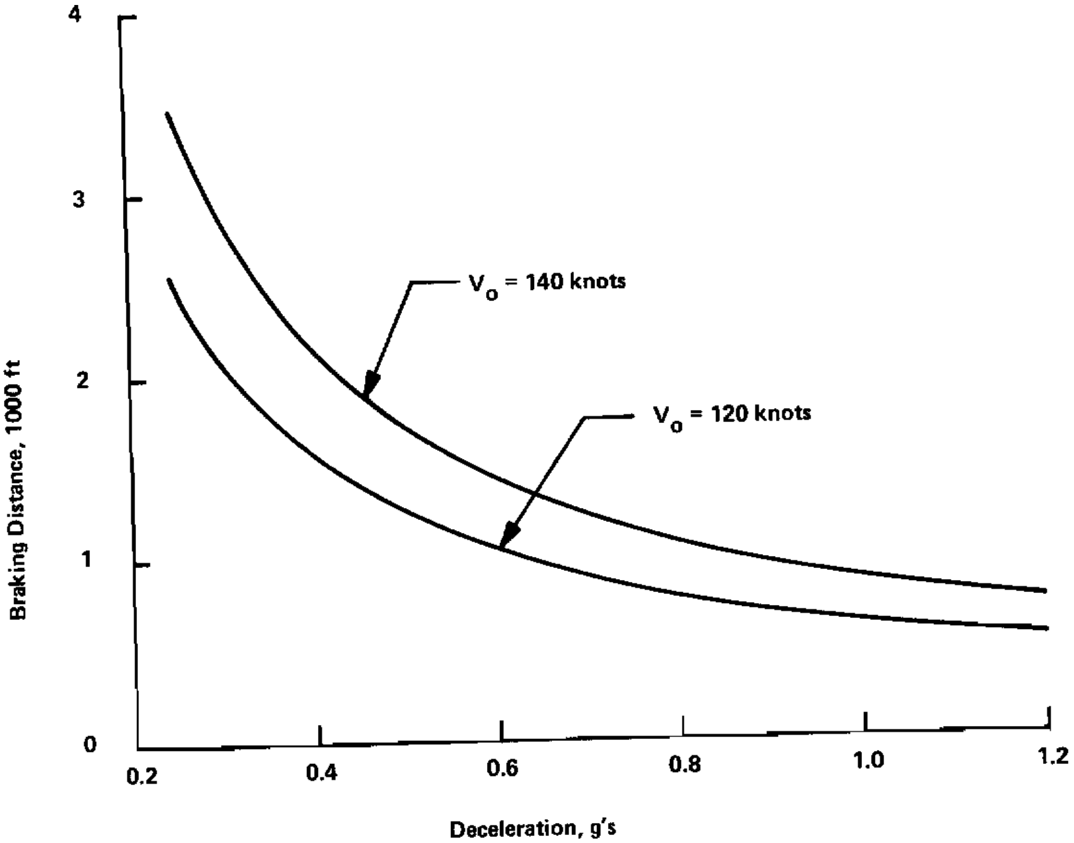


Figure 50. Braking Distance versus Deceleration

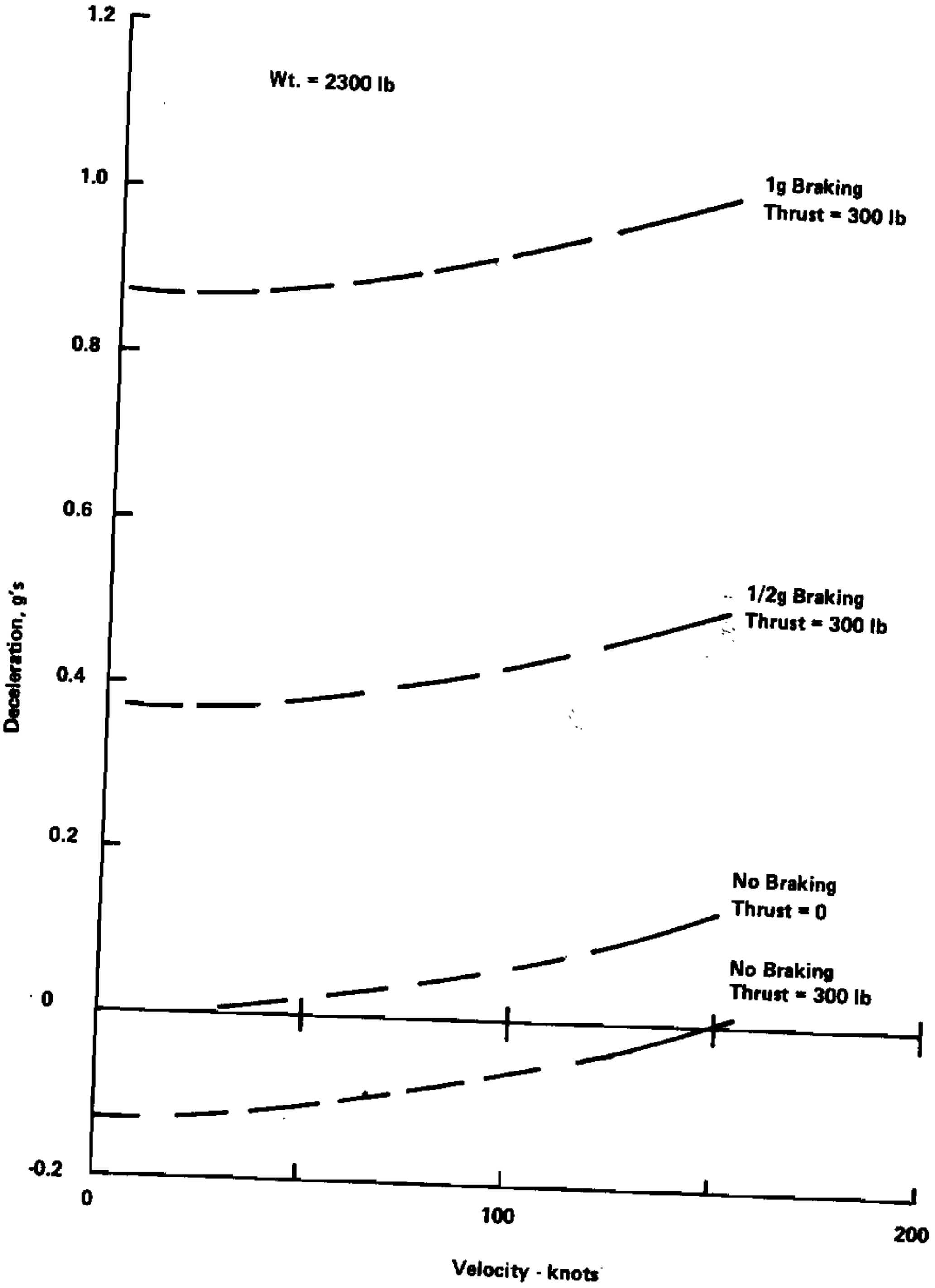


Figure 51. Effects of Aerodynamic Drag, Thrust, and Braking on Deceleration

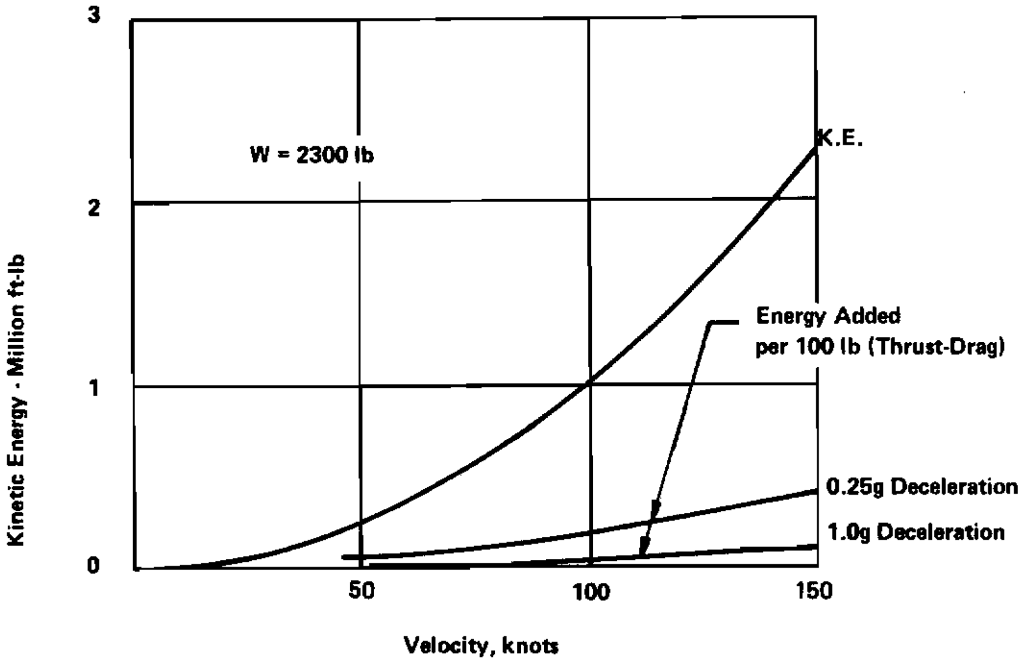


Figure 52. Kinetic Energy versus Velocity

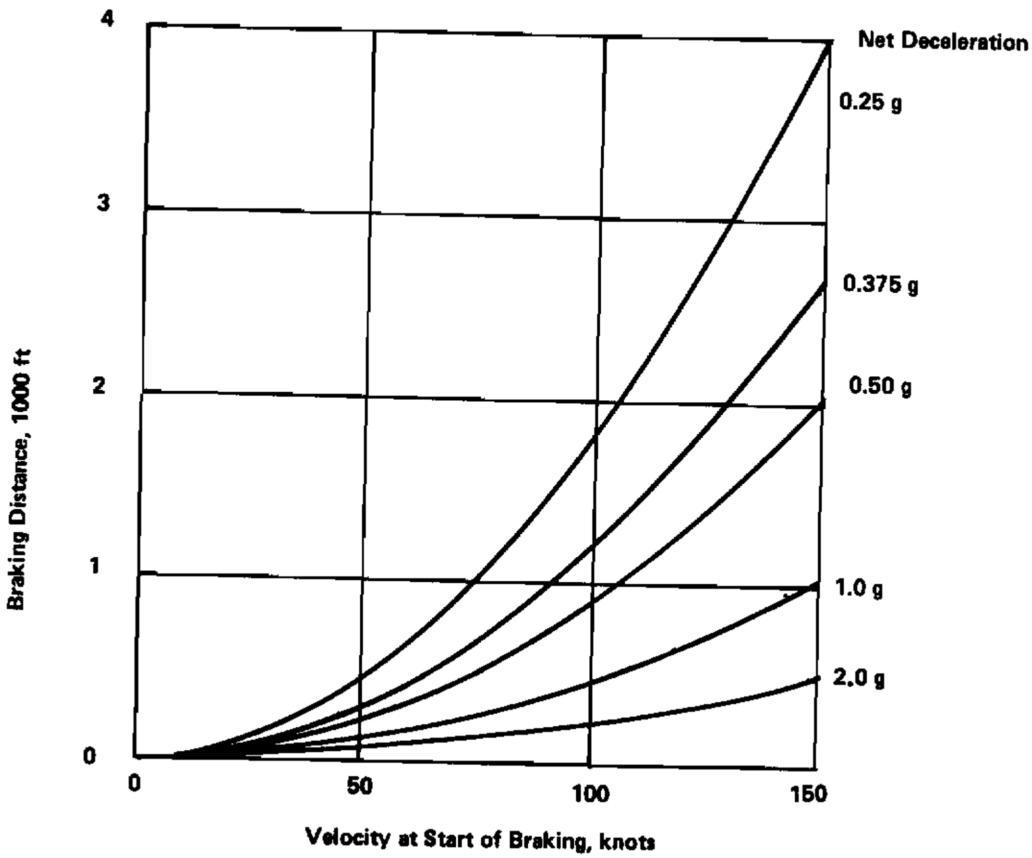


Figure 53. Braking Distance versus Velocity

(2) Pillow Brakes

Figure 5 (Introduction) illustrates this concept which was used very effectively on the LA-4 and is being incorporated in the CC-115 ACLS. Inflation of the pillows depresses treads against the surface and simultaneously vents the cushion to transfer load to the treads. Proportional braking has been achieved by varying the pillow pressure.

On the LA-4 and CC-115 the treads are accordion-pleated so they can fold when the elastic trunk cross section decreases in length to retract against the fuselage. The resulting protrusions are acceptable on these low speed aircraft but will be undesirable on the high speed 147G.

If pillow braking is used with an inelastic trunk, the tread can be attached flush to the trunk, thus, avoiding any significant drag penalty. Pillow braking with inelastic trunks has been shown to be effective on several ACLS models.

The principal objection to pillow braking is that pressures several times trunk pressure must be used in the pillows to achieve maximum braking. This results in high tread pressures which together with high landings speeds is expected to result in excessive rates of tread wear. (See Section II.5.c, Tread.) Wear might be reduced to an acceptable level by using a large number of pillows at lower pressure, but this complicates pillow and air line installations. Also higher temperature elastomers, elastomer/wire composites, or even metals could be used for treads. However, these require development and/or have low friction coefficients. For these reasons, and because there are other braking concepts which can provide greater decelerations with low tread wear, pillow brakes are not recommended for 147G ACLS demonstrations.

(3) Variable Trunk Orifice Braking

Figure 39 (Air Supply) illustrates a concept for closing trunk orifices to reduce or eliminate air flow to the cushion and air lubrication between the trunk and the landing surface. The reduction of flow also reduces the average gap beneath the trunk so more of the trunk drags on the surface. When all flow is shut off, cushion pressure drops to zero, vehicle weight is all supported by the trunk, and the deceleration, in g's, is equal to the tread to surface friction coefficient. For tread materials developed for ACLS, this can be as high as 1.3 on dry concrete. Figure 36 shows that even with a coefficient of 1.0, this concept can vary deceleration from less than 0.4g to 1.0g, if the nominal air flow is 1.5 lb/sec.

This effect has been demonstrated with Bell's braking model by performing low speed friction tests with and without flow from the trunk orifices. Zero flow was obtained by placing tape over the orifices. This model did not incorporate the inflatable cylinders of coated fabric which cover and uncover the orifices. However, they are quite similar in principal to trunk to cushion vent valves demonstrated for the CC-115 trunk to cushion trim ports.

Pressurization of the inflatable cylinders to 0.1 to 0.2 psi above trunk pressure is all that is required to uncover the orifices. Total volume of the cylinders is less than 3 ft^3. Thus, a very small ejector (1 inch diameter x 6 inch; weight = 1 lb), drawing secondary air from the trunk, could fully inflate them in less than 1 second. Similarly rapid deflation could be accomplished by shutting off the ejector and allowing reverse flow into the trunk. Light elastic cords will force the cylinders to their flattened shape when internal pressure is released. Trunk pressure will then force them against the trunk orifices to seal them.

Operation of the orifice valves on the left or right side could produce directional control. Proportional linear and/or differential braking could be achieved by varying the primary flow to the ejectors.

(4) Suction Braking

This concept has developed to the point where Bell can confidently offer it in the present application – for which it is most suitable. It can provide a deceleration as high as 2g. It is self-evident that the resulting dramatic reduction in landing distance can greatly improve operations. The system operates by two separate and simultaneous actions:

(a) The direct flow of augmented bleed air to the cushion cavity is reduced or stopped. This may be by rapid acting pillow valves which close off the orifices or by cushion feed ports (Figure 54).

(b) A major portion of engine bleed air is ducted to an ejector which bleeds off cushion pressure to a value less than atmospheric. The difference between atmospheric pressure acting on top of the vehicle and the below atmospheric pressure in the cushion cavity produces a down force on the vehicle. The down force creates a resultant high friction equivalent to a deceleration of one or more g's. Braking drag is reacted on tread attached to the bottom of the trunk. Thus, tread bearing pressure is low, equal to trunk pressure, and wear will be low.

This concept offers decelerations and stopping distances approaching those of aircraft arresting gear. For some applications, this could be a great advantage. Consequently, along with new methods of supplying ACLS air, the suction-braking concept is considered to be one of the unique and most significant features of this study.

Calculations indicate that a suction-braking system, employing an ejector to evacuate the cushion, is a feasible way of providing 147G decelerations from near zero to about 2g (Figure 55). Either proportional or on/off systems can be provided.

Although engine bleed seems to be the preferable source of primary air for the suction-braking ejector, other sources may offer advantages if high braking forces are desired. With high decelerations, braking times can be very short and the total required air flow small. For example, at a 1g deceleration, braking from 150 ft/sec only requires 5 seconds.

If cushion feed ports or trunk orifice valves are used to shut off all air flow to the cushion, an air flow less than the nominal 2 lb/sec flow to the cushion will maintain a negative cushion pressure of 50 to 100 lb/ft^2 on a runway or other smooth surface. With friction coefficients of 1 to 1.3, this will result in decelerations of 1.25 to 2g. Total air flow required for such cases would be less than 10 lb or 13 scf. An ejector and stored gas system could be used for such short duration suction braking. Weight of such a system could be as low as 10 lb. However, on rough surfaces, suction braking will be less effective, braking times will be longer and the weight of a stored gas system becomes excessive.

The suction-braking system recommended for the 147G will use an ejector to develop negative pressures in the cushion cavity (Figure 54). Engine bleed, will be the source of primary

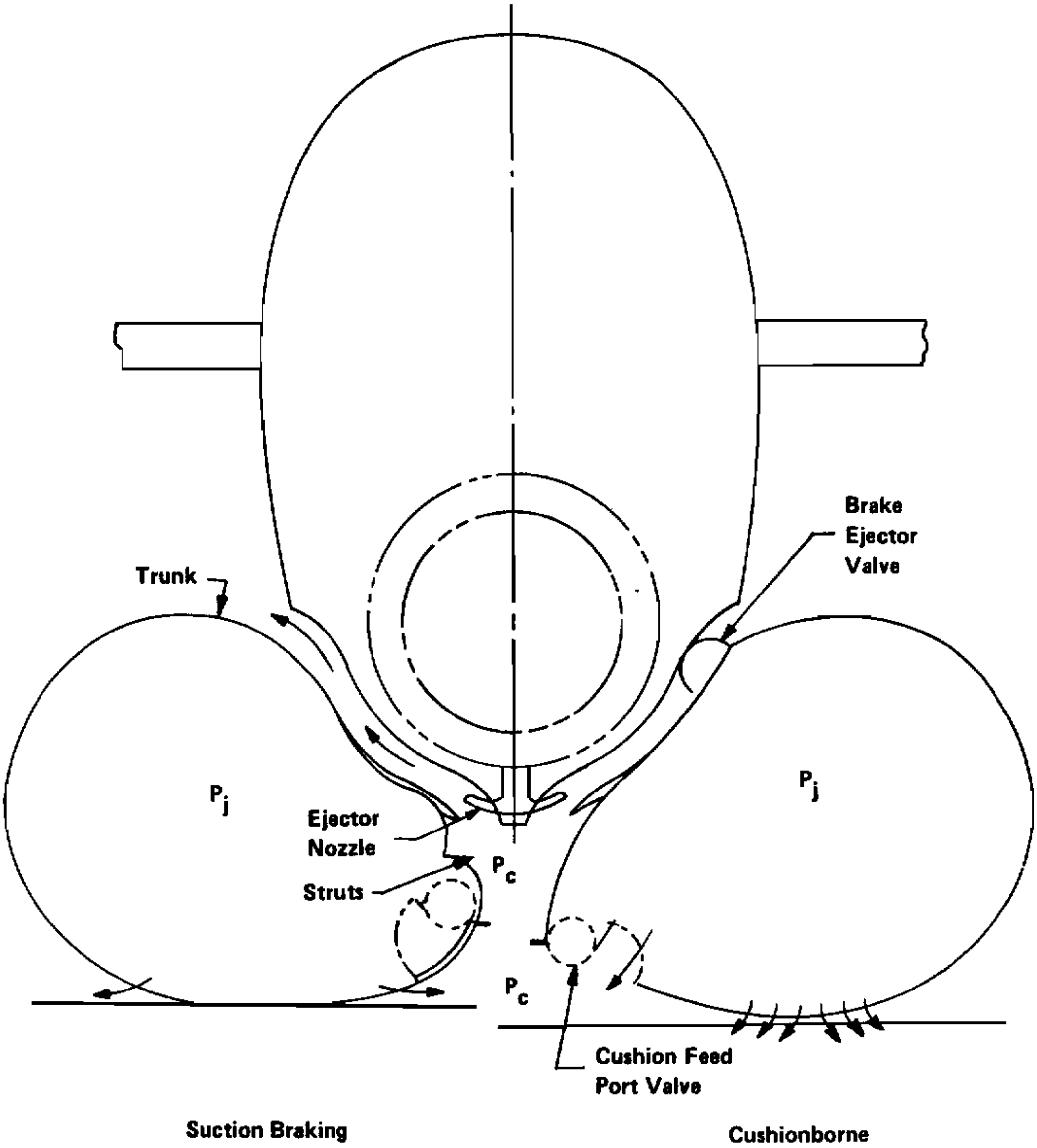


Figure 54. Suction Braking Concept

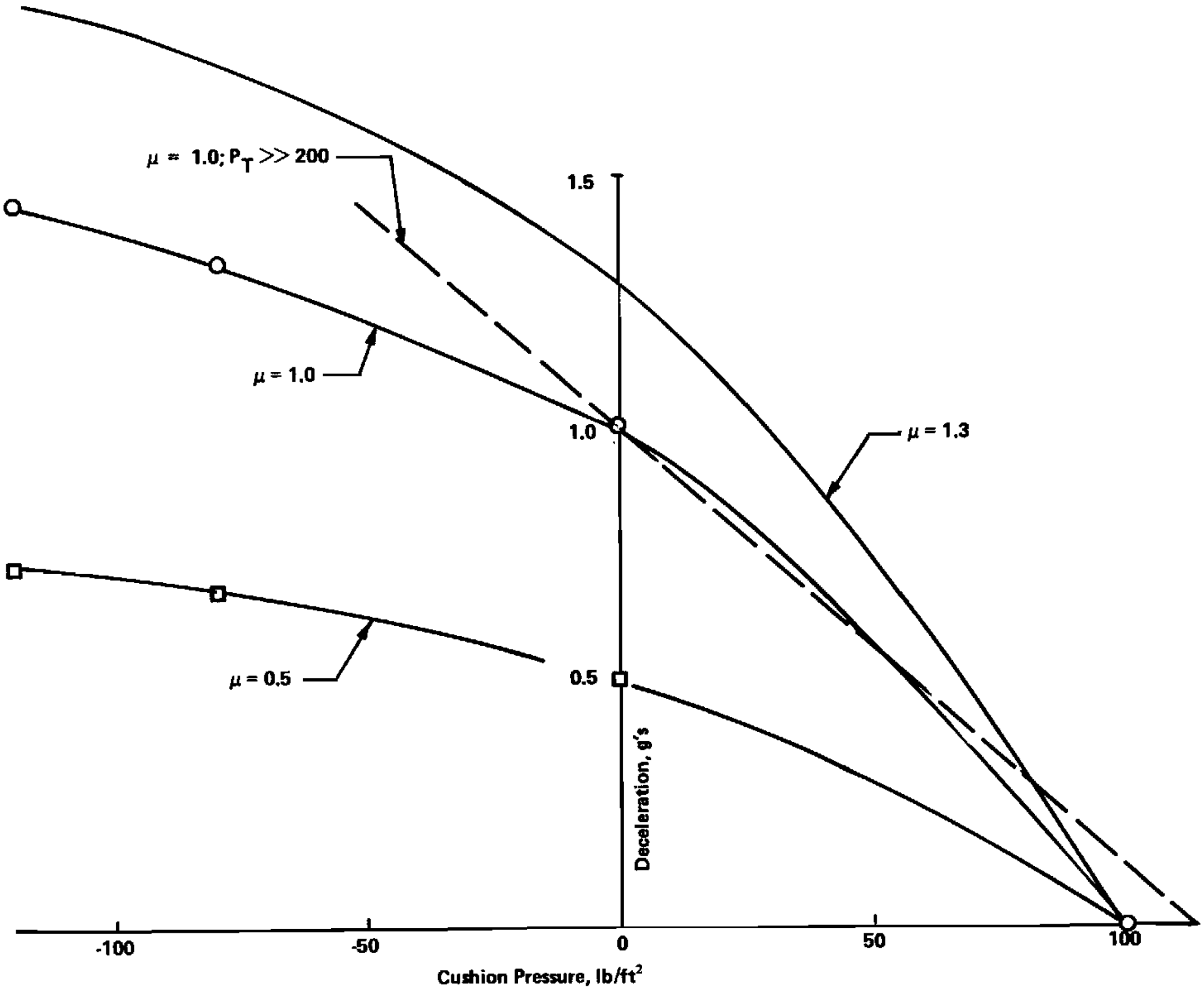


Figure 55. Braking Deceleration versus Cushion Pressure (Trunk Pressure = 200 lb/ft^2)

air. The required air flow can be reduced by closing the cushion feed ports or trunk orifices. Reducing flow from the trunk, reduces the requirement for engine bleed air from the trunk inflation ejector, so bleed air can be diverted to the braking ejector. For limited-air flow systems, these ports and associated valves may not be required (see Section II.5.b.(4)(a), Suction Braking Model Tests). However, such ports and valves will provide a convenient means of varying air flow and evaluating performance versus air flow during a demonstration program.

A single ejector for such a suction braking system would be approximately 4 inches in diameter x 10 inches long. Two somewhat smaller ejectors and non-circular cross sections, could be used to permit integration into the fuselage as shown in Figure 54.

An interesting possibility would be to also use the suction braking ejector in a reverse flow mode to supply air to the cushion during initial phases of the landing. Figure 56 illustrates this concept. A motor-operated bleed air valve would provide all degrees of operation from cushion borne to maximum braking. As discussed, in the air supply section, a supply of air directly to the cushion would increase the total amount of air that could be provided with a given amount of engine bleed. Such a concept would eliminate the need for the brake ejector valve (Figure 54) which would be required to prevent leakage from the cushion in the non-braking mode. It could also eliminate the need for the trim port valves, whose function is to reduce flow from the trunk to the cushion when in the braking mode.

(a) Suction-Braking Model Tests

Figure 57 shows a schematic of the Bell Aerospace suction-braking model and Figure 58 shows a test in which a static force equivalent to more than 2g was developed. Two methods of developing suction were tested: (a) Recirculation of air from the cushion back to the inlet of the fan, with the normal inlet to the fan partially or fully closed. (b) An ejector to evacuate the cushion with the fan used only to pressurize the trunk.

Figure 59 presents some of the results from this model. Braking force is plotted against cushion pressure. With a suction pressure of 6 inches of water (3 times the normal, positive, static cushion pressure of 2 inches of H_2O or 0.072 psig), a braking force equivalent to a 2g deceleration was measured. With a 10-inch suction, the force exceeded the 100-lb capacity of the spring scale used to measure the forces. When the fan was used to both pressurize the trunk and to evacuate the cushion, the maximum force attainable was slightly under 1g. The limiting factor was the maximum pressure rise that the fan could provide without stalling. Tests results correlated very well with predictions similar to those for the 147G, shown in Figure 55.

Although not shown in Figure 59, a force of approximately 2g was measured with a 1/2-inch diameter hollow tube placed under one side trunk to partially vent the cushion. This is equivalent to a 2-inch hollow log on a 2,000-lb aircraft. A force of 2g was also measured with the trunk orifices open so, prior to application of the suction, the model was supported on its cushion. This indicates that, if sufficient suction air flow is available, a large deceleration can be achieved without reducing flow from the trunk.

c. Tread

Whether or not a braking system is provided to supplement the friction between the trunk and the landing surface, a wear resistant material must be used to protect portions of the trunk near

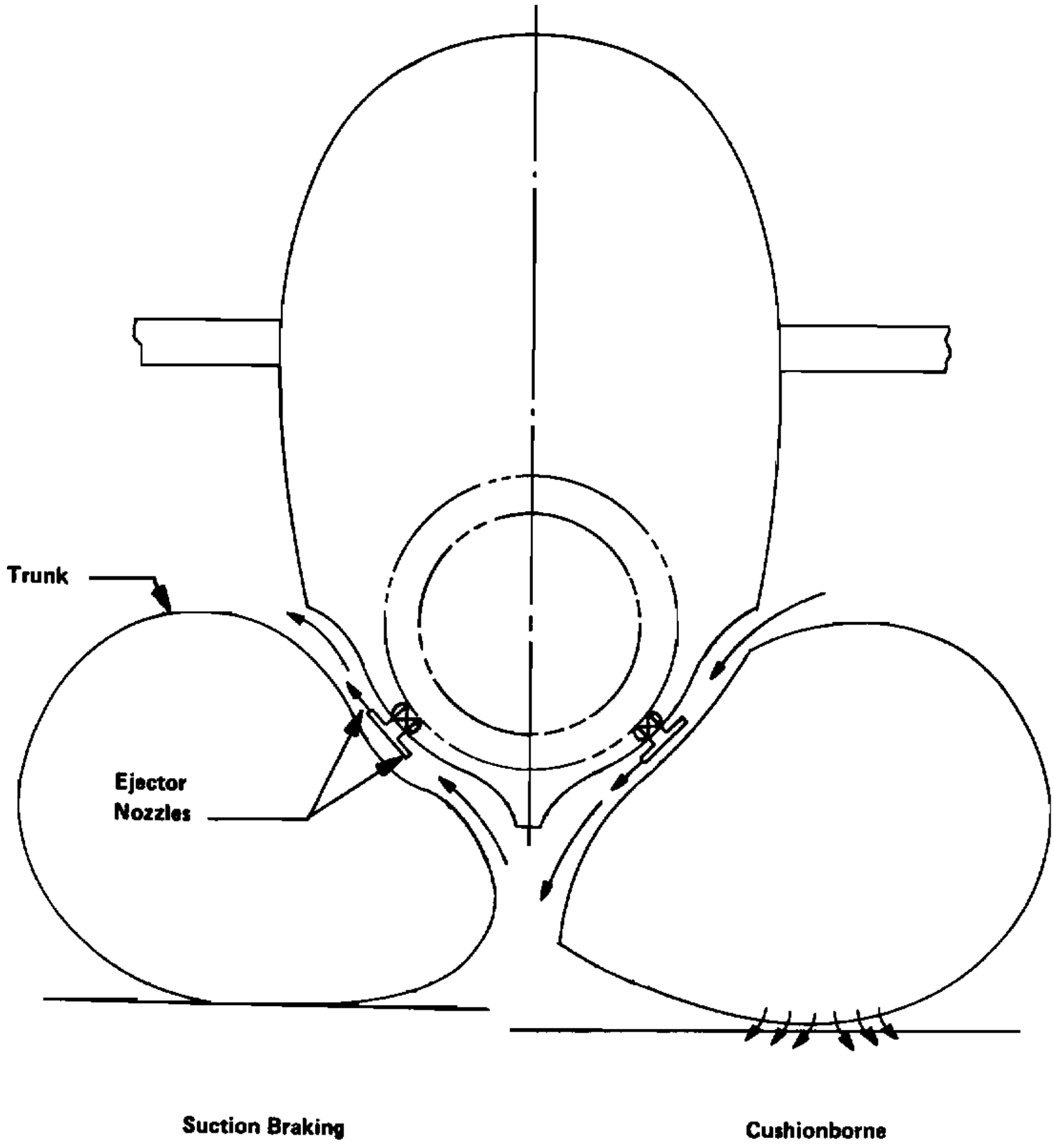


Figure 56. Combined Cushion Flow and Suction Braking Concept

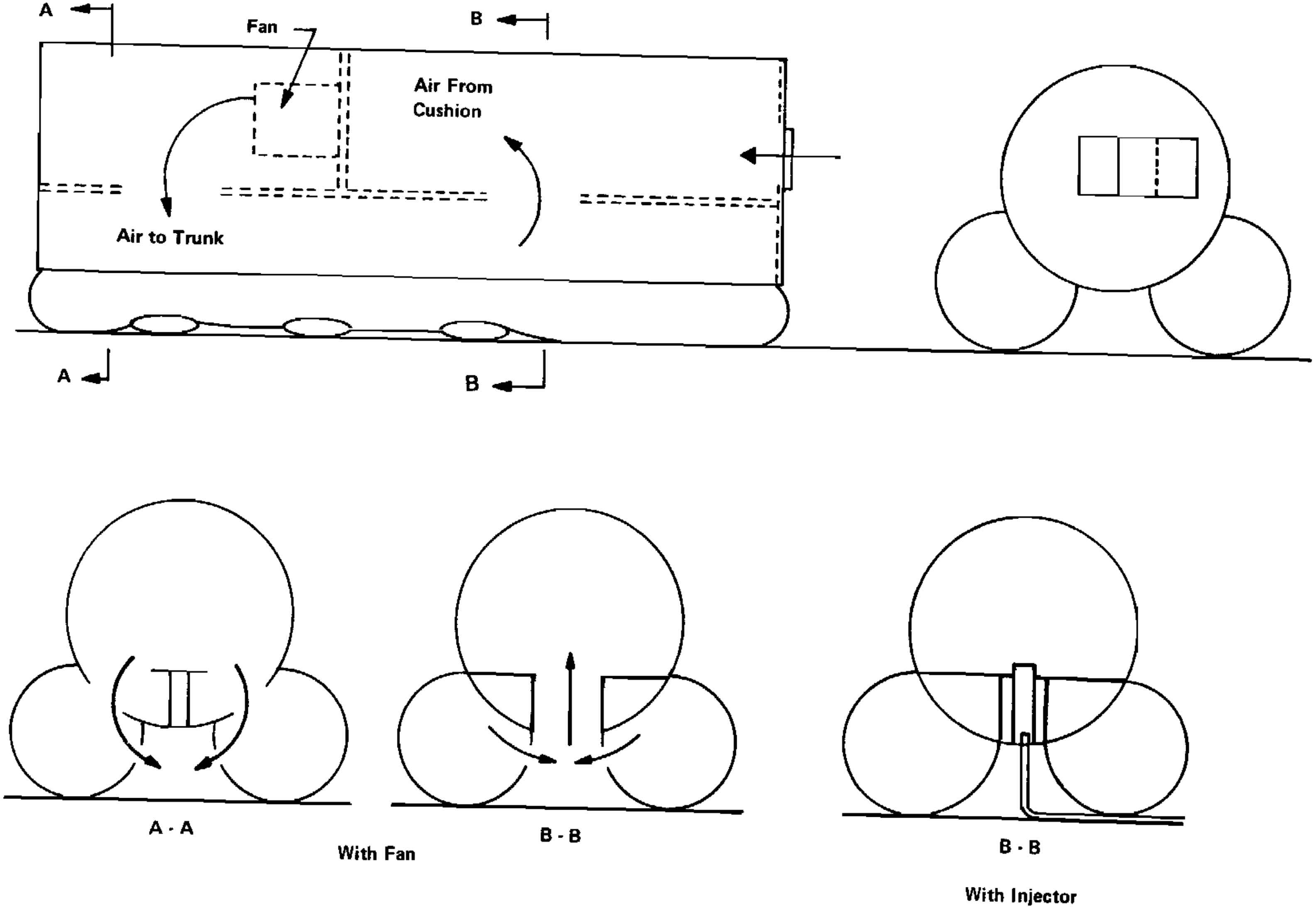


Figure 57. Schematic of Suction Braking Model

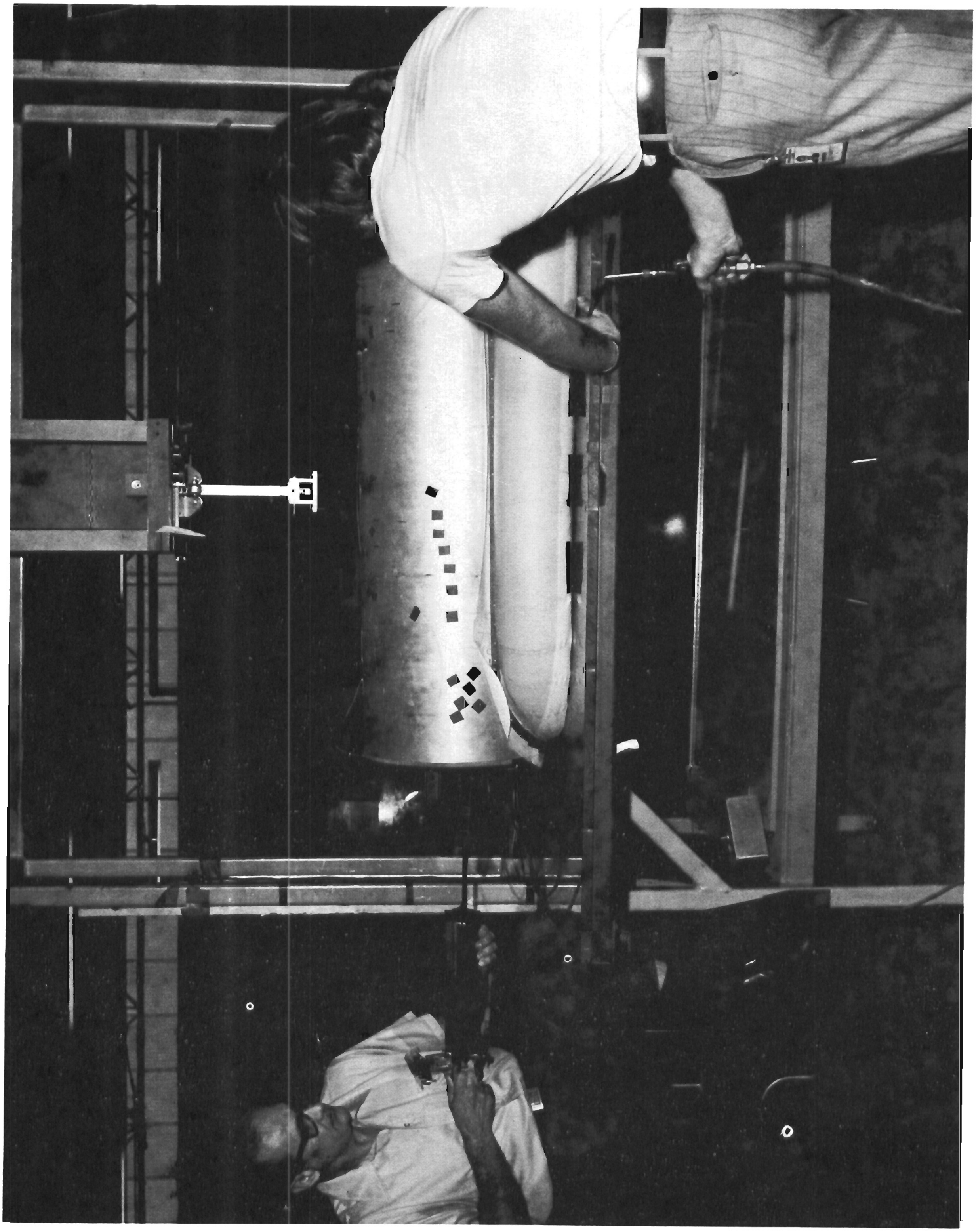


Figure 58. Test of Suction Braking Model

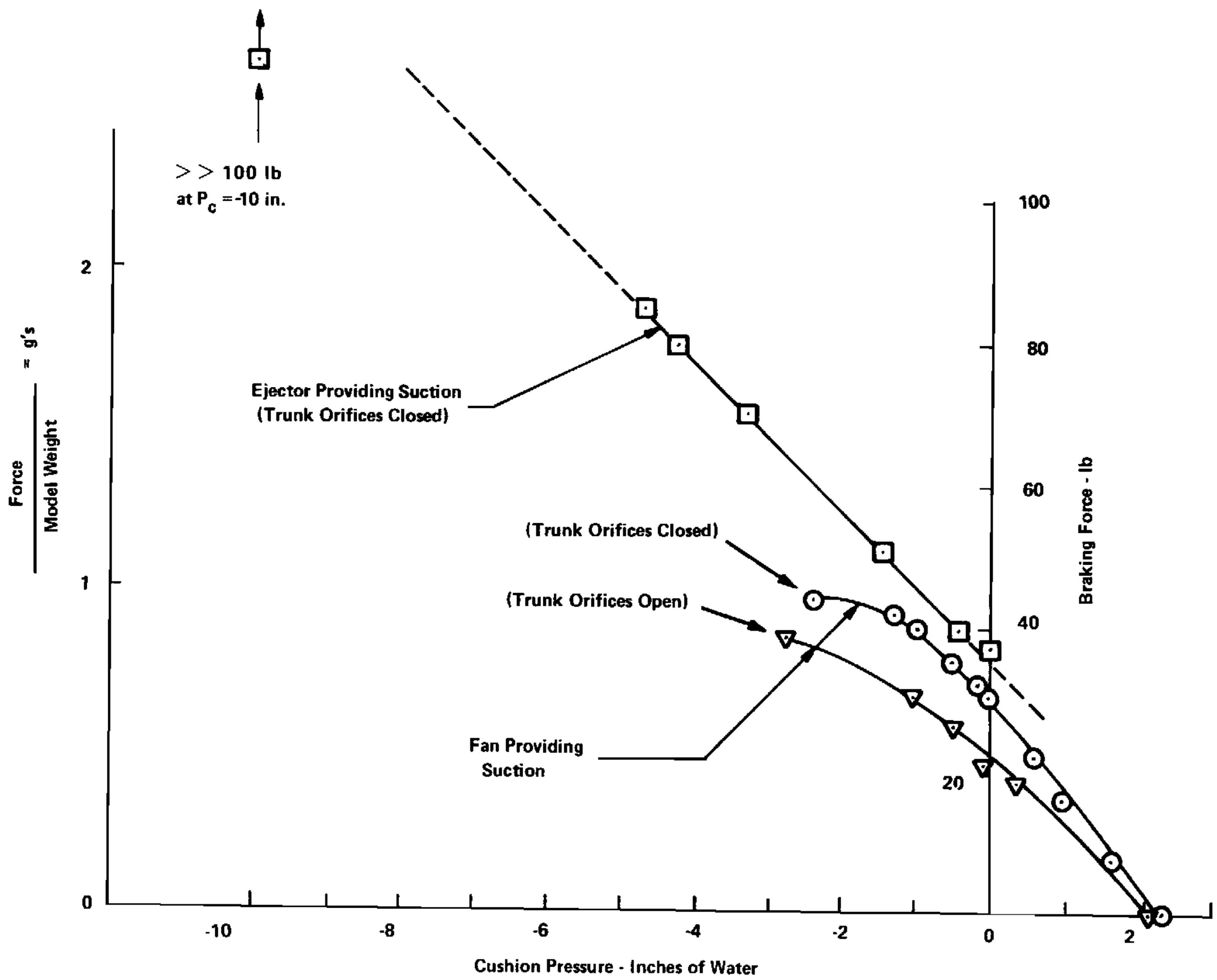


Figure 59. Suction Braking Model Test Results

the ground tangent. Bell has evaluated a number of elastomeric tread materials for ACLS brake tread applications.

On a concrete surface, a Butyl H.T. material specially compounded by Bell for such applications had a wear of less than 0.1 lb per 10^6 ft-lb of energy dissipated when tested with a bearing pressure of 6.5 psi or 935 lb/ft^2. At 9.6 psi or 1380 lb/ft^2 the wear increased to 0.14 lb per 10^6 ft-lb. These data showed the tread weight loss per million ft-lb of energy to be proportional to tread bearing pressure.

The data showed a rapid increase in wear when the rate of energy input exceeded 120,000 ft-lb/sec per ft^2. With the above bearing pressures, this occurred at velocities of 50 to 60 knots.

On the 147G ACLS, trunk pressure will be in the 200 to 250 lb/ft^2 range except for a fraction of a second during the landing transient, when it will be allowed to increase to 500 lb/ft^2 Even at a velocity of 150 knots, with a friction coefficient of 1.3 (the maximum measured for these materials on concrete), and a pressure of 250 lb/ft^2, the rate of energy dissipation for the 147G tread will only be 82,000 ft-lb/sec per ft^2. This is well below the critical value of 120,000 ft-lb/sec per ft^2, and wear of less than 0.1 lb per 10^6 ft-lb of energy dissipation is expected.

Figure 52 shows that the kinetic energy of the 147G at landing will be about 2 x 10^6 ft-lb. Thus, if all of the energy is dissipated by the tread, tread weight loss will be about 0.2 lb per landing on concrete. On less abrasive surfaces wear will be less.

This indicates that ideally a 4 lb tread would be adequate for 20 landings. Four lb of tread distributed over the 11.5 ft^2 of trunk required to support a 2300 lb vehicle if cushion pressure is reduced to zero would give a tread thickness of about 0.05 inch. Although this might give adequate wear protection to the 11.5 ft^2 area, the protected area is not considered adequate. (A 6-inch wide strip along the ground tangent would give an area of 11 ft^2.) To protect additional areas of the trunk that may contact the ground during the landing impact, when the vehicle rolls, and (for suction braking cases) when down loads are greater than one g, an area from the centerline to at least 8 inches outboard of the ground tangent plus additional areas on the front and rear trunks must be protected. This gives a total tread area about 46 ft^2. An 0.05 inch thick tread over this entire area would weigh about 16 lb.

Temperature of the tread must also be considered. Reference (8) shows temperatures of 220 to 260°F through the outer half of an 0.52 inch thick tread at the end of a test that dissipated 386,000 ft-lb per ft^2 of tread. If 2 x 10^6 ft-lb of 147G energy are dissipated by 11.5 ft^2 of tread, the energy per sq ft will be less than half of that during the above test. Thus, a tread thickness of the order of 1/4 inch on a 11.5 ft^2 area will be sufficient to keep temperatures at the trunk interface in the 220 to 260° range. Thickness can be tapered to 0.05 inch at the edges of the tread because edge areas will have only limited contact with the ground. This will add an additional 16 lb to the previous 16 lb for a total tread weight of 32 lb.

This weight is probably conservative. It is also a large percentage of the estimated total ACLS weights of 60 to 130 lb (see Section III.1, Weights). Further testing of present tread and trunk materials will probably show that it can be reduced. On the basis of presently available data, tread/trunk interface temperatures rather than tread wear establish required tread weight.

The continuous tread sheet will be attached to the trunk with velcro plus 20 to 25 mechanical fasteners along the edge of the tread. It is predicted that the tread will have a life of 20 landings on concrete; more on grass, dirt, etc. When replacement is required, it can be accomplished by two men in less than an hour.

The continuous tread concept discussed above can only be applied to an inelastic trunk, because the low elongations of the tread material prevent it from elongating along with an elastic trunk when the trunk is inflated. Figures 60 and 61 show two strake type tread concepts that could be applied to elastic trunks. By using localized strips of tread, the elastic trunk is free to extend and retract.

Both of these concepts will require more fasteners than the continuous tread concept for the inelastic trunk. Bearing pressure are 2 to 4 times the pressures for the continuous tread; hence, wear rates will be higher.

The strakes would be used only on the side trunks where they would be aligned with the airstream. Air lubrication would be used to limit wear on the front and rear trunks.

Aerodynamic drag due to the tread strips should be low, especially for the Figure 60 concept which, on an elastic trunk, retracts to a corrugated surface aligned with the airstream.

Both strake concepts provide longer thermal paths from the surface to the trunk than does the 1/4 inch thick continuous tread. Because trunk thermal limits dictated tread weight for the continuous tread concept, these strake concepts with lower heat transfer to the trunk have a potential for lower tread weight. Estimated weight of the Figure 60 concept, including attachments, is 12 lb versus 32 lb for the continuous tread. Despite the large weight penalty, the continuous tread on an inelastic trunk is being recommended for the demonstration vehicle. This concept is mechanically simpler, provides many more flights without refurbishment, and provides better trunk protection from mechanical damage.

d. Ground Tracks

Section II.5.b discussed slideout distances and the ability to vary slideout distances with an ACLS. This section discusses techniques for maintaining the desired ground track after touchdown.

The ACLS is inherently a good crosswind landing gear. Because of its lack of side force due to yaw, the usual landing technique in a crosswind is with wings level and $\beta = 0$. As velocity decreases after touchdown, the aircraft is turned into the wind, with yaw and/or thrust perturbations to maintain a balance of forces perpendicular to the runway centerline as shown in Figure 62. If a small thrust is maintained during the slideout, the yaw required for this sideforce balance will be less than if thrust is zero.

Figure 63 shows a ground track computed for the 150K maximum touchdown speed selected for ACLS design. In this example, with a 30 knot crosswind, β was maintained equal to zero and thrust was kept constant at 300 lb. A 1/2g deceleration due to ACLS friction was assumed. With this technique the aircraft came to rest in 2,280 ft, yawed 90 degrees into the wind. The ground track deviated 55 ft from the runway centerline. This lateral offset was caused by the ever increasing component of thrust minus drag as drag decreased while yaw was increased to maintain $\beta = 0$.

If the heading at touchdown was misaligned $\pm 1/2°$, the total offsets would have been approximately 75 ft or 35 ft. These offsets would be acceptable if touchdown were on the centerline of a 150 ft wide strip.

Note:

A Strake tread is recommended only for use with elastic trunk for takeoff capability option.

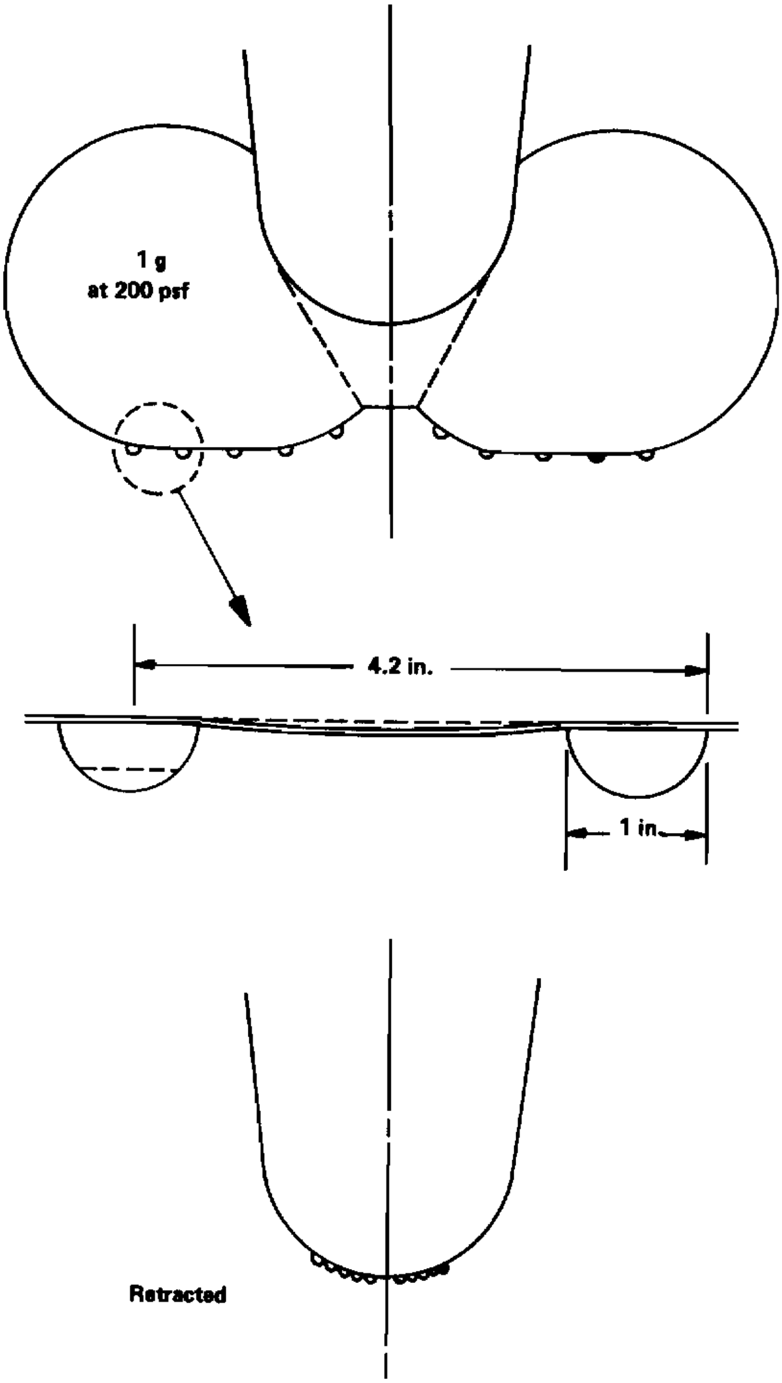


Figure 60. Tread Strake Concept 1

Note:
A strake tread is recommended only for use with elastic trunk for takeoff capability option.

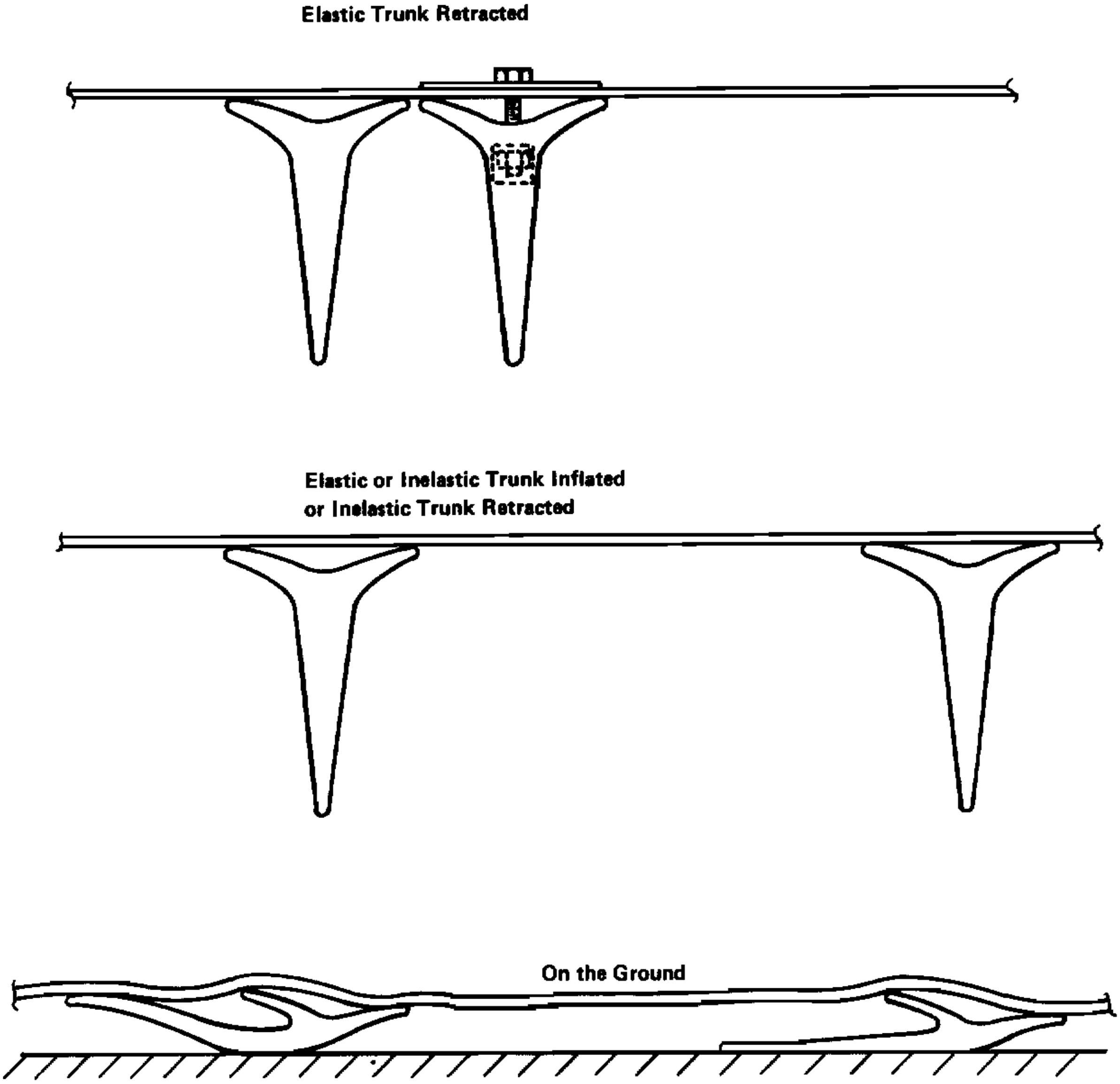


Figure 61. Tread Strake Concept 2

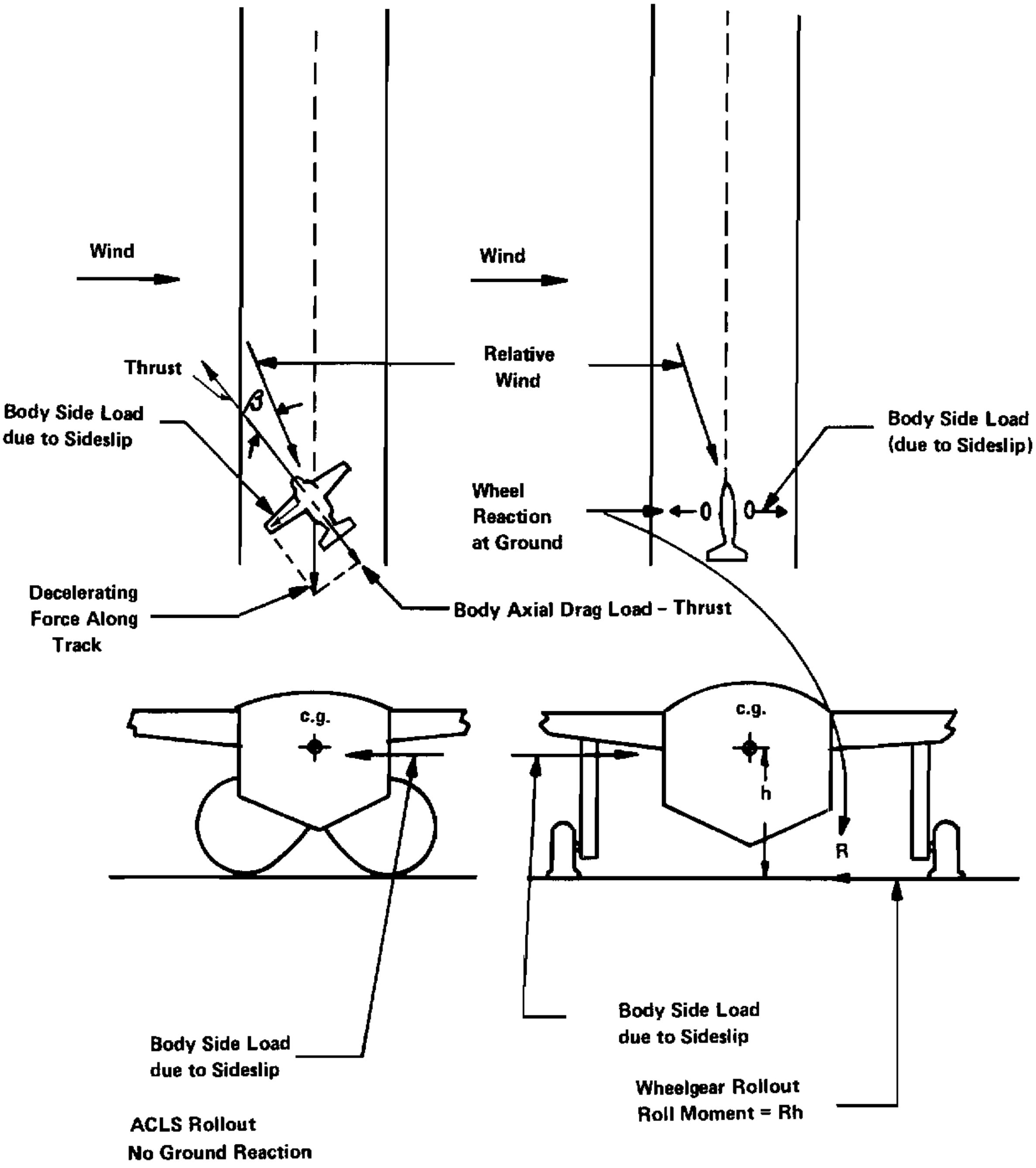
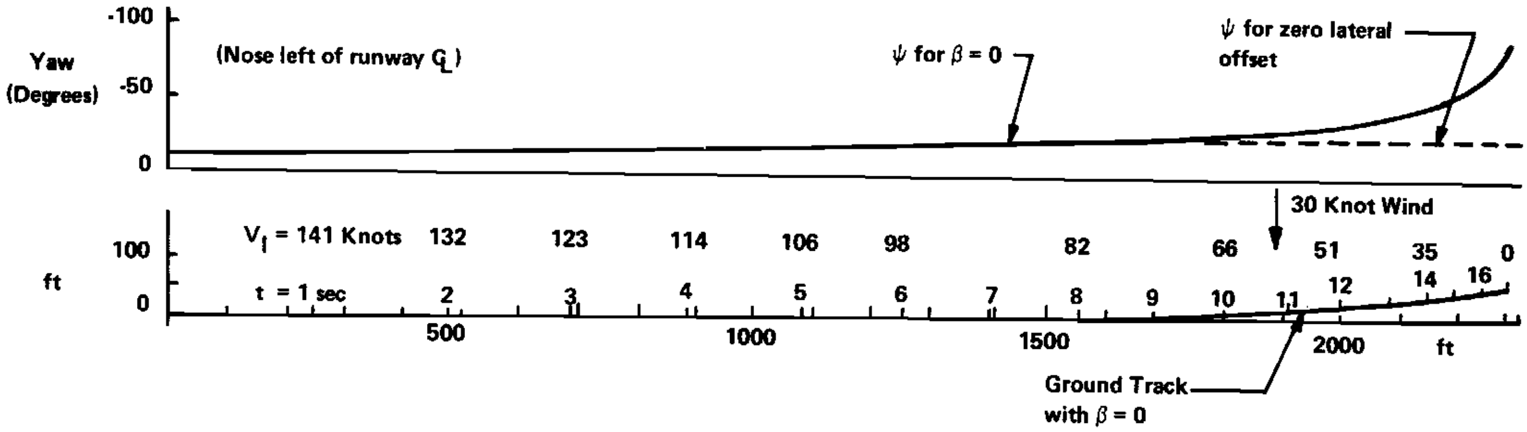


Figure 62. Crosswind Landing Rollout Comparison

Vehicle Aligned with Relative Wind ($\beta = 0$); $\frac{1}{2}$ g Braking
30 knot Crosswind
Initial Velocity: Inertial = 150 knots; Relative to Air = 153 knots
Thrust = 300 lb, Lift = 0



Note: Reducing thrust and/or limiting ψ (dashed curve) as vehicle decelerates will reduce lateral offset to << 50 ft.

Figure 63. Ground Track and Yaw Angle

The preceding example, serves to illustrate a case where yaw was increased to maintain $\beta = 0$ in a strong crosswind. However, Figure 64 shows that maintaining $\beta = 0$ to zero velocity is not practical when high decelerations are used. This is because the ACLS does not provide sufficient roll stiffness to prevent wing tip contact with combinations of high yaw relative to the ground track and high decelerations. For example, that figure shows that a 90 degree yaw relative to the runway ($\beta = 0$ at velocity near zero) a deceleration of 0.3g will cause wing tip contact.

Therefore, although a very acceptable lateral deviation in the above example could have been achieved by reducing thrust, the technique of maintaining $\beta = 0$ throughout the slideout in a crosswind is not recommended for the 147G ACLS with its high deceleration capability.

To give a zero summation of forces perpendicular to the runway as the velocity approaches zero, a yaw of about 23 degrees would be required if thrust is maintained at 300 lb. At higher speeds, yaw angles less than those shown in Figure 63 for $\beta = 0$, would be required. The dashed curve of Figure 63 is the estimated ψ variation required to maintain the 147G on the centerline.

The situation with a large deceleration (high ACLS friction) is quite different from an "on the cushion" case, because the friction prevents the aircraft from being blown downwind when aerodynamic control is lost. Thus, requirements for directional and thrust control are less severe than for cases with a slideout on a cushion. Also as decelerations are increased, the lateral offsets due to side winds or less than perfect directional control become less because of the reduced time for these forces to act. It appears that if decelerations of 1/2g or more are used, that aerodynamic controls will be sufficient to maintain an acceptable ground track without use of differential braking. The omission of a differential braking system would be a desirable simplification. Further analysis, simulations, and model tests are recommended to determine ground track control capability with aerodynamic control only.

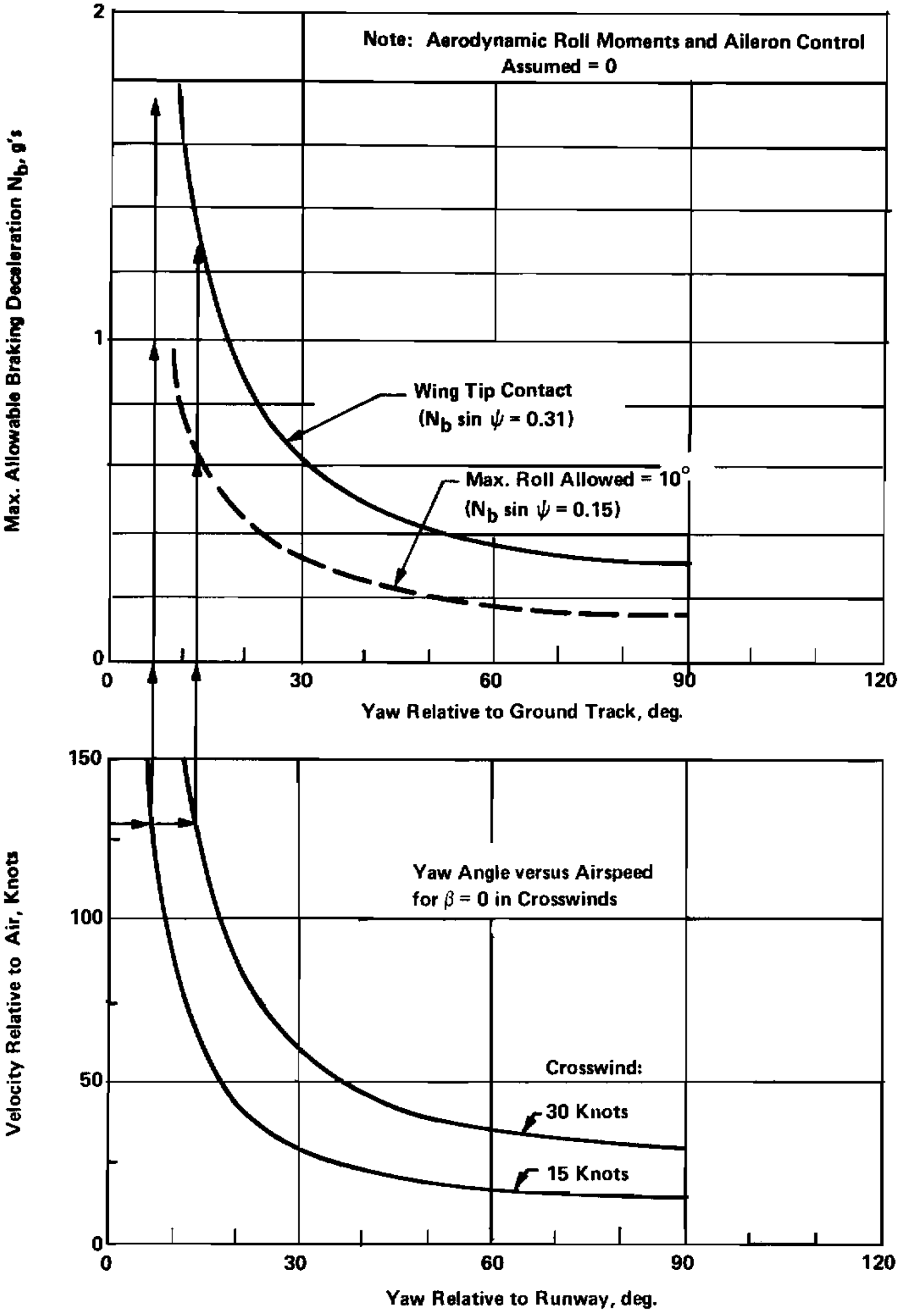


Figure 64. Maximum Allowable Braking Deceleration versus Yaw Angle

6. STABILITY

The pitch stiffness of the 147G ACLS is estimated to be 1550 ft-lb/deg. The static attitude on the cushion will be about 1.8 degrees nose up. At 1/2 g deceleration the attitude will be approximately 1/2 degree nose down, and at 1 g deceleration it will be about 2.6 degrees nose down. Because of the pitch moment provided by cushion cp ahead of the cg, transient nose down attitudes are estimated to be less than 5 degrees. Thus, pitch stability is excellent and no pitch problems are anticipated.

An ACLS, with or without air flow, is neutrally stable in yaw. This has been confirmed by model slideout tests. Aerodynamic and/or differential braking control must be used if a yaw attitude change is required to control the ground track. Longitudinal tread patterns or strakes on rear portions of the trunk could provide some directional stability (tendency to align with the inertial velocity vector) on some unprepared sites, but they would have little or no effect on hard surfaces. When effective, they would oppose yaw moments due to the rudder and, therefore, do not seem to offer any advantage for directional stability or control.

Roll stability of the ACLS is low; estimated 112 ft-lb/deg. Several aircraft and drones have landed on narrow metal skids and a single air bag, showing that a large roll stability is not required, at least if crosswinds are low.

With crosswinds, the roll situation is somewhat comparable to a parachute landing on a decelerator bag; a landing at 150 knots in a 30 knot crosswind with $\beta = 0$ gives a lateral velocity component of nearly 30 ft/sec. However, there are two significant differences between parachute/air bag landings and ACLS landings. The most significant is the lower friction (reduced side load) due to ACLS air lubrication and the cushion pressure. A significant cushion pressure is developed on hard landings due to the dash pot effect, even if a low ACLS air flow is provided. Also an ACLS will normally be landed on an area free of major obstacles. Aerodynamic roll damping and aileron control also limit roll. Therefore, for comparable lateral velocity components, the ACLS has less tendency to roll over than does a decelerator air bag system.

Roll stability is still one of the critical design factors for an ACLS for the 147G because of its narrow fuselage. It will probably be limited to crosswinds of 30 knots or less on smooth landing sites and lower values on unprepared sites with surface irregularities.

Inflated sausage shaped wing tip skids could be provided to ensure safe landings in crosswinds and/or on rough surfaces. These should not be required if the above limitations are observed. However, they could extend operational limits and provide assurance against pilot/controller errors. Such skids need not have air flow. Air for inflation could be via 1/2 inch lines from the trunk inflation system. They could be of inelastic coated fabric, stowed in a volume of less than 30 in.^{3} per wing tip. They could be automatically deployed by their internal pressure via a spring loaded door, when the trunk is inflated.

Simple dynamic model tests are recommended to further define limits on yaw attitudes and surface conditions.

7. WATER LANDINGS, FLOTATION, PARKING

The LA-4 has successfully demonstrated landing and taking off from water. The 1/10 scale CC-115 ACLS model has also landed successfully on water with and without ACLS air flow. Both of these configurations had fixed wing floats to provide lateral stability.

The 147G ACLS will be laterally unstable in the water, so wing floats will also be required for it. Fixed floats are not desirable, but small inflatable floats could easily be provided (see Section 2.6). These would be required only at low speeds after aerodynamic roll control became ineffective.

Based on LA-4 and CC-115 experience, water landings with the 147G would have to be limited to relatively calm water; waves or chop less than 1 ft high. Thus, water landing operations would generally be limited to lakes, rivers, or harbors on calm days.

Flotation, after shutdown of the ACLS air supply, can be provided by very light weight (2 to 3 lb) air tight bladders inside the trunk. Inflation can be from engine bleed or a small air bottle. Such bladders can also support the vehicle on land after air supply shutdown. The need for such a parking bladder on the 147G is questionable, because the vehicle is designed to rest on its fuselage and a wing tip.

8. AERODYNAMICS

Effects of the ACLS on basic aerodynamic characteristics were estimated for the modified (short fuselage) Ryan Model 147G. The ACLS increments were evaluated with respect to estimated aero coefficients for this vehicle supplied by the Air Force. Subsequent to these estimates, the Air Force decided to retain the long fuselage. Although ACLS aerodynamic effects were not reestimated for this configuration, the ACLS increments presented here are not expected to be significantly different for that configuration.

With the ACLS trunk smoothly retracted against the fuselage, it is estimated that the drag coefficient at high speeds will be increased about 3.5%, and the maximum velocity will be decreased by less than 2% (approximately 10 knots). The major contributors to the increased drag are the trunk stowage toggles of Figure 28. These toggles could be recessed into the side of the fuselage to reduce their drag. Then the effect of the stowed ACLS on maximum velocity would be insignificant. The external mounting is recommended for a demonstration vehicle to minimize cost.

With the trunk inflated, the zero lift drag will be approximately doubled. Wind tunnel tests of other ACLS configurations have shown that the variation of ACLS drag with angle of attack is very small and the ACLS will not have a significant effect on lift. Figure 65 presents the C_L versus α curve supplied by the Air Force and used for landing calculations. Figure 66 shows the estimated drag polar without the ACLS and with the trunk inflated.

Figure 67 illustrates the effect of the inflated ACLS trunk on the pitching moment of the 147G vehicle. The drag vector of the trunk was estimated to result in a pitching moment increment of $\Delta C_{m_0} = -0.023$. The change in pitching moment versus pitch attitude was estimated using the method developed by Multhopp (Reference 10), resulting in a pitching moment slope increase of $\Delta C_{m_\alpha} = 0.0144$. Since the ACLS system causes little or no change in lift, the pitching moment slope may be translated into an increment in static margin of $\Delta(\frac{dC_m}{dC_L}) = 0.193$. This change is also shown in Figure 67.

Comparison of the above estimates to unpublished wind tunnel test results from a model of the LTV F-8 with an ACLS indicates that the above estimate of $\Delta C_{m_\alpha} = 0.0144$ is conservative. Based on the tests of the F-8/ACLS, which has a trunk very similar to that of the Model 147G, it is estimated that the $\Delta(\frac{dC_m}{dC_L})$ will be approximately 40% of that predicted by Multhopp's method.

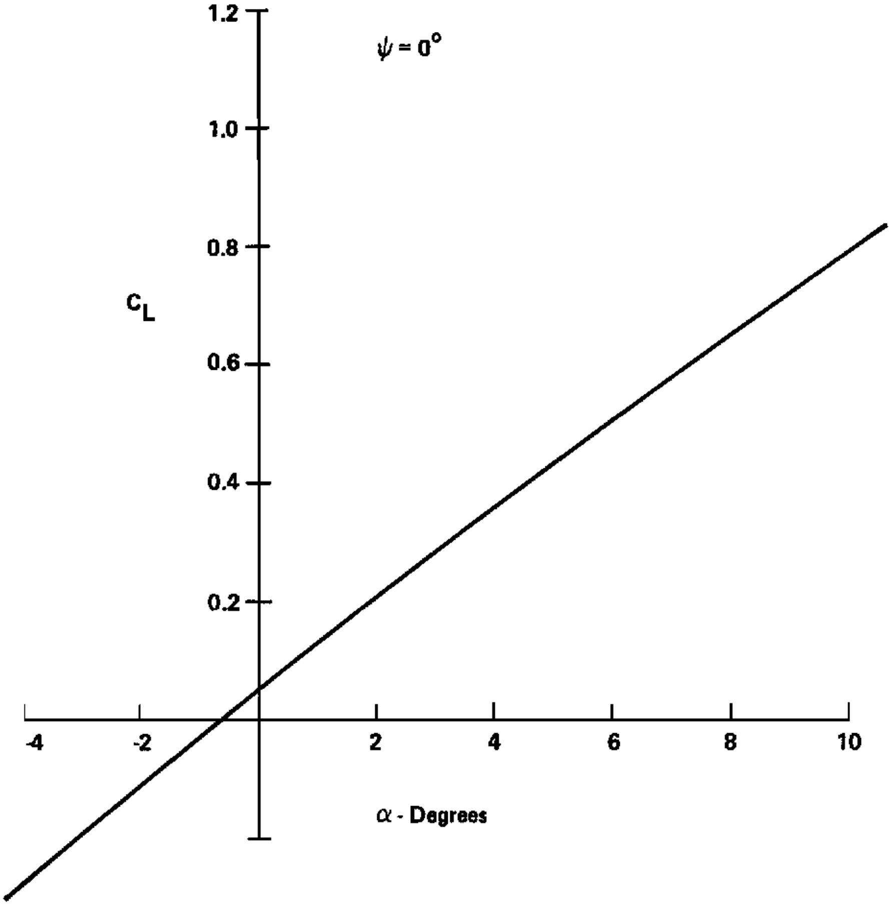


Figure 65. C_L versus α for Short Fuselage 147G

Sufficient elevator travel is available (34 degrees total) to trim at maximum speed and at an approach velocity less than 150 knots without the trunk inflated as well as at α greater than 10 degrees with the trunk inflated. An up elevator increment of about 20 degrees will be required to increase α by 6 degrees, while decreasing thrust, to reduce velocity from 500 to 150 knots at sea level. As the trunk is inflated, the trunk produces a nose up moment and a downward elevator increment of about 9 degrees will be required to maintain a constant altitude and air speed as thrust is increased approximately 150 lb to counter the ACLS drag.

Estimates of the effect of the inflated trunk on $C_{n\beta}$ resulted in increments of -0.0029 to -0.0037 relative to an estimated value of +0.0015 for the short fuselage 147G without the engine pod extension or trunk. Based on wind tunnel data for an F-8 with similar trunk geometry, but without added area comparable to the 147G engine pod extension aft of the c.g., even the lower estimate of the increment seems high.

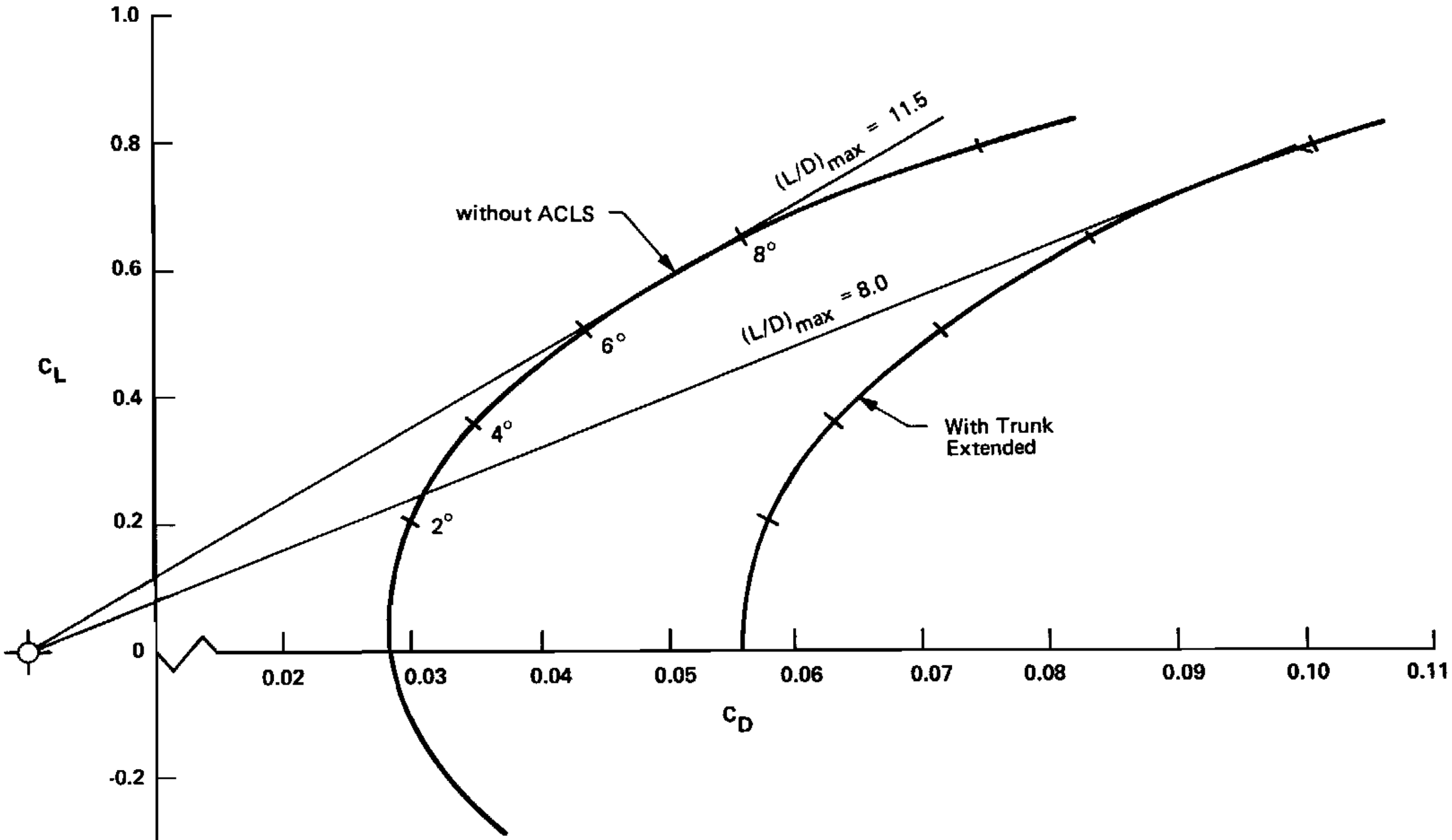


Figure 66. Drag Polar with and without ACLS

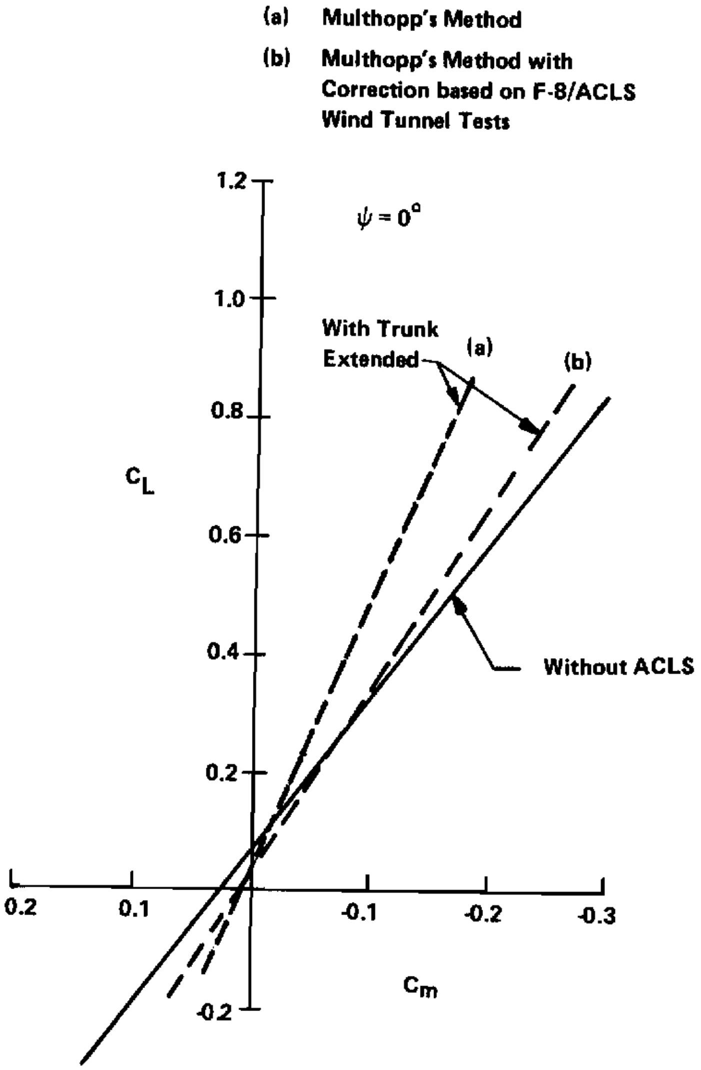


Figure 67. Pitching Moment Coefficient with and without ACLS

With the "long fuselage" 147G presently planned for the REPEX program, estimated values of $C_{n\beta}$ without the ACLS are 0.0022 and 0.0028 for c.g.'s at 25 and 50% MAC. Even with this configuration, the present design of the inflated trunk may result in poor directional stability. Larger stabilizer end plates are available for use with external stores which are also destabilizing. They could be used to give the required directional stability with the present trunk design. However, because of uncertainties in estimates of moments due to the trunk, wind tunnels tests prior to finalization of the ACLS design, are recommended to determine ACLS effects on both pitch and yaw moments. If necessary, ACLS moment increments in both axes could be decreased by decreasing the depth of the front of the trunk, moving the front attachment aft and decreasing the radius of the trunk cross-section at forward portions of the trunk. Such changes will reduce energy absorption at low altitudes, but for the present design the allowable sink rates are considerably in excess of expected sink rates at touchdown.

9. LANDING GUIDANCE AND CONTROL

Command guidance system functions include tracking the vehicle, generating and transmitting commands, and transmitting and displaying flight data.

The salient characteristics of the existing radio command guidance systems for drones are summarized in Table I.

The abbreviated nomenclature for the systems listed are as follows:

ITCS:	Integrated Target Control System
MCGS:	Microwave Command Guidance System
VTCS:	Vega Target Control System
MTTS:	Mobile Target Tracking System
RMS:	Range Measurement System

All of the existing systems (1 through 5 in Table I) are similar in that they utilize range and angle tracking to determine vehicle position. Such tracking is performed either as an integral operation resulting from transponder interrogation or by a tracking radar. The Vega Precision, Inc. system can operate in either mode. It will be used in the REPEX program. The MCGS system has been used for other Ryan drones.

While the General Dynamics system is not generally considered a drone control system, it has the requisite capabilities. It is included to represent the class of systems currently in test or development which utilize trilateration techniques for vehicle location. Trilateration can provide tracking accuracies that are as good as or better than precision radars. Other trilateration systems include the CLASS and ACMR (Air Combat Maneuvering Range) systems by Cubic and a developmental system by IBM, Owego, New York.

All of the systems provide proportional telemetry data; however, neither the EPSCO nor the operational Univac system provide proportional commands. One MCGS set was recently modified for a feasibility demonstration program to provide four proportional command channels of 7 bits each at an update rate of 35 per second (unfiltered) along with 62 discrete commands.

Three of the command guidance systems have small portable stations which can be set along side a runway for visual control. These include the ITCS Foxcart, MCGS Backup Director, and the VTCS portable tracking unit. Figure 68 shows the MCGS Backup Director Station which has been used for landing of unmanned low speed aircraft.

In addition to the command guidance system, the guidance and control system includes the vehicle, AFCS (Automatic Flight Control System), the control station (specifically the control/display console), and the video system (including the data link), when one is used. While the equipment modifications required for landing a drone will depend on the specific equipments to be used, certain comments can be made in general and others with respect to available equipments. The basic reasons for modifying any of the equipments are to either (1) obtain proportional control, (2) provide a new control mode or improve controllability, (3) achieve a flight condition which is not normally available, or (4) provide landing or arresting gear.

TABLE I
COMMAND GUIDANCE SYSTEMS

Equipment Characteristics	1 Motorola ITCS AN/USW-3 (1)	2 Univac MCGS AN/UPQ-3 (2)	3 Vega VTCS (3)	4 EPSCO MTTS	5 Babcock BCRD-31	6 General Dynamics RMS 2
Frequency	C-Band	X-Band	C-Band or Radar	UHF Command S-Band TM	UHF Command L-Band TM	L-Band
Tracking Technique	Range and Angle, Integral	Range and Angle, Integral	Range and Angle, Integral or Radar	Range and Angle Integral	Radar	Trilateration Integral
Track Accuracy Angle	0.94 mil Azim 1.4 mil Elev	<1.5 mil	Integral: 1 mil	0.5 mil Azim 3 mil Elev		
Range	34 yds	20 yds	20 yds	10 yds		3 meters
Data Modulation	Pulse Code	Pulse Code	Pulse Position	Pulse Code	Pulse Code	Pulse Code
Data Rate (bps)	25,600	1425	5000		4800	2×10^5
Commands:						
Proportional	to 13	–	8	–	4	8
Discrete	74	31	to 64	40	32	>32
Update Rate/sec	45 (16)	35	>10	8	>10	>10
Resolution (bits)	up to 10	–	10	–	8	8
Telemetry:						
Proportional	15	8	8 to 32	8	8	>8
Discrete	>32	16	to 64	30	16	>16
Update Rate	45 (16)	35	5-20	8	>10	>10
Resolution (bits)	up to 10	6	10	9	6	8

NOTES:
(1) Data for TSW-10 Ground Station Controlling One Drone. Data for MSW-10 Foxcart (Runway Control) is in Parenthesis.
(2) Data for TPW-2 Ground Director. MPW-3 Backup Director has no Angle Track.
(3) Can Operate Through Tracking and Search Radars, such as FPS-16, FPQ-6, MSQ-51, SPS-5.

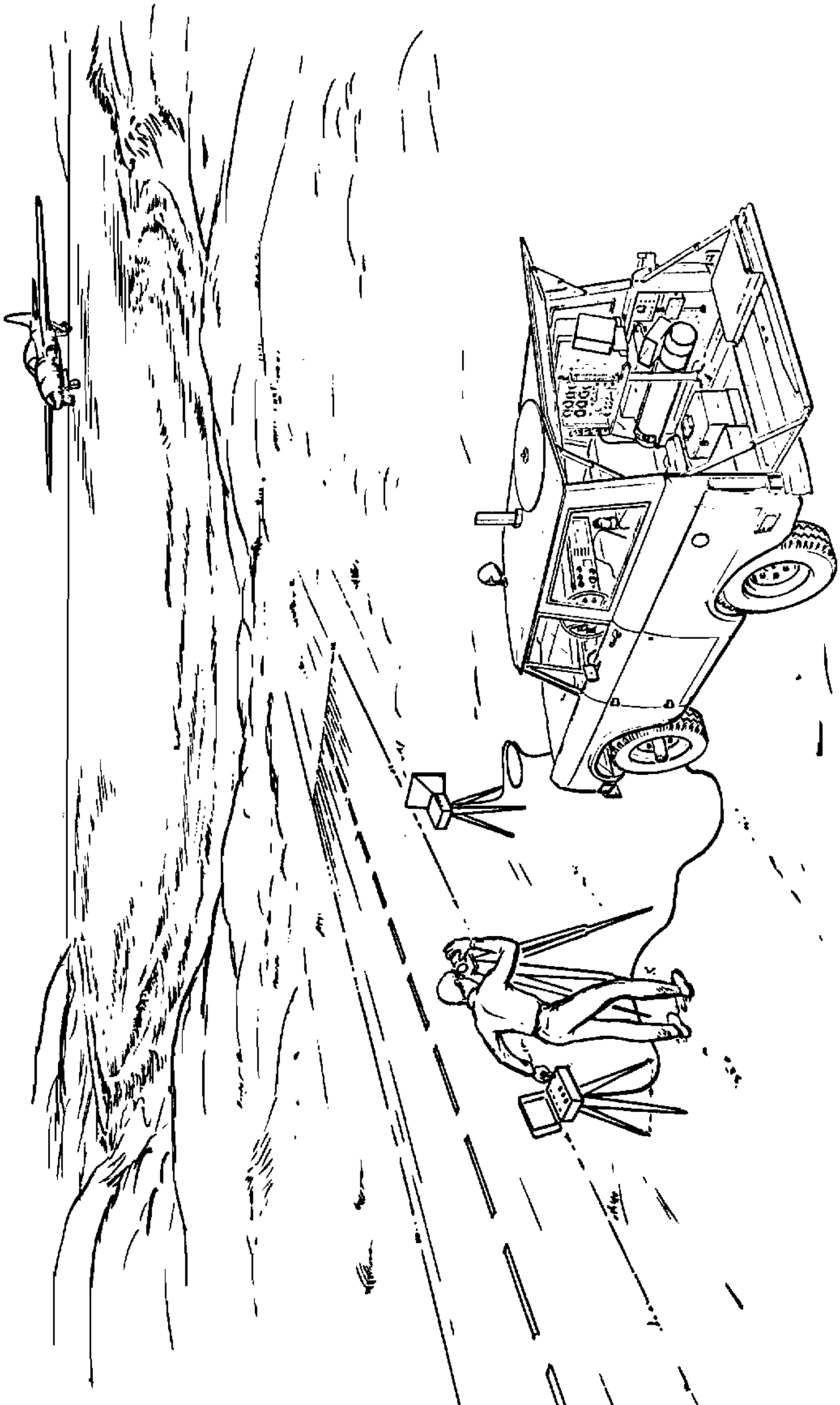


Figure 68. AN/MPW-3 Recovery Area Director Station

The capability of obtaining proportional control for the 147G lies primarily in the selection of the command guidance system. Neither MCGS, MTTS, or any target control systems provides proportional commands. The remainder of the guidance and control system operates with continuous, proportional data. As noted above, a recent modification to the MCGS provides proportional commands. The modification has been made to one control station with a second under way. Other proportional systems are available as is noted in the summary chart.

Part of the control station modifications for proportional control include changing the controls and displays. In particular, the manner of displaying data for current operations and their type is not sufficient for real time control of the drone during landing. Hence a new control and display will very likely be required. Even if completely automated landing is contemplated, control and data for backup control may be necessary.

While the AFCS of the Ryan 147G operates proportionally, it may not be capable of operating in a specific control mode desired for low speed approach control. The normal control modes include:

- Airspeed or Mach hold
- Altitude hold (radar or barometric)
- Attitude hold
- Heading hold

Two BQM 34A vehicles have been flown proportionally. In one the command parameters are pitch and roll attitude; in the other they are vertical velocity and roll attitude. Vertical velocity is not measured in the second case, it is derived by commanding altitude at a rate proportional to stick position. The vehicle follows the altitude command quickly enough to perform as if in a vertical velocity mode. However, the accuracy of such control would not be nearly as good as in a true vertical velocity mode which may be desirable for landing control. Modifications,albeit not difficult, would always be required to insert proportional commands into the AFCS. Such changes are being incorporated into the modified 147G for the REPEX program. All of the Teledyne Ryan operational drones currently accept only discrete commands.

Not all drone AFCS have three axes control. The majority have pitch and roll control with a small rudder tab providing yaw trim. Where yaw control via rudder inputs or yaw damping is required for landing, a third axis would be required. This modification has been or is being made on three types of such vehicles having originally two axis controls. This includes the 147G for the REPEX program.

Other vehicle changes could include adding speed brakes, spoilers, flaps, or other high lift devices to help slow the vehicle during the landing approach. Such changes are not considered necessary for ACLS demonstrations, although they would reduce slideout distances and may have advantages for some operational vehicles. Speed brakes are available on the BQM 34A series and are planned for the REPEX modified 147G. These are located on the parachute can.

None of the currently operational Ryan drones have proportional throttle control. The actuator can be set at four discrete positions. Some have additionally a limited capability to keep the throttle away from the discrete position. Further, drone engines respond quite sluggishly to commands in comparison to man-rated engines and have a high idle speed due to their inexpensive fuel control. A proportional throttle or airspeed command system could be achieved with relative ease and appears necessary for landing; however, only small improvements can be expected in throttle response without incurring considerable expense. The use of speed brakes helps solve this problem.

In planning for a change in recovery technique from the MARS (Mid Air Recovery System) to horizontal landing, there are two distinct aspects to be considered:

(a) Physical requirements and mechanical design of the landing gear, be it wheels, skids, or air cushion.

(b) Guidance and control requirements and system design to accomplish final approach and touchdown within the allowable constraints.

More stringent guidance and control requirements arise due to the change from simple navigation and rendezvous with the MARS helicopter. The return flight must be scheduled to a specific RPV base (with possible alternate field considerations) and handoff to a final approach and landing controller may be required. Following this, the landing controller must guide the RPV to the touchdown area within speed and sink rate tolerances of the airframe. The physical configuration and design of the landing gear will determine these touchdown limitations but hardly affects any other characteristic of the landing guidance requirement.

Control through final approach and landing requires guidance corrections which are determined from present position error and present velocity vector data. This determination may be effected by various means as illustrated in Figure 69.

It is important to note that while neither MARS or visual/TV approach and landing guidance offer any IFR capability, MARS does have the operational flexibility to seek out VFR conditions for rendezvous, beyond or above the local weather system. In lieu of this capability, instrumented approach and landing data may be provided so that IFR approaches can be conducted to touchdown either by adequate synthetic displays to the remote pilot or by automatic coupling. In general, existing command link radars or associated long range tracking radars cannot provide smooth and accurate position data through final approach and touchdown due to the severe multipath environment and probable line of sight obstructions between the radar/terminal site and the landing runway. Thus, a short range, runway based landing data instrumentation system is needed to meet an IFR requirement.

As indicated in Figure 69, this landing data could be obtained from a system such as ILS (augmented by a radar altimeter), from a trilateration (or multilateration) scheme, or from a precision tracking radar specifically installed for landing control. Such a radar is being considered by the Air Force Aeronautical Systems Division at WADC for use initially at Edwards AFB on RPV developmental programs. The system configuration is designed for air transportability and rapid deployment.

For the immediate purpose of demonstrating and evaluating the Air Cushion Landing System as applied to an RPV, fair weather operation under visual/manual guidance would be acceptable. Only if other programs had established the required guidance facility and procedures, would automatic landing or other IFR capability be justified for the ACLS demonstrations.

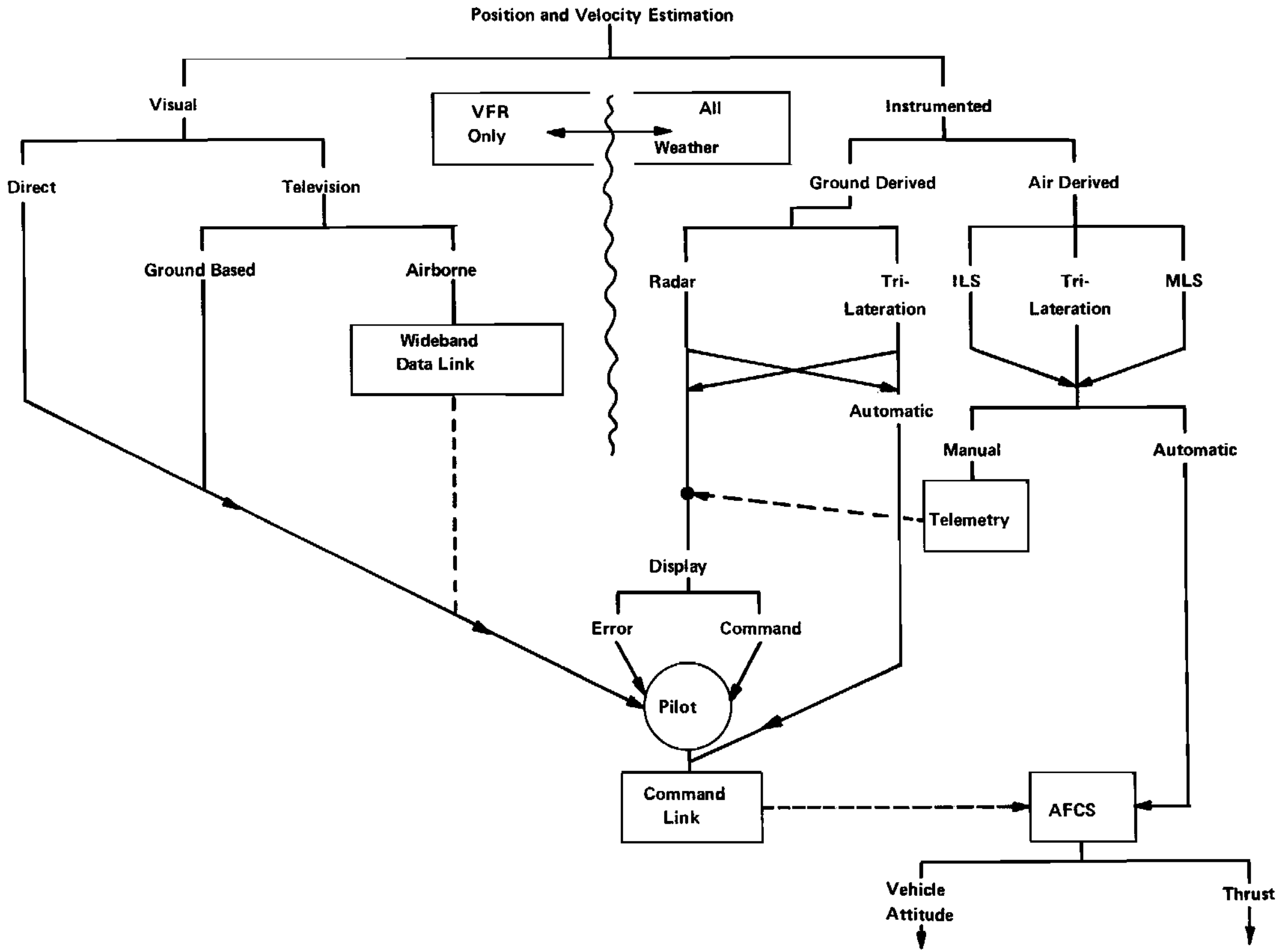


Figure 69. Landing Guidance Concepts

The command control system recommended for ACLS demonstrations as part of the REPEX program is the Vega pulse position modulated command data link, which has "add on" capability to many existing tracking radars. This system, with a FPS-16 radar, is planned for use in prelanding phases of the REPEX program.

The Vega 626C Portable Tracking Radar can provide the radar link where existing radar installations are unavailable. Although this radar, operating at C band, cannot provide the low angle, close in tracking accuracy necessary for "all weather" landing guidance, it can maintain the command link through a visual/manual landing. Should an automatic landing qualified radar be available at the REPEX RPV operating site, then the Vega interrogator coder and decoder can be readily interfaced with that radar and its cooperating transponder beacon to give fully automatic IFR operation.

The remote pilot's displays and controls used during mission phases prior to landing may require some additions or modifications for landing. Their location, near the landing strip or remote, must also be considered.

There is some evidence that landings of the 147G can be made with a minimum sophistication of displays and controls. For example, NASA at Edwards has remotely controlled a Hyper III vehicle to successful landings. NASA personnel have stated that this vehicle had an L/D_{max} of about 4½. Its approach was at 120 knots. Based on the above L/D, sink rate during approach must have been over 16 ft/sec. Touchdown was at about 80 knots and a sink rate of 5 ft/sec. The vehicle was talked into the approach via ground tracking as with the X-15. A pilot in a simulator type cockpit near the runway controlled the landing (Reference 9).

NASA has also landed a twin engine Comanche aircraft with the "pilot" in a control room over 5 miles from the landing site. Techniques were similar to those for the Hyper III except that a forward looking TV provided the only visual cues. The remote pilot landed the Comanche and taxied it back to the ramp. At least one airframe contractor has also used this technique with a light plane.

The above experiences indicate that for a low cost demonstration program whose primary objective is to demonstrate only minimum capabilities of an ACLS, very few modifications of the planned airborne and ground based systems for the 147G REPEX program will be required. If near zero, crosswind restrictions are imposed and landings are on the Edwards lake bed, it may even be feasible to land other 147G or BQM 34A drones without rudder control or proportional commands. This would be accomplished by varying the commanded altitude at a constant rate, as mentioned earlier. It might also be necessary to change the 30 degree bank angle resulting from a turn command to some lower value for the final approach. A pilot near the runway could then use the MCGS Backup Director to control the final approach.

Use of such a minimum system is a relatively high risk operation and should not be used without further study, simulation, and possibly flights to simulate landing approaches. However, the ACLS with its large tolerances on touchdown conditions could help to make such minimum guidance and control concepts feasible for certain restricted operations where minimum cost is a major factor.

The present study has permitted only a very preliminary examination of landing guidance and control requirements for ACLS landings of 147G type vehicles. Several possible landing guidance and control possibilities have been suggested. Further study is recommended before final selection of guidance and control techniques and equipment.

SECTION III
COMPARISON OF ACLS WITH MARS RECOVERY

1. WEIGHT

Table II presents an estimated weight breakdown for an ACLS for a low cost demonstration program on a modified Ryan Model 147G. The 87.9 lb estimate for the basic ACLS for landing only is considered to be quite conservative. It is equivalent to 3.1% of a 2800 lb gross weight. It compares to 180 lb for the mid-air recovery system (MARS).

By using a less conservative approach, performing tests to justify trunk system and tread reductions, and designing for minimum weight throughout, the weight of the basic ACLS for landing only could probably be reduced to 60 lb, or 2.1% of a 2800 lb gross weight. Comparable reductions (20% or 8 lb) may be possible in the total of the optional features.

With the present 147G design, it may not be possible to capitalize on all of the weight differentials between the estimated weights of the ACLS and the weight of the MARS, because of the cg shifts associated with removal of the MARS from the tail cone. It is understood that a 30 lb ballast is planned for the nose of the long fuselage REPEX version of the 147G. Removal of such ballast and a comparable weight from the tail cone would result in a near even weight trade with the 60 lb estimated weight of a basic production ACLS for landing only.

TABLE II
ESTIMATED ACLS WEIGHT*

Basic ACLS (Landing Only)

Item	lb	lb
Inelastic Trunk	15.7	
Trunk Attachments	14.7	
Stowage Toggles, etc	4.3	
Σ Trunk System		34.7
Tread	32.0	32.0
Ejector, Air Manifold, Ducts	16.2	
Bleed Air Valve	5.0	
Σ Air Supply System		21.2
ΣΣ Basic ACLS		87.9 *
Optional Features		
Suction Braking		12.0
Differential Braking (Trunk Orifice Shutoff Valves)		5.0
Δ(Elastic Trunk - Inelastic Trunk)	5.0	
Ejector, Manifold, Ducts, Valve	20.0	
Σ Takeoff Capability		25.0
Σ Optional Features		42.0
Total With All Optional Features		129.9

* Weights are for a low cost demonstration program. Weight of a basic ACLS for a production vehicle could be as low as 60 lb.

The above weights do not account for the engine pod and tail pipe extensions that will be required to permit attachment of the ACLS trunk. The weights of these modifications are estimated to be 20.9 and 45.7 lb for a total increment of 66.6 lb.

Thus, if an experimental (low cost) ACLS with all the optional features was added without removing the MARS, the weight penalty could be as high as 129.9 + 66.6 = 196.5 lb or 7% of a 2800 lb gross weight. If a low weight basic ACLS for landing only was substituted for MARS on a comparable new vehicle designed for an ACLS, the weight saving could be at least 180 lb (MARS) + 30 (ballast) - 60 lb (basic ACLS) = 150 lb. An additional 10 or 20 lb might be saved by elimination of structure for parachute loads and ground impact loads, and integrating trunk attachments with fuselage primary structure. The total weight saving then would approach the weight of the entire MARS system.

2. OPERATIONAL FLEXIBILITY

a. MARS

The primary MARS – contingent surface impact recovery system combination provides a highly reliable minimum damage recovery capability with an emergency backup contingency. With it:

(1) retrieval may be effected in mid-air with no SPA damage under VFR conditions with an IFR surface recovery contingency.

(2) the SPA may be launched in darkness with a planned daylight MARS recovery and a contingent night/day surface impact recovery.

(3) an option exists to surface recover and delay retrieval if required.

(4) the retrieval operation has high mobility with few geographic or terrain constraints.

(5) a damaged or malfunctioning SPA does not have to be flown over friendly forces to an air base recovery area.

(6) no critical line of sight communications link for aerodynamic control need be maintained with the SPA after high altitude parachute deployment.

b. ACLS

An ACLS is a very simple and hence reliable system. Its capability for landings at high sink rates (without flare), in crosswinds (without decrab), and on runways or unprepared surfaces should reduce the percentage of landing accidents relative to those with wheel gear or skids. Although there are no ACLS statistics to support this, it is expected that with an ACLS the percentages of successful recoveries without vehicle damage should equal or exceed those for MARS. For night or IFR conditions, the number of ACLS recoveries resulting in vehicle repairs should be much less than for MARS.

The ACLS restricts recoveries to clear areas of the order of 150 ft x 1500 to 5000 ft and line of sight communication must be maintained during landing, whereas MARS has few geographic or terrain restraints and no communications requirements after chute deployment. The required length of the ACLS landing site depends on the degree of braking that is provided and the sophistication of the landing guidance system.

The ACLS can land on runways or on unprepared sites of any bearing strength. Because of the very low ACLS pressures, repeated landings result in little or no degradation of even very soft surfaces. The ACLS is insensitive to surface irregularities (i.e., bumps or depressions having heights/depths up to about 6 inches will have little effect on the ACLS equipped 147G). Thus, selection of landings sites will be much less restricted than for wheel gear or metal skids and little or no site preparation/maintenance will be required.

Currently two helicopters are used to support a MARS mean recovery rate of 1 per day. The maximum rate of recoveries with MARS is estimated to be one recovery per hour per helicopter, whereas ACLS landings can be made at a rate of the order of 1 per minute. This can be a large advantage where sortie rates are high.

For vehicles much larger than the 147G, MARS recoveries will not be practical because of helicopter load limitations. There is no known limitation to the size of vehicle that can effectively use an ACLS.

3. RECOVERY, GROUND HANDLING, MAINTENANCE AND REFURBISHMENT

a. MARS

A MARS recovery begins in the flight operations area where the SPA free flight is terminated by commanding recovery initiation via a remote radio link from a ground or airborne control station. In the SPA, the recovery command:

(1) cuts off engine fuel to shut down the engine

(2) deploys a small drag parachute to decelerate the SPA

(3) switches the electrical system from the engine driven generator to a short duration battery power source

(4) switches some on-board systems off or changes mode of operation as required for the recovery descent

(5) deploys the main recovery parachute when the correct combinations of altitude, airspeed, time, etc., have been met.

The SPA then descends under the main parachute until it is either snatched from the parachute by a Mid-Air Retrieval System (MARS) equipped CH-3 helicopter or impacts in a land or water recovery area.

In a MARS retrieval, the helicopter transports the SPA to the maintenance area from the recovery area. To support a SPA mean sortie rate of 1 per day, two CH-3 helicopters are required due to helo availability. The CH-3 crew consists of 4 personnel: pilot, copilot, flight engineer and tow reel operator. Helicopter flight time during a MARS operation is generally about 1-1/2 hours. Four helo mechanics are provided for maintenance of the two CH-3 helicopters.

On a surface impact retrieval, the SPA and any reuseable recovery system parts may be retrieved by helo or truck depending on nature of the recovery surface, weather, surface accessibility, etc. In any case, the SPA must be picked up and transported to the maintenance area. Percentage of recoveries where recovery system parts are retrieved and value of the parts are so small as to be insignificant for comparative purposes. For truck retrieval, two vehicles are used, one equipped with a hoist and one equipped with a SPA storage cradle. The hoist is used to lift the SPA from the ground to the cradle equipped truck. Three to four personnel are required to complete the retrieval task which includes operation of the retrieval vehicles and the manual handling tasks involved in lifting the SPA, guiding it to the cradle, securing it, and retrieving any reuseable recovery system parts such as parachutes and chute containers. The recovery system parts are normally lost during MARS or water retrieval and are retrieved on approximately 80% of land recoveries in friendly areas where truck retrieval is used.

MARS is the primary retrieval method in use today, having been attempted on 98.1% of the recoveries made (84% of sorties ended in recovery initiation). 97.5% of the MARS attempts were successful and 4.6% of the recoveries resulted in surface impact. On 15% of the recoveries which ended in surface impact the SPA received major depot level repair. On these vehicles, a repair cost has averaged $36,000 with a maximum of $57,800 and a minimum cost of $20,300. In one instance on another program, repair cost for a heavily instrumented SPA after land surface impact was $130,000. Cost of the MARS installation on a SPA is approximately $5500 – (this figure will vary depending on method and quantity of hardware purchased).

In the maintenance area, the SPA is transferred to a 3000 A/E transportation trailer to facilitate between flight turnaround. In the case of truck retrieval, a hoist is used to transfer the SPA from the truck to the transportation trailer. After MARS retrieval, the CH-3 helicopter sets the SPA on the ground in a retrieval "dock" area. A hoist is then used to lift the SPA to a transportation trailer.

The SPA is then moved through the turnaround and repair maintenance channels which include refueling, replenishment of recovery system, systems test, engine run and servicing and preflight configuration and preparation. The SPA is then transferred to a positioning trailer and uploaded to the launch aircraft.

b. ACLS

When recovery is by a horizontal landing with an ACLS, the aircraft will be flown to the general area of the landing site and an altitude of 500 to 1000 ft by the mission guidance system. Level flight airspeed will be reduced to about 150 knots by reducing thrust while increasing pitch attitude to approximately six degrees. An "inflate trunk" trunk command will initiate air flow into the trunk; the resulting pressure in the trunk will release the trunk stowage toggles. Full inflation will occur in approximately three seconds.

As the trunk inflates, thrust can be increased about 150 lb to maintain level flight, or pitch attitude can be decreased to initiate the descent at a constant air speed. The landing controller will guide the vehicle to a landing primarily by varying pitch attitude, while maintaining a crab angle to counteract crosswinds. No flare or decrab is required at touchdown because of the high sink rate tolerance of the ACLS and its crosswind landing capability.

If a low air flow ACLS is used, the vehicle will have limited taxi capability. Even with this low airflow ACLS system it may be possible to use aerodynamic control to make a turn off the runway so several landings could be made before recovering the vehicles. However, it will generally be necessary to recover it from the end of its slideout with presently existing ground support equipment (truck mounted Mobile crane and transportation cradle). An alternative would be for ground crewmen to restrain one wing to effect a 90° turn while vehicle thrust is used to turn the vehicle and taxi it off the runway after the end of its slideout, for later return to the servicing area.

Time for removal from the landing area and return to the servicing area could be decreased by employing a jeep or small truck as a tow vehicle. This tow vehicle could carry a small ($<$100 hp) gasoline engine/fan to provide ACLS air via a flexible duct or hose attached to the aircraft with a quick-disconnect fitting.

The incorporation of ACLS differential braking would ensure that a turn off the runway can be made without ground crew assistance. This will permit rapid landings of a dozen or more vehicles before recovery via mobile crane and transporter.

A significant improvement in speed of return from the end of slideout, and a decrease in the ground crew, can be achieved by providing trunk orifice valves or trunk to cushion port valves, together with differential braking. This will provide an increased air flow for remote taxiing of the vehicles back to the servicing area.

This taxi capability, in addition to speeding operations, can be of considerable value if landings are made on low bearing strength sites where operation of the crane and transporter are either impossible or would result in severe rutting of the surface.

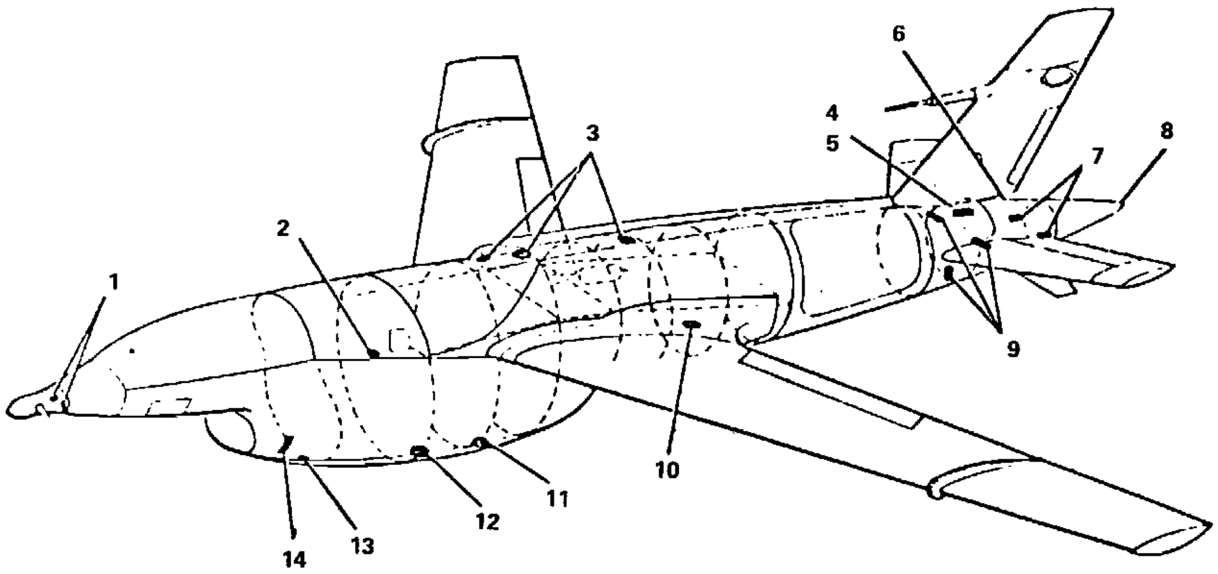
After return to the servicing area, post flight and preflight operations will be essentially the same as after MARS recovery. Visual inspection of the ACLS trunk and tread will be made as soon as practical so replacement can be made if necessary. Tread replacement will be required only after 20 flights and other components will generally last for the life of the vehicle with little or no checkout between flights. Tread replacement, with the vehicle supported by its hoist sling and/or workstand, can be made in less than an hour. Since MARS reinstallation will not be required, ACLS turn around time will generally be the same or less than for the MARS system.

Access to service locations (Figure 70) on the bottom of the fuselage can be provided by a longitudinal slit down the lower centerline of the trunk. This will permit the side trunks to be moved aside for complete access to the bottom of the fuselage. Closure of the access slit will be by lacing or a zipper with a light fabric flap inside the trunk for a pressure seal.

Prior to installation on the launch aircraft, the trunk will be manually stowed and held in place by the stowage toggles. This can be accomplished by two men in about 15 minutes, with the vehicle lifted a few inches above the transporter by the existing A-frame gantry hoist or the mobile crane.

4. COSTS

Table III summarizes costs of midair recovery system (MARS) operations. Table IV summarizes MARS recovery statistics. Analysis of these tables shows that although costs of vehicle field and depot level maintenance required after surface recoveries are high, with the MARS the percentages of surface recoveries are so low as to give an average maintenance cost of only $800/sortie. This is small compared to the $5500 cost of MARS hardware which is normally lost on each recovery.



1. Air Inlet Assembly Release Chambers (Two P8A0 Squibs, Two Places)
2. Lubricating Oil Filler Cap
3. Fuel Filler Caps
4. Swivel Squib or Mars Explosive Bolt
5. Mars Mechanism Pin Puller (If Installed)
6. Main Parachute
7. Drag Parachute Release Chambers (Two P8A0 Squibs, Two Places)
8. Drag Parachute
9. Main Parachute Release Chambers (Two P8A0 Squibs, Three Places)
10. Fuel Tank Sump and Drain
11. Engine Burner Drain
12. Lubricating Oil Filter
13. Lubricating Oil Tank Drain Valve
14. Lubricating Oil Level Indicator Window

Figure 70. Servicing Locations for Unmodified Model 147G

TABLE III
MARS COST FACTORS SUMMARY

CH-3 Data:

(1)	Quantity/Squadron	2
(2)	Initial Cost	$0.8 million each
(3)	Crew Size	2 Officers + 2 Airmen
(4)	Crews/Squadron	5
(5)	Fuel Cost/Flight Hour	$18
(6)	Support Equipment Cost/Aircraft	$87,000
(7)	Maintenance Cost/Flight Hour	$246
(8)	Flying Hours/Aircraft/Month	30

Drone Data:

(1)	Initial Cost	$260,000
(2)	MARS Installation/Recovery	5,500
(3)	Estimated Maintenance Cost/Recovery	
	(a) Surface, Field Level	2,600
	(b) Surface, Depot Level	$36,000
	(c) MARS, Field Level	500

TABLE IV
MARS RECOVERY STATISTICS

Basis: > 1000 Sorties

		Percent
(1)	Sorties terminated in recovery of SPA	84.1
(2)	Recoveries on which MARS attempted	98.1
(3)	Attempts on which MARS successful	97.2
(4)	Recoveries resulting in surface impact	4.6
(5)	Surface impacts resulting in depot level damage	15.0
(6)	Sorties on which MARS attempted (item 1 x item 2)	82.5
(7)	Sorties on which MARS successful (6 x 3)	80.2
(8)	Sorties recovered to surface (1 x 4)	3.9
(9)	Sorties resulting in depot level damage (5 x 8)	0.6

The other principal costs associated with MARS are those attributed to the two CH-3 helicopters per squadron. The cost of one of these helicopters, at 0.8 million dollars, is comparable to the estimated cost of a development program for an ACLS for the 147G.

From the data of Table III, the helicopter operating and maintenance costs, including crew costs, were estimated to be $600/recovery for 1000 recoveries/yr., $856/recovery for 365 recoveries/yr. and $1700/recovery for 240 recoveries/yr.

The costs (if any) or preparing and maintaining a strip for ACLS landing would be negligible compared to the helicopter operating and maintenance costs.

Figure 71 summarizes costs per recovery for the MARS system and the ACLS versus the number of recoveries. The MARS costs per recovery are composed of costs of the vehicle borne elements of the system which are seldom recovered or reusable, costs of maintenance or repair required because of vehicle damage, costs due to maintenance and operations of the helicopters and costs due to amortization of the helicopters.

ACLS costs per recovery depend primarily on initial system costs and vehicle life. Figure 71 shows the $1000 cost per recovery of a $20,000 ACLS on a vehicle with a life of 20 flights. Because of ACLS simplicity, ACLS maintenance costs are negligible compared to costs of the system divided by vehicle life. ACLS maintenance will also be negligible compared to costs of helicopter operations and maintenance.

It is estimated that an ACLS for landing a 147G size vehicle can be made in small quantities (10 to 20 units) for $20,000 each. This assumes a vehicle similar to the 147G but one for which engine bleed is available and for which vehicle modifications such as the engine pod and tailpipe extensions would not be required. With a concerted effort to reduce costs and with production of 50 or more units, it should be possible to reduce the cost of an ACLS for landing only to less than $10,000 each. Table V gives a cost breakdown for such an ACLS.

The cost of engine pod and tailpipe extensions for the Model 147G should not exceed $20,000 per vehicle even if these changes are retrofitted on only 10 to 20 vehicles. If the modifications are incorporated during vehicle manufacture, and production quantities are of the order of 50 units or more, it should be possible to reduce these costs to less than $10,000 per vehicle. Such costs should not be incurred if a new vehicle is designed for ACLS recovery.

Costs of required on-board flight control and guidance system modifications must also be considered. For the REPEX flight test vehicles, which will have 3-axis proportional systems, no significant changes are anticipated. Similarly, the costs of incorporating a capability of several discrete pitch and roll attitude commands, or proportional pitch and roll commands during manufacture of 147G's could be as low as $1000 or $2000. (The Jindivik lands without yaw axis controls.) If a rudder and 3-axis proportional command capability were to be retrofitted to Model 147G vehicles, costs could be an order of magnitude greater.

Figure 71 also indicates the cost increment per recovery that would be incurred if a ground based landing guidance system with a total installation plus operating cost of $1,000,000 were used. Although not required for all operations, such a system could provide all weather recovery in addition to greatly increased recovery rates (see Guidance and Control). Even with such a ground based

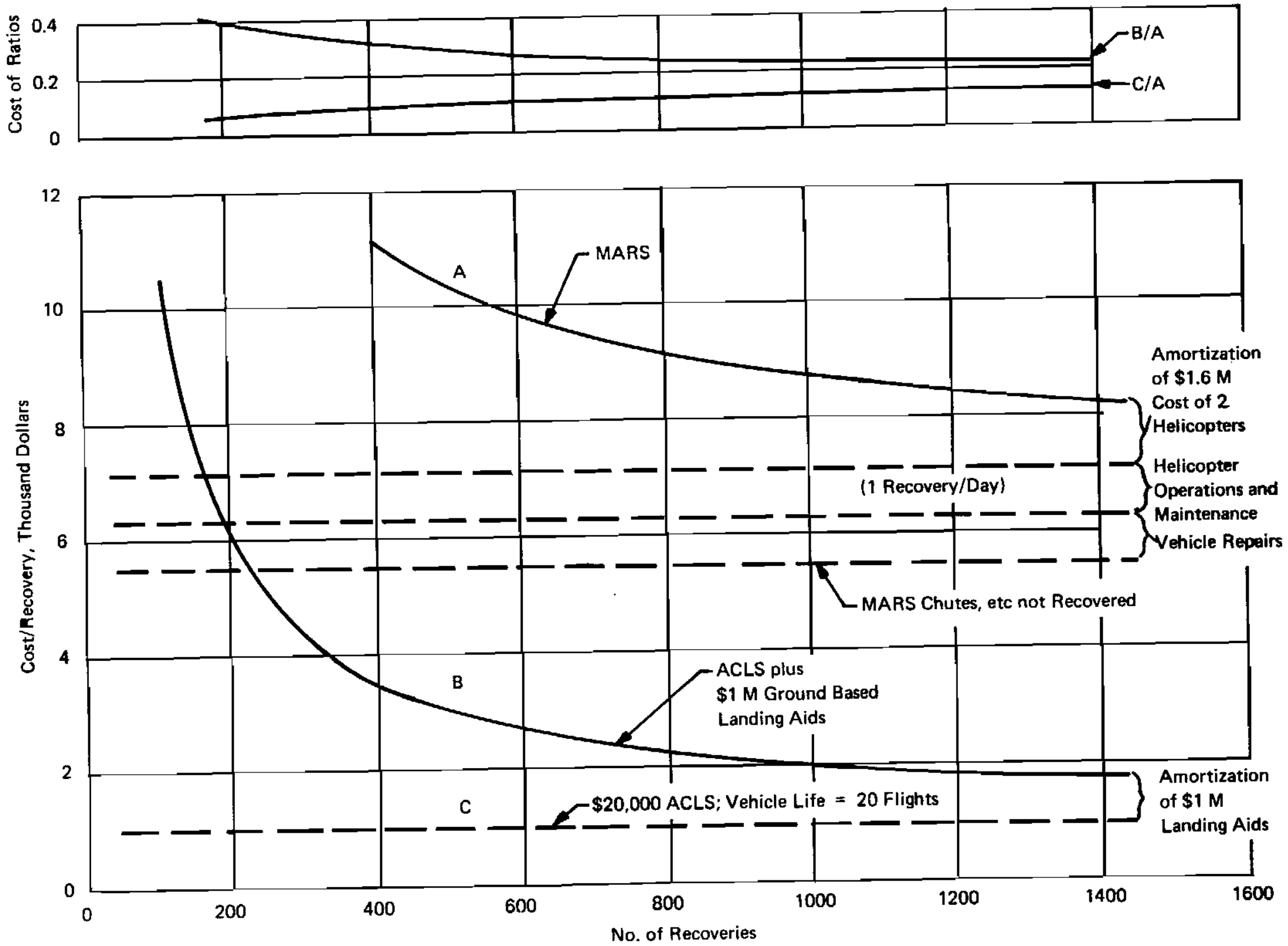


Figure 71. Cost Per Recovery with MARS and ACLS

TABLE V
ESTIMATED PRODUCTION COST OF ACLS FOR LANDING ONLY

Assumptions:
- More than 50 units.
- No braking system.
- Propulsion Engine has bleed provisions.
- Vehicle designed for ACLS.
- ACLS designed for low production cost.
- Installation during vehicle manufacture.
- Design/Development costs not included.

Item	Unit Cost, $	
Trunk	3,000	
Tread	600	
Trunk Attachments	1,500	
Stowage Toggles, etc.	1,800	
Σ Trunk/Tread System	6,900	
Ejector	900	
Relief Valve	500	
Bleed Air Plumbing, Ducts	700	
Bleed Air Valve	600	
Σ Air Supply System	2,700	
ΣΣ Total ACLS		$9,600

NOTE: Costs include installation.

system, and a $20,000 ACLS on a vehicle with a lifetime of 20 flights, the costs per ACLS recovery are only 40% of MARS costs after 200 recoveries or 23% of MARS costs after 1,000 recoveries as indicated by curve B/A at the top of Figure 71.

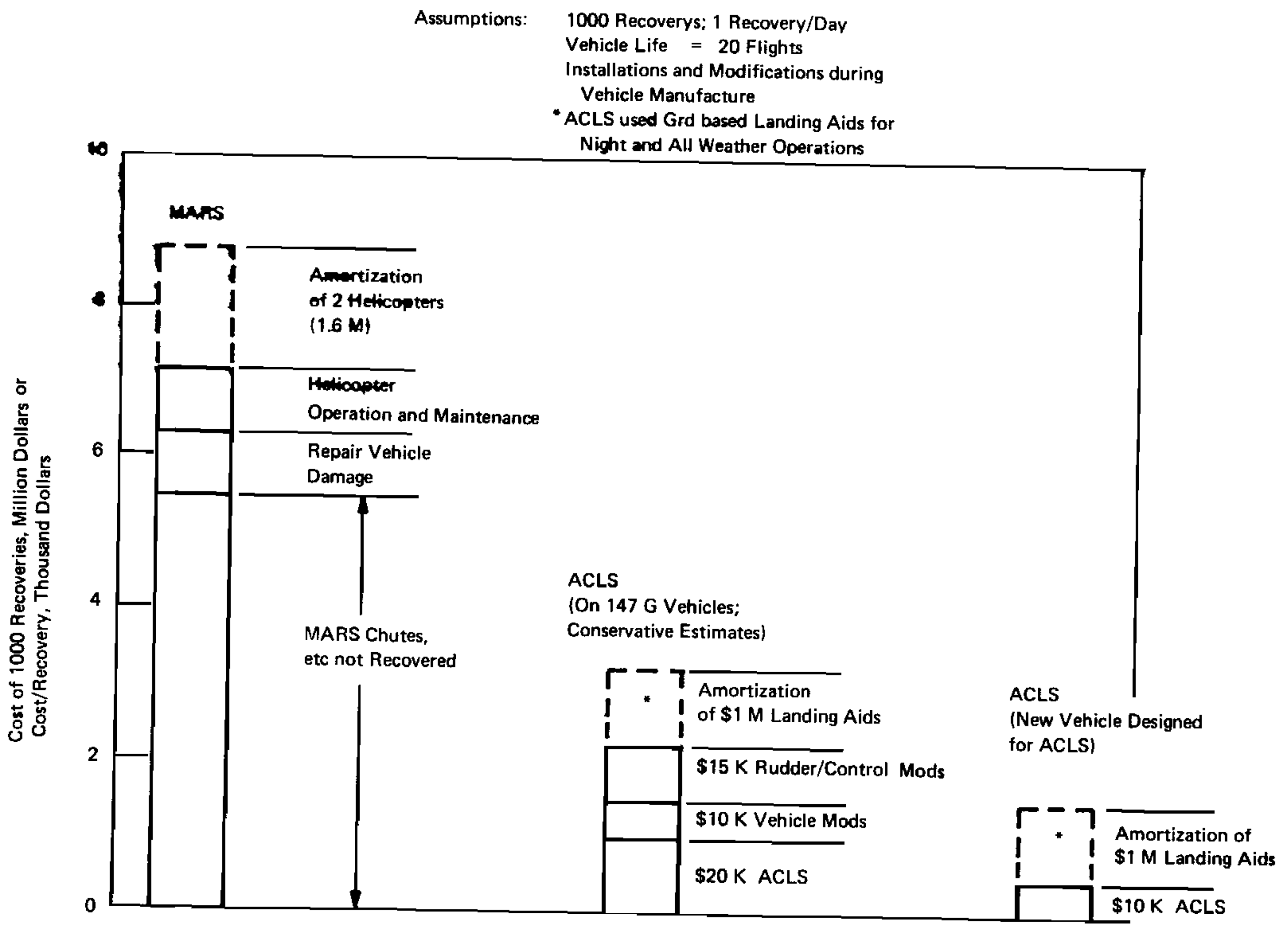
If the vehicle is landed without ground based landing aids, the cost of recovery with a $20,000 ACLS is reduced to less than 12% of the cost of MARS recovery. This is shown by curve C/A at the top of Figure 71. The saving would then be at least $7750 per recovery or $7,750,000 for 1000 recoveries. If ACLS cost is reduced to $10,000 (Ref. Table V), savings will be increased by another $500 per recovery.

Figure 72 compares the costs of 1000 recoveries with MARS, with a $20,000 ACLS on 147G vehicles which require vehicle and control modifications, and with a $10,000 ACLS on new vehicles which have the necessary controls and do not require airframe modifications. For this example, including the costs of modifications of the 147G's and amortization of $1M ground based landing aids, the costs of ACLS recoveries of the 147G are only 37% of costs of MARS recoveries. With the assumed vehicle life of 20 flights, the costs of ACLS recovery would be less than the cost of MARS recovery even if the total cost per vehicle for the ACLS, vehicle modifications, and control and guidance system modifications were $140,000. This is over three times the $45,000 total of the estimated costs of these elements, shown in Figure 72.

With a $10,000 ACLS on new vehicles which have the necessary guidance and control systems and do not require airframe modifications, the ACLS plus ground based landing aid costs of Figure 72 are only 17% of MARS costs. The saving would then be over $7,000,000 for 1000 recoveries. The savings could approach $8,000,000 if the nighttime and all weather recovery capability was sacrificed and very low cost landing aids were used.

Helicopter availability, investment costs, and manpower may be more significant than costs per recovery if recovery rates are high. Figure 73 shows that a recovery rate of 10 per hour or 120 sorties per 12-hour day would require 12 to 24 helicopters, costing $9,600,000 to $19,200,000. 100 to 200 men would be required to fly and maintain these helicopters. The cost of even the most sophisticated landing aids to provide nighttime and all weather ACLS recovery would be a small percentage of the cost of helicopters for MARS recoveries at a rate of 10 per hour.

Much higher sortie rates may be used in the future if RPV's assume a major role. (The news media report that three hundred or more manned sorties per day are currently being flown in the Far East.) For such cases, the investment for helicopters could approach $50,000,000 and the space required for parking and maintaining the helicopters could exceed the area of the strips required for landing the RPV's.



Assumptions:
1000 Recoverys; 1 Recovery/Day
Vehicle Life = 20 Flights
Installations and Modifications during Vehicle Manufacture
* ACLS used Grd based Landing Aids for Night and All Weather Operations

Figure 72. Costs of 1000 Recoveries

Note: Helicopter Cost = $800,000
Assumes no helicopter losses

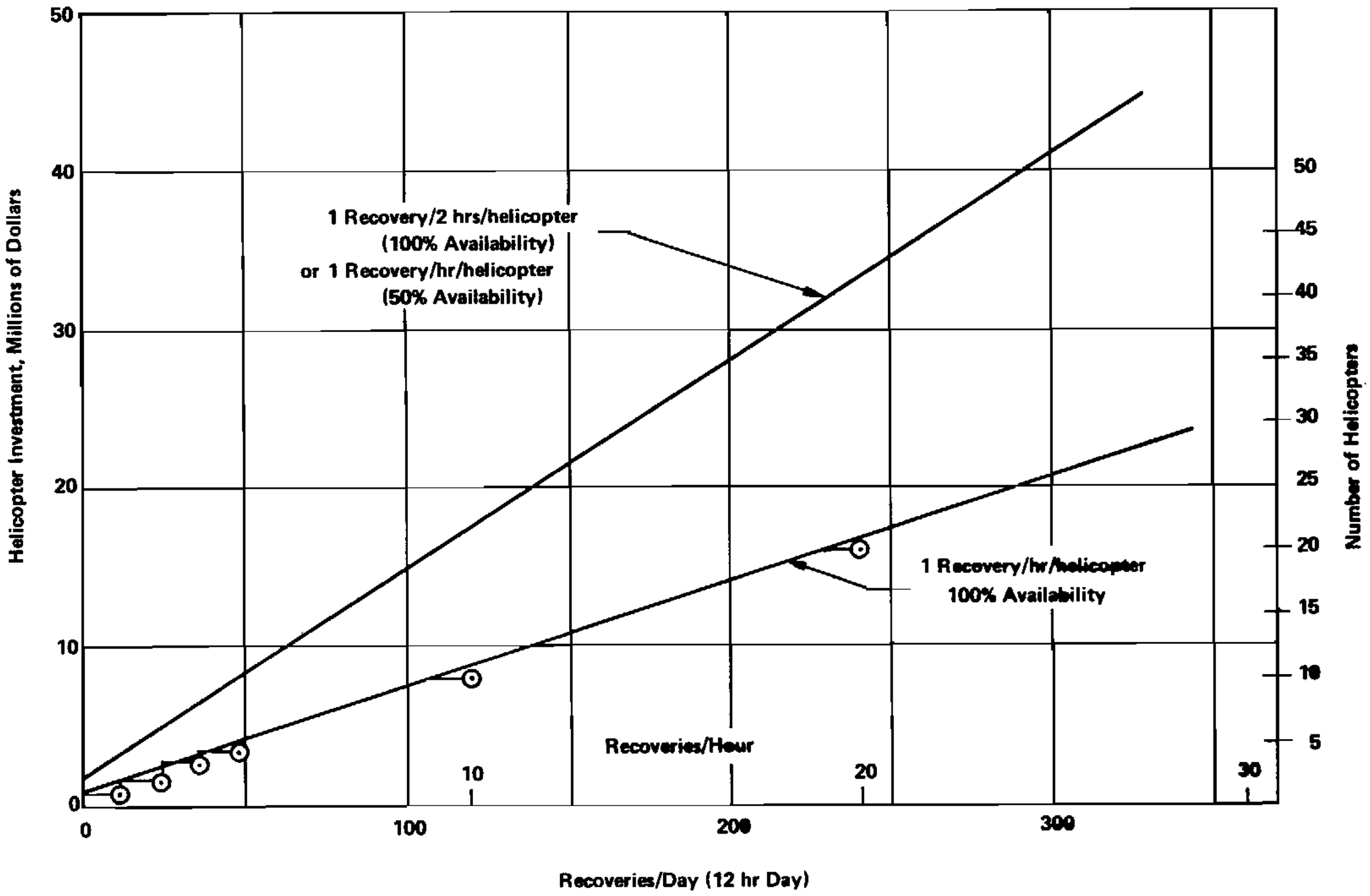


Figure 73. MARS Helicopter Investment versus Recovery Rate

SECTION IV
CONCLUSIONS

1. Recovery of unmanned aircraft by horizontal landings with an Air Cushion Landing System (ACLS) is feasible and offers several advantages relative to the present Mid Air Retrieval System (MARS).

2. If launch is by another system, the ACLS trunk can be made of commercially available inelastic material and can be manually stowed prior to launch.

3. Propulsion engine bleed supplemented by an ejector (jet pump) will provide sufficient air flow for landing. Such an air supply is very simple, reliable, and light weight.

4. Optional features can be incorporated to provide differential braking for heading control during taxi, suction braking which can provide controllable decelerations up to 2 g's and a smooth surface takeoff capability.

5. An ACLS for the Ryan Model 147G has potential for a 120-lb. weight reduction compared to the 180-lb. MARS recovery system. However, the fuselage of the Ryan Model 147G will require modifications to accommodate the ACLS and c.g. limits for the 147G (designed for MARS or chute recovery) will limit the weight that can be removed. Therefore, the maximum weight saving with an ACLS on this vehicle will be about 60 lb or 2% of the gross weight. On a new vehicle of this size, designed for an ACLS, the weight savings could be as much as 180 lb or 6% of the gross weight.

6. The ACLS will require a larger ground recovery area than the MARS. However, for high sorties rates (i.e. ~ comparable to the 300 manned missions per day which the news media report are currently being flown in the Far East) the area required for operation and maintenance of MARS helicopters can approach the area required for ACLS landing.

7. The ACLS has operational advantages over metal skids or wheel gear because of its capability for repeated landings on very low bearing strength surfaces, and its crosswind capability. It also can be taxied to clear the landing area for other aircraft. With suction braking it can provide varying slideout decelerations up to 2 g's and slideout distances less than 500 ft for landing speeds of 136 knots.

8. Landing aids can be used with an ACLS to provide night and all weather landing capability, whereas MARS recovery is generally limited to VFR conditions.

9. An ACLS will permit much higher recovery rates (order of 1 per minute) than MARS (maximum of one per hour per helicopter).

10. There is no inherent limit to the size of vehicle that can use an ACLS whereas MARS is limited by the capacity of the recovery helicopter.

11. MARS recovery costs are of the order of $7000 per recovery. ACLS recovery costs for a simple ACLS incorporated into the design of a new vehicle would be of the order of $1000 per recovery.

12. Only minor changes to the guidance and control systems planned for the REPEX modified Ryan Model 147G will be required for ACLS flight test demonstrations. Additional changes would be required to the corresponding systems of unmodified 147G's to provide the proportional commands required for landing. Further studies are required to determine if it is feasible to land these unmodified vehicles without adding a rudder and the corresponding guidance and control elements.

13. The ACLS concepts of this report and conclusions drawn relative to their use on the Ryan Model 147G will generally be applicable to other existing or planned unmanned aircraft in the 2000 to 12000-lb class. However, each vehicle must be examined to ensure that its configuration and subsystems are suitable for recovery with an ACLS.

SECTION V
RECOMMENDATIONS

1. A flight demonstration program of an existing drone or RPV is recommended to confirm predicted ACLS capabilities, to develop operational procedures, and to more firmly establish ACLS and landing guidance design requirements for operational vehicles. A principal objective should be to determine operational flexibility and/or limitations versus ACLS capability (i.e., with/without air flow, with/without braking, with/without taxi capability).

2. The Australian Jindivick should be briefly examined as a possible alternate to the Ryan 147G for the demonstration program. This vehicle has a fuselage which is more suitable for ACLS application and is already designed for landing on a metal skid.

3. Model or full-scale ACLS drop tests, slideout tests, wind tunnel tests, and tread material tests should be made to confirm predicted ACLS characteristics.

4. Further analyses, simulations, and flight tests should be conducted to determine flight control and guidance system requirements for landing versus operational requirements and ACLS capabilities. This should include factors such as field size, crosswinds, IFR versus VFR, 2 versus 3 axis control, and ACLS braking deceleration.

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13. ABSTRACT

This report presents results of a concept feasibility and formulation study of Air Cushion Landing Systems for recovery of unmanned aircraft (Remotely Piloted Vehicles) A modified Ryan Model 147G drone or special purpose aircraft was investigated for possible use in a low cost flight test demonstration of air cushion landing gear concepts on an existing unmanned aircraft. Recovery by horizontal landing on an air cushion landing system is compared with recovery with a mid-air recovery system (MARS)

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