SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFFDL-TR-75-135	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Tests of the Bell Aerospace LA-4 ACLS Fitted With Suction Braking and Predictions for Other Aircraft		5. TYPE OF REPORT & PERIOD COVERED Final 1/75 – 5/75 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) T.D. Earl C.L. Stauffer C.E. Satterlee		8. CONTRACT OR GRANT NUMBER(s) F33615-75-C-3038
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bell Aerospace Company P.O. Box 1 Buffalo, N.Y. 14072		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Flight Dynamics Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE November 1975 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) AFFDL (FEM) Wright-Patterson Air Force Base, Ohio 45433		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Air Cushion Landing System
Braking
Suction Braking
LA-4 ACLS Tests

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A test program was conducted by Textron's Bell Aerospace Company, using their ACLS equipped Lake LA-4 aircraft to investigate the potential of a suction braking ACLS subsystem. The new braking subsystem was tried on dry and wet runway and rough grass. Deceleration up to 0.5g was recorded with the suction flow available; however, the potential of a developed system applied to a cushion planform designed to utilize suction braking far exceeds this, and the report predicts effective potential application to the C-130, Jindivik, and XC-8A.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

FOREWORD

This report covers work performed by Textron's Bell Aerospace Company, P.O. Box 1, Buffalo, N.Y. 14207 under USAF Contract No. F33615-75-C-3038, Project No. 136 90 210, Task.

The program was directed by the Air Force Flight Dynamics Laboratory (Mr. B.J. Brookman, AFFDL/FEM, Project Engineer) and carried through by the authors. The work was performed from January through May 1975.

A 16mm color movie of the tests included in the work was produced.

The technical report was released by the authors in September 1975 for publication as an R&D report.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

A test program was conducted by Textron's Bell Aerospace Company, using the ACLS equipped LA-4 aircraft, to investigate the potential of a suction braking ACLS subsystem.

The subsystem consists of a cold gas driven fan installed to pump air out of the cushion cavity, creating suction instead of pressure, thus forcing the trunk onto the ground. Existing brake skids (for pillow brakes) were retained to absorb wear but not actuated as pillow brakes and nozzle plugs were added for trunk protection in other areas.

The results were spotty, due to faulty nozzle plug retention. However deceleration up to 0.5g was measured and the cushion cavity pressure was negative on several occasions reaching –18 lb/sq. ft, 60 lb/sq. ft below the normal airplane-supporting pressure of 42 lb/sq. ft.

Calculations of C-130, Jindivik, and XC-8A system requirements are made and show potential for very effective braking (much greater than wheelgear can provide) particularly on the C-130.

TEST ARTICLE DESCRIPTION

General

The ACLS LA-4 (Figure 1) is a Bell-owned, light amphibian aircraft manufactured by the Lake Aircraft Corporation of Sanford, Maine. Particulars of the aircraft in its original builder's configuration, as certified by the FAA, are as follows:

Wing Span	38 ft.
Length	23 ft. 6 in.
Height	8 ft. 10 in.
Wing Area	170 ft^2
Gross Weight	2400 lb.

The craft as modified for an ACLS has the following specifics:

Cushion Pressure	60 psf
Trunk Pressure	140 psf
Cushion Area	42 ft^2
Trunk Length	13.5 ft.
Trunk Width (max)	4.4 ft.
Trunk Outer Radius	0.92 ft.
Trunk Inner Radius	1.60 ft.

Suction System

For suction braking, the air in the ACLS cushion cavity is evacuated with sufficient potential to overcome its replenishment by the trunk nozzles. The cushion planform area operating pressure is reduced from its normal value. When it reaches ambient air pressure, the aircraft load (weight-lift) is completely transferred to the trunk. Resultant drag increases stop the vehicle. If cushion pressure less than ambient is realized, the suction produced will increase the down load by the product of the new cushion area and the pressure below ambient.

The Lake has been used as an ACLS test bed since 1967. For suction braking investigations, a 1-way stretch (lateral) trunk of a construction proven in previous tests was utilized. This highly elastic composite (nylon, rubber, neoprene) has a 160% elongation at the ACLS working pressures. The trunk does not incorporate pillow brakes; however, individual pads associated with the pillows (3 per side), are used to accept wear in braking. These 12 x 18 inch skids of a chlorobutyl composite are fabricated to fold or extend with trunk deflations/inflations. Additionally, the trunk was configured with 523 nozzle inserts (or plugs) distributed in a symmetrical pattern throughout the nozzle area (1070 holes). The purpose of using the plugs was twofold, (a) to absorb wear, and (b) to act as an automatic closure device so that cushion airflow is reduced as footprint is increased. By this means suction requirement can be minimized. Evidently a plug in every hole would result in total closure in the footprint and also destroy air lubrication, which is needed at the rear for taxi. The chosen configuration was intended as a preliminary compromise for this test series. It consisted of installing the plugs in approximately half of the longitudinal slits cut in the trunk as jet nozzles to a suitable distribution pattern (Figure 2). Nozzle area was initially reduced from the formerly used 0.56 ft^2 to 0.40 ft^2 to insure airflow rates within the capabilities of the suction braking equipment. Six 15°

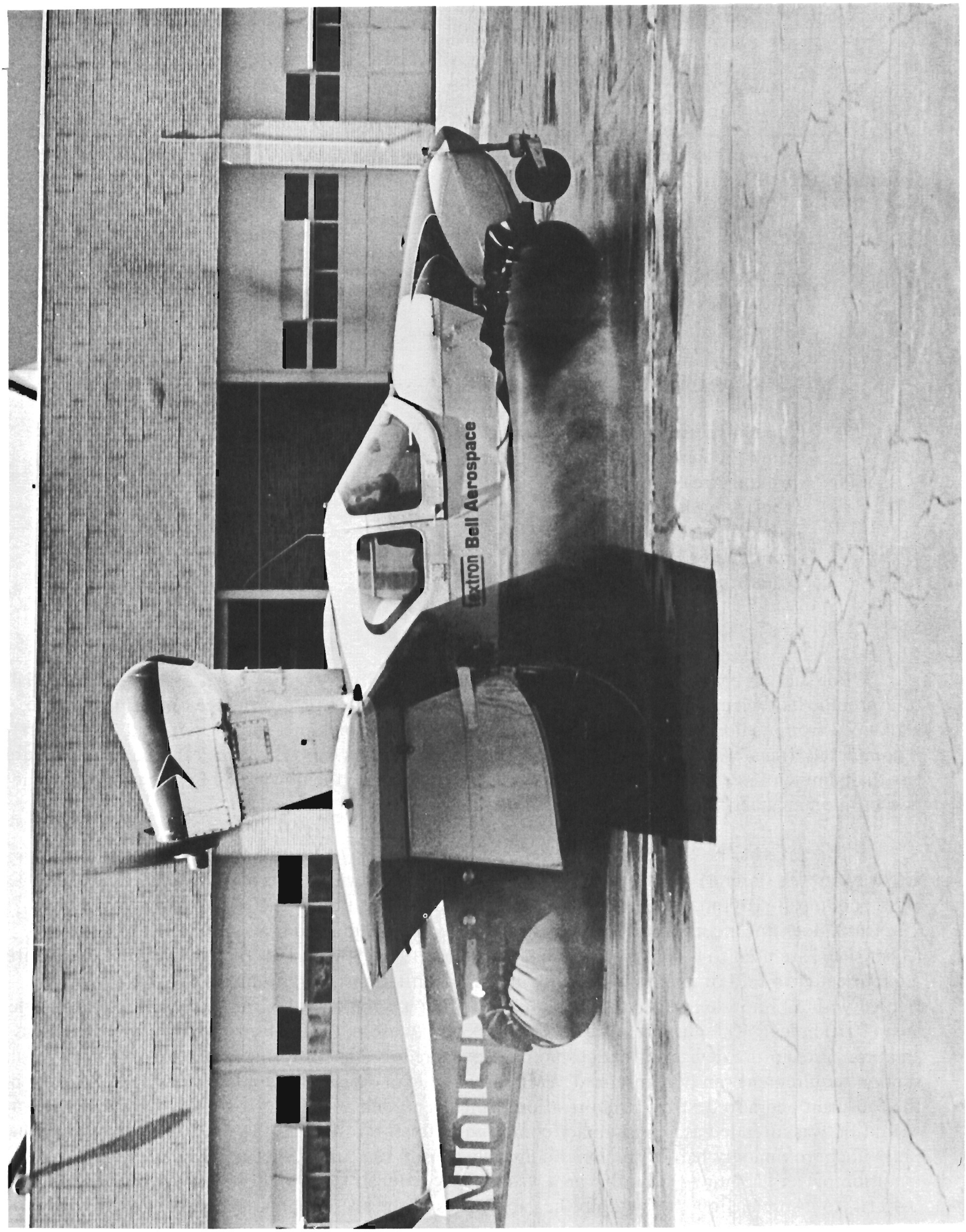

Figure 1. ACLS LA-4 Aircraft

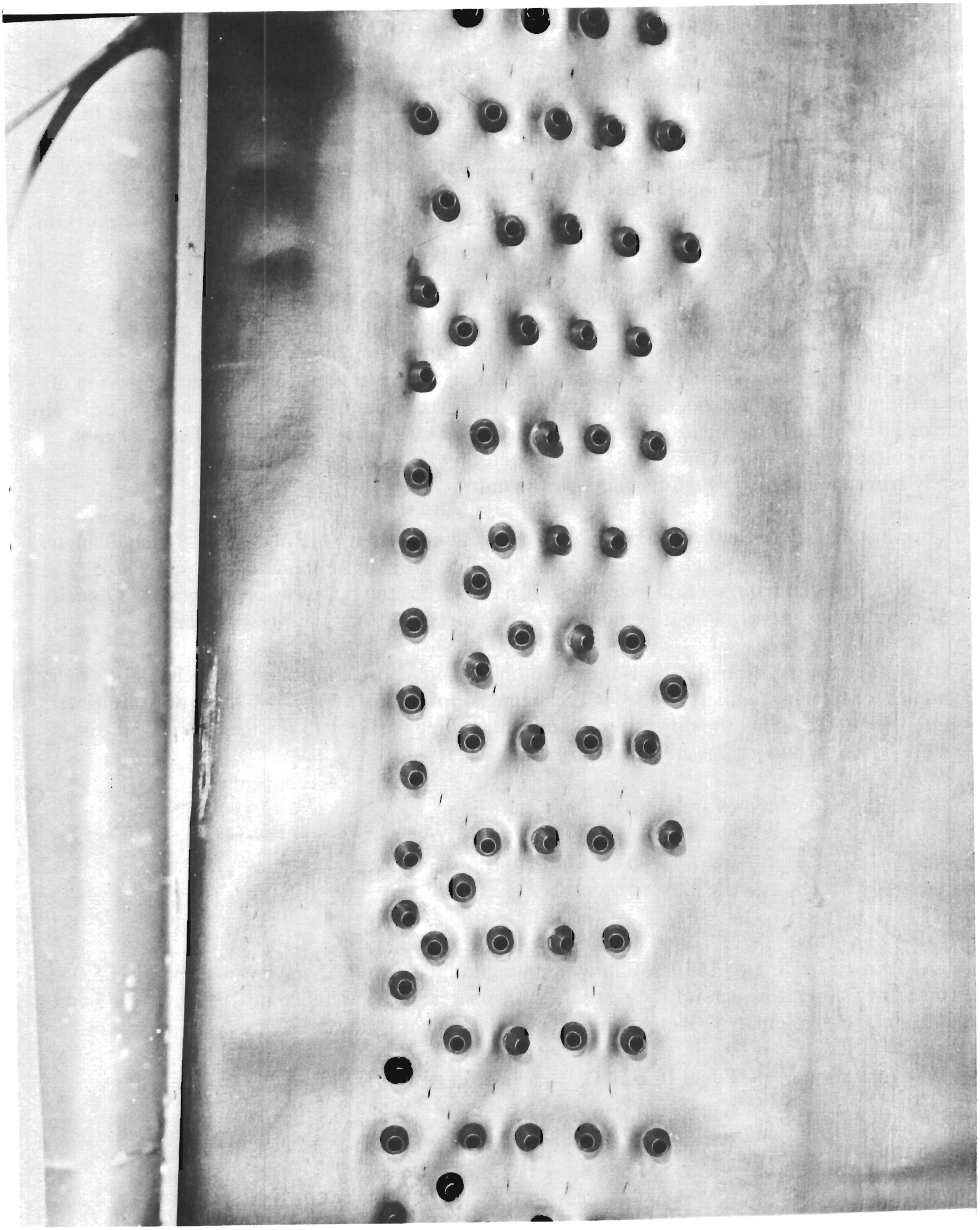

Figure 2. Trunk with Plugs Installed (Inside Surface, Retracted Trunk)

cones with 3-inch diameter outlets were installed in the ACLS engine bay to compensate and to provide total nozzle area adjustment capability for optimum fan performance.

All components of the pillow brake system were removed from the aircraft to provide room for the new braking system. Four rectangular holes (2 ft^2 area) were cut through the ventral fuselage at approximately Stations 82.0 and 108.0 into the cushion cavity. An air-tight compartment of approximately 3 cu. ft. in the underfloor space was made by extending frames and closing control rod/cable penetrations with rubber boots (Figure 3). A new flooring was installed and the space sealed over by mounting a 2 cu. ft. aluminum plenum chamber with two 8.0-inch diameter ports on the right outboard side.

A Tech Development Inc. tip turbine fan (Model 840A-S/N 323) was installed at R.B.L. 23.0, W.L. 11.0 between stations 100.0 and 107.0. The fan is mated to the plenum chamber. A high pressure air bottle of 800 cu. in. capacity is installed aft of the pilot's seat. When pressurized to 1600 psig it supplies the primary air to the suction fan. Regulation of the maximum pressure of the tip turbine fan is by hand operated ball valves. The maximum pressure of the turbofan drive air is 350 psig. The unit is protected from over-pressurization by a burst disc (Safety Head Assembly B-16593) suitably rated. Feed lines of 3/4 in. diameter hydraulic hose (3000 psig rating) run separately from the bottle through the valve to the unit.

For installation in the LA-4, the fan exhaust was extended by mating to an 18-inch diameter duct assembly protruding through the right side of the aircraft and dumping to atmosphere. A 6.9-inch diameter cylindrical section extending 11 inches from the fan plane is reduced by a 4-inch long 15° cone section having an outlet diameter of 5.2 inches (21 $in.^2$, 0.146 sq. ft. area).

The lever controlled ball valve is mounted on the pitch trim control panel at the pilot's right hand, immediately below and aft of the ACLS engine control panel. The valve has a pressure gauge at its outlet for determining the downstream pressure and regulating it to the maximum 350 psig. The cockpit controls and gauges are shown in Figure 4.

The fan characteristics are presented in Figure 5.

Test Configurations

Loadings

A standard loading of 2650 ±50 lb with a longitudinal center of gravity position of 105.0 ±0.1 inches datum was used throughout the test series. The aircraft was weighed on 27 March 1975 and the longitudinal c.g. calculated. Weight and balance data are as follows:

Configuration: Fuel (46 U.S. Gals.) = 276 lb at Sta. 118.0
Ballast = 0.0 lb.
Modifications Completed

Net Reaction	Weight	ARM	Moment
Main Gear	2294	+121.12	277,849
Nose Gear	256	-8.44	-4,096

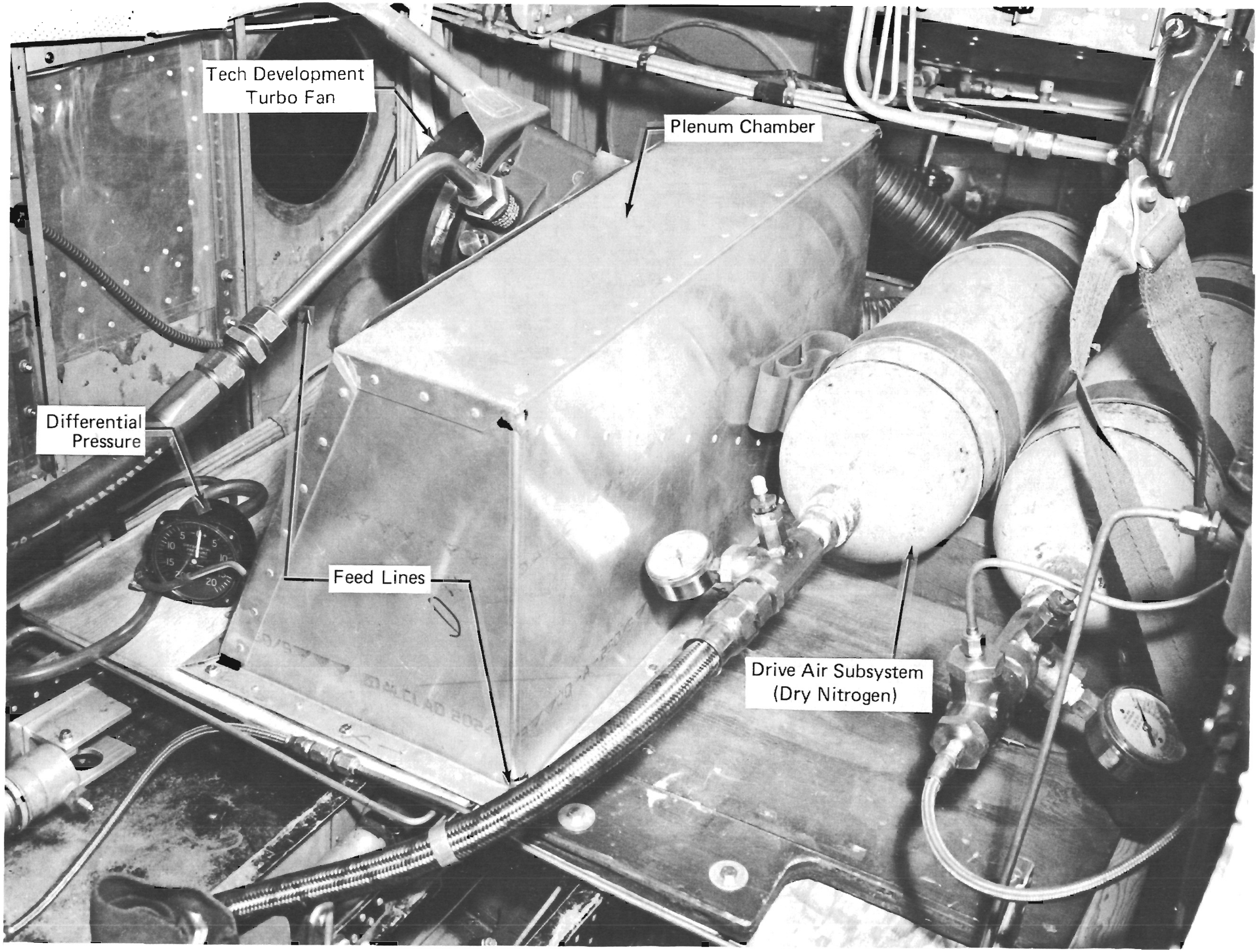

Figure 3. ACLS Suction Braking System

Figure 4. Cockpit ACLS Controls and Gauges

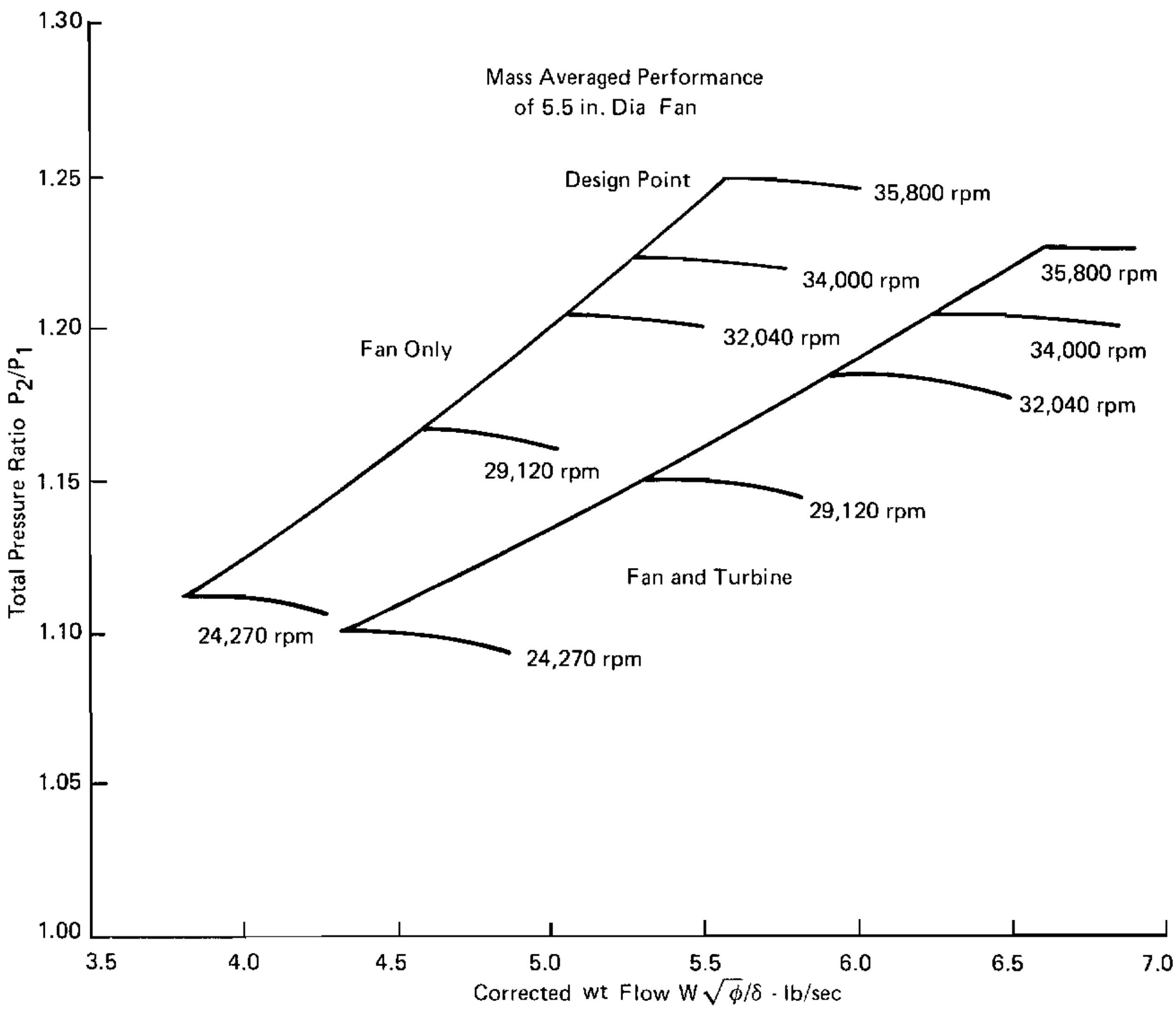

Figure 5. Suction Fan Characteristics

For all tests, the following addition applies:

	Weight	ARM	Moment
Pilot	143	62.25	8,902
Loading (Start)	2,693	105.0	282,655

Pitch attitude on cushion as measured in static tests was +1.0° (nose up).

In subsequent testing, there were no configuration changes and the same pilot performed all operations. Since engine run times were relatively short, selective refueling was used to maintain the desired test loading.

Air Cushion System

To obtain the two airflow conditions required, a plan was adopted in which the trunk was initially configured with 1070 5/16-inch long slits which in the inflated condition had an effective nozzle area of 67 in.^{2} for the lower flow condition. Two 3-in. diameter ports having an outlet area of 14 in.^{2} were opened into the engine bay to permit the ACLS lift fan to operate near the peak of its pressure/flow curve.

After operation T12-0424, a higher flow configuration was obtained by adding 278 additional holes (no plugs) inside the ACLS ground tangent adding 14 in.^{2} for a total effective nozzle area of 81 in.^{2}. The two bay ports were sealed to retain the same fan operating condition.

In the first three taxi operations, a total of 62 plugs separated from the trunk, primarily on/near the ground tangent line in the rear corner sections. Replacements were inserted before Op. No. T4 but plugs continued to be pulled out during taxi. Another attempt at replacing missing plugs was made during Op. No. T-8 but the losses continued. Figure 6 shows the approximate number of nozzle inserts remaining versus accumulated taxi time. The nozzle plug population is thought to have had a significant influence on the braking effectiveness.

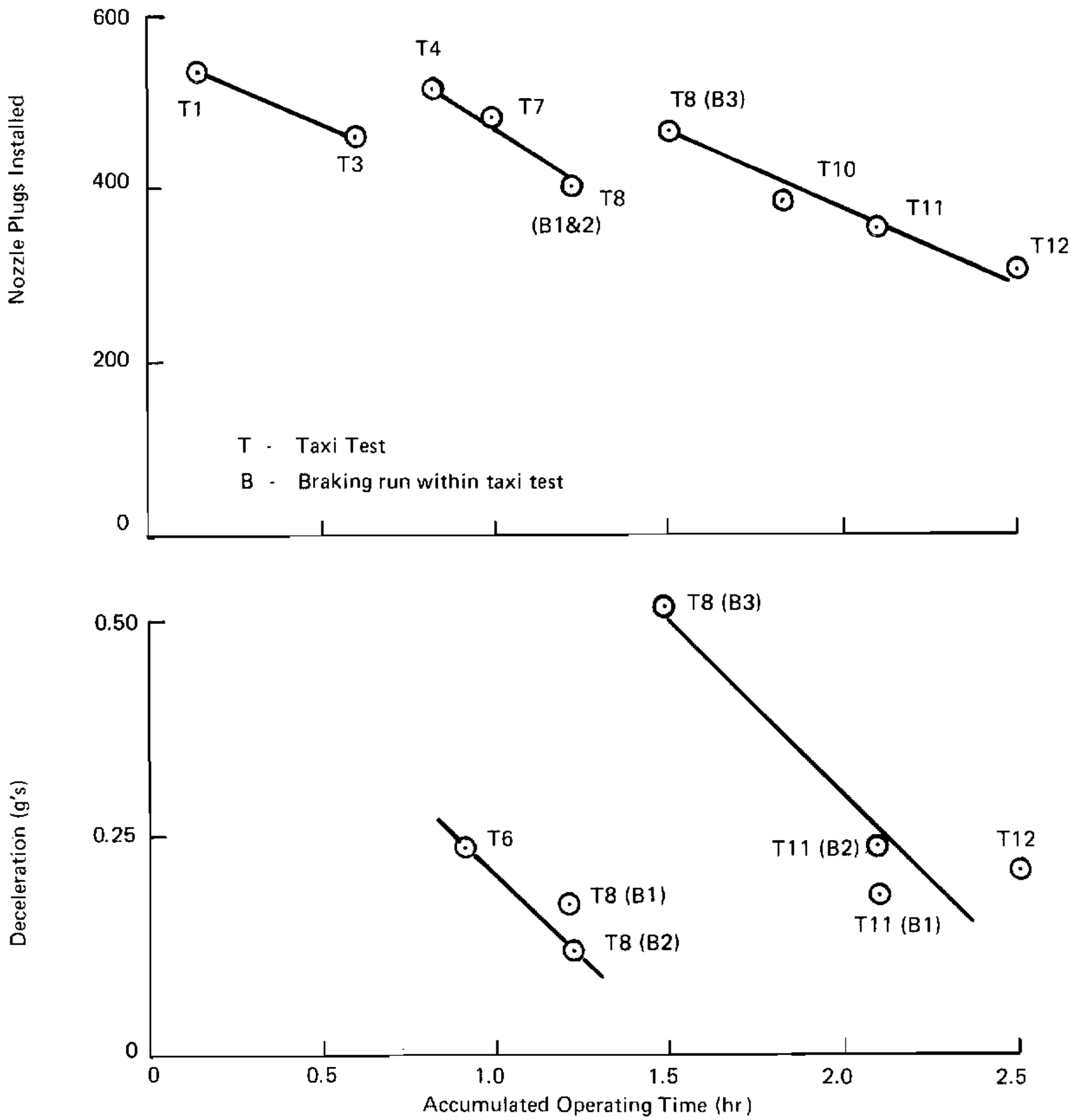

Figure 6. Nozzle Plug Retention and Deceleration Rate Histories

INSTRUMENTATION

An instrumentation system was installed to measure pressures, accelerations, craft crab angle and velocity. The system consisted of 8 transducers, a balance box, transducer power supply, a calibration and trace identification box and oscillograph. A block diagram of the system is shown in Figure 7. The parameters and transducers are tabulated in Table 1.

The oscillograph used was a 3-1/2 in. paper width, Midwestern Model 560A. The oscillograph was operated from 24 volts dc, the source of which was derived from the additional battery used to start the lift fan engine and the normal 12 volt ship's battery, with which it is connected in series.

The data system which fed the 3-1/2in. oscillograph recorder was tied together into a system by a unit containing both the transducer power supply and a calibration/trace identification stepper switch. A calibration resistor network and timing system to drive the stepper switch at a preset rate allowed verification of trace identification, calibration and paper speed. A six channel balance box was installed to condition the strain gage transducers, i.e., pressure and acceleration.

Lift fan plenum bleed flow was determined from outlet total load which was sensed at one starboard exhaust nozzle by a Statham PL731TC transducer.

Trunk pressure was sensed at a forward starboard location by a Statham P6BTC transducer.

Cushion pressure was sensed at approximately the center of the cushion area at the craft bottom using a Statham PM96TC transducer.

The suction fan flow was determined from outlet total head which was measured at one point in the outlet nozzle on the starboard side of the craft. This pickup point was checked to determine its representation of average flow conditions

TABLE 1

PARAMETER LIST

Channel No.	Parameter	Transducer
1	Lift Fan Pressure	Statham PL731TC
2	Trunk Pressure	Statham P6bTC
3	Craft Heading Angle	130-50
4	Longitudinal Acceleration	Statham A69TC
5	Cushion Pressure	Statham PM96TC
6	Vertical Acceleration	Statham A69TC
7	Suction Fan	C.E.C. 4-312
8	Craft Speed	Elinco PM-2

and found to be 6% low; data therefore was corrected to reflect actual flow. The transducer utilized here was a C.E.C. Model 4-312.

Horizontal and vertical accelerations were measured by two Statham A69TC accelerometers mounted on the aft cabin wall, on the craft's centerline near the center of gravity. Craft crab angle was sensed by a potentiometer mounted at the port skid swivel point. As the skid rotated to align

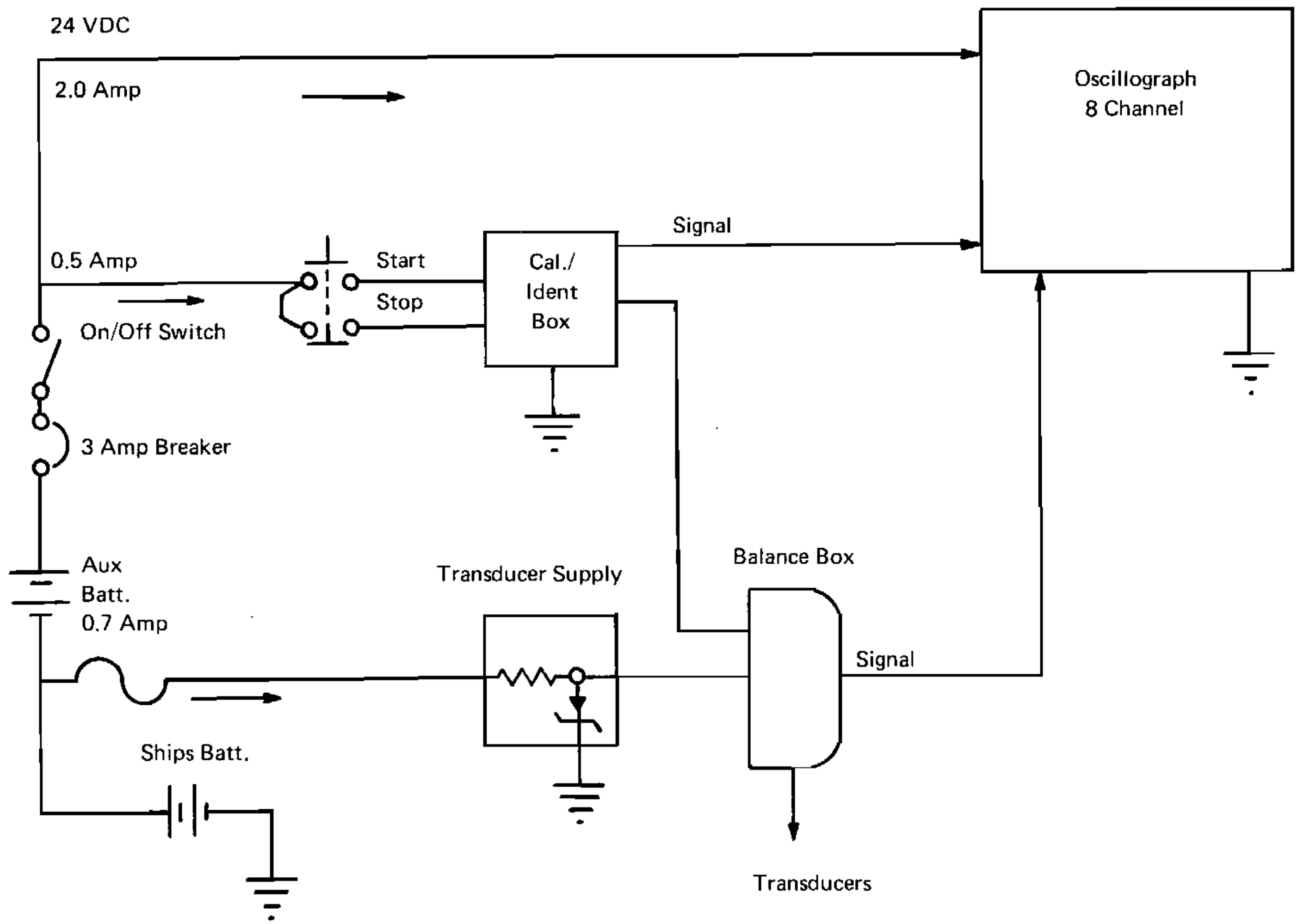

Figure 7. Instrumentation Block Diagram

itself with the craft direction, craft speed was sensed by a bicycle wheel mounted to trail the skid. Belt drive attached the wheel to an Elinco d.c. tachometer which was calibrated to yield craft speed in miles per hour (Figure 8).

The data system was installed at the normal location of the starboard seat (Figure 9). The system, other than transducers and their interconnecting cables, occupied approximately 0.9 cubic feet and weighed 23.6 pounds. Power and calibration controls were mounted on the instrument panel convenient to the pilot. The transducers were calibrated prior to installation and functionally verified after installation. The craft crab angle transducer was calibrated after installation was completed.

Figure 8. Speed and Crab Angle Wheel

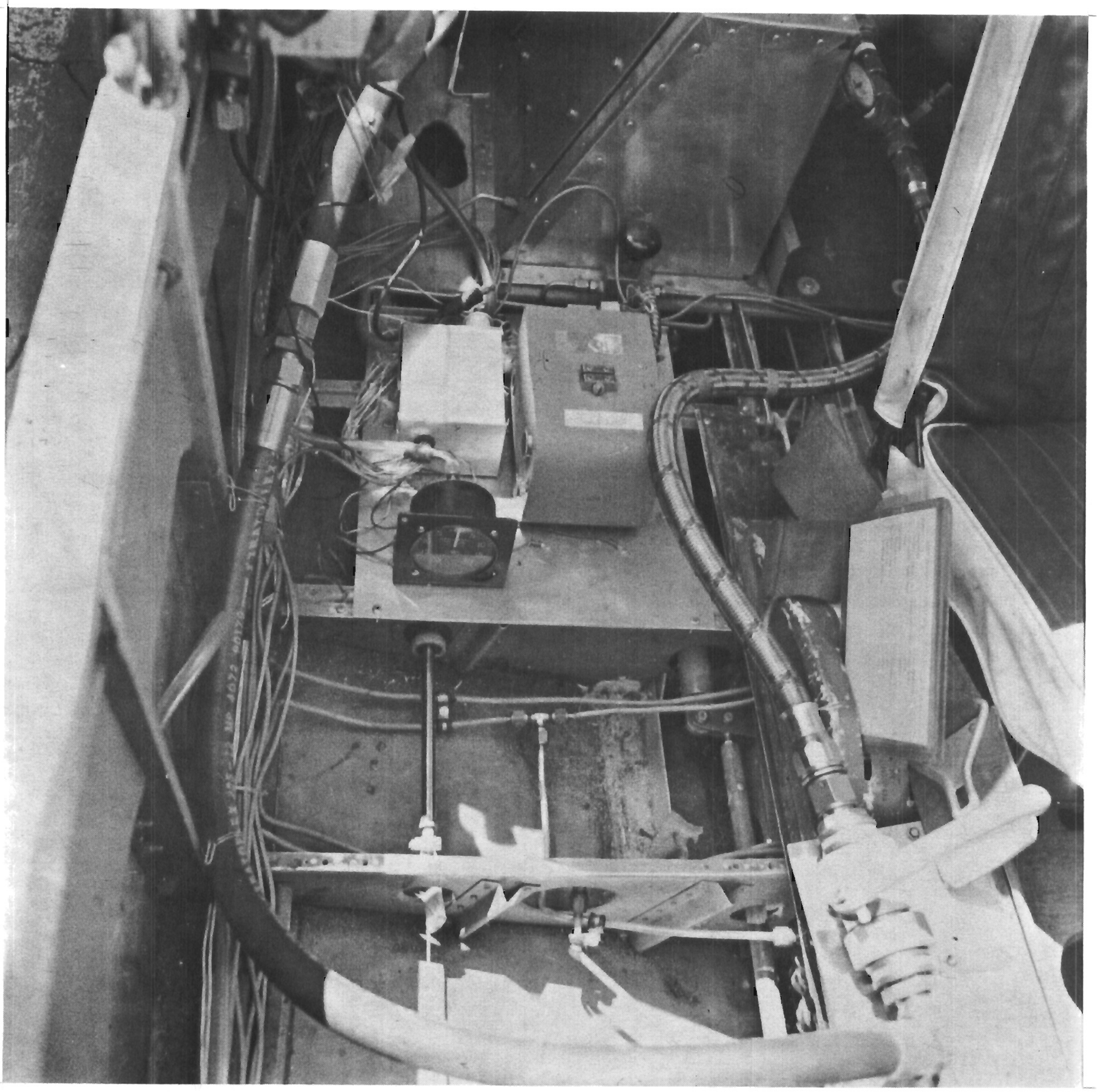

Figure 9. Data System

TEST SUMMARY

Test operations to investigate suction braking were initiated on 14 March 1975 following modification/preparation of ACLS LA-4 test bed aircraft and were completed on 29 May 1975. Approximately five hours of running time were accumulated on ACLS/LA-4 systems and an estimated 12 miles taxied over various surfaces. Table 2 is a chronological listing of tests performed.

TABLE 2
TABLE OF OPERATIONS

Operations Number	Tests Performed	Engine Time (hr) Propulsion	Lift
R1-0314	First Run of replacement McCullough		0.1
S1-0320	Initial trunk inflations; functional tests of suction brakes		0.3
S2-0324	Configuration/shape check of inflated trunk out of ground effect; in hangar pull tests on concrete/without skids		0.3
R2-0325	Depreservation run of Lycoming engine; functional test of LA-4 systems (hydraulic, electrical, etc.)	0.7	
S3-0326	In hangar pull tests with skids on concrete		0.1
T1-0326	First taxi test over dry concrete	0.3	0.2
T2-0327	Taxi demonstration over dry concrete	0.2	0.2
T3-0327	Taxi tests on dry concrete	0.3	0.2
T4-0402	Taxi tests on dry concrete	0.2	0.2
T5-0402	Taxi/braking tests on dry concrete	0.2	0.2
T6-0407	Taxi/braking tests on wet concrete	0.2	0.2
T7-0410	Taxi/braking tests on dry concrete	0.2	0.2
T8-0411	Taxi/braking tests on dry concrete (photos)	0.2	0.2
T9-0414	Taxi/braking tests on grass (photos)	0.3	0.3
T10-0415	Taxi/braking tests on dry concrete (photos)	0.3	0.3
S4-0416	Pull tests on grass	0.1	0.1
T11-0417	Taxi/braking tests on grass (photos)	0.3	0.3
T12-0418	Taxi/braking tests on wet concrete	0.4	0.7
T13-0528	Qualitative taxi/braking at higher flow	0.2	0.1
T14-0528	Taxi/braking tests on wet concrete (photos)	0.2	0.2
S5-0528	Pull tests on dry concrete; configuration/shape check of inflated trunk out of ground effect		0.2
T15-0529	Taxi tests on grass	0.3	0.2
S6-0529	Pull tests on grass		0.1
	Total Run Times	4.7	4.9

Legend
R = Run of engine/s for checkout
S = Static tests
T = Taxi
OXOX = Date of Test
Exp: 0314 is 14 March 1975

RESULTS AND DISCUSSION

General

The intent of the suction braking program using the ACLS (LA-4) test craft was to accomplish a series of tests under specified conditions in which data could be gathered to evaluate the potential of the concept. All of the planned test conditions were accomplished and the significant data obtained and evaluated. However, an unanticipated test variable occurred which precludes certain direct comparisons and complicates the overall analysis.

To conserve cost, the identical nozzle plug to that in use on the XC-8A was selected, the plugs being inserted in approximately alternate jet slits. They perform two functions:

1) They absorb wear.

2) They reduce flow in a footprint since the footprint load (equal to trunk pressure multiplied by footprint area) is supported upon the plugs whose individual footprint sum is less than the total trunk footprint; thus the contact pressure exceeds trunk pressure, and flow across the membrane into the footprint is reduced by closure of the nozzle plugs against the ground. Air lubrication is reduced by this process, a phenomenon which is highly desirable in the suction braking case.

Use of the XC-8A nozzle inserts (or plugs) in the LA-4 ACLS trunk was an expedient which proved to be unsatisfactory because a basic incompatibility in the nozzle shape/plug design resulted in many plugs in the ground tangent area of the trunk being pulled out by surface protruberances at rates that can be only generalized (see Figure 6). Air lubrication of the trunk is increased as plugs are lost, and application of the suction brake has less effect since the total ACLS drag is decreasing.

The results reported herein are therefore in more generalized terms than desired. However, they show the potential of the suction braking concept and establish approximate relationships between suction pressure and flow and cushion pressure and flow.

Shakedown Tests

Following the modification/refurbishment of the LA-4, a series of tests was first performed in preparation for investigation of the ACLS suction braking subsystem. The lift fan and replacement McCullough 0-100-1 engine were run and initial trunk inflated functional tests of the suction brake subsystem successfully accomplished. On Op. No. S2, the bay nozzle areas were varied to arrive at a satisfactory trunk pressure of 140 psf for follow-on tests. The Lycoming propulsion engine was operated and functional checks of all aircraft systems were performed. Minor discrepancies in lift engine tachometer, fuel feed, etc., were corrected.

Pull Tests

In no-wind conditions (in hangar) and near calm wind conditions on grass, a series of pull tests were accomplished. A 60-ft. tow bridle was rigged to the propulsion engine support brackets to approximate the normal propeller thrust plane and the airplane was pulled with an 18,000 lb.

tug. On each test, a series of measurements were made of the breakaway and free sliding force required. The average values are shown in Figure 10. Additionally, with the airplane underway at an estimated 3-4 fps, the suction brakes were actuated and the peak pull force observed and recorded.

The data for low and high trunk airflow conditions over dry concrete and grass are generally as expected. Figure 10 also contains data extracted from ACLS (LA-4) pull tests performed on previous AFFDL programs. The change relative to surface is similar and the magnitude of the increase over both terrains is accountable by the fewer nozzle holes (1070) in the present trunk (approximately 2200 in the 1969 trunk) providing a significantly lower air lubrication. Additionally, the present trunk has approximately 500 nozzle plugs which increases friction drag over that experienced in trunks having no plugs.

Taxi/Braking Tests

Following completion of baseline tests to confirm trunk shape, calibrate instrumentation, and verify functional operation of test systems, a series of taxi tests was initiated on the low flow ACLS trunk configurations. In general terms, the programmed sequence was: low speed taxi over dry pavement in straight ahead (0° crab or heading angle) and yawed (crab or heading angle $\neq 0$), at high speeds over the same surfaces, and a repeat of hard surface tests over wet concrete and grass. The technique used was to taxi at a specific power setting that maintained a constant speed and apply suction without changing throttle setting until after suction was discontinued when it was brought to idle. (Illustrations of the test surfaces are contained in photographic coverage submitted in conjunction with this report.) Selected tests were later performed in a configuration producing a higher ACLS airflow.

Data gathered from significant tests are included as Table 3. The values shown have been normalized (corrected for deviations from the +15°C, 29.92 in. hg NASA 1962 Standard Day) where applicable and corrected/calibrated for all known instrumentation system's errors. Where deviations in reference trunk/cushion pressures appear, they have been verified to be in agreement with aircraft ACLS operating instrument readings and are assumed to reflect the actual magnitudes. The variances must then be dependent on the test surface, changes in effective nozzle area with loss/replacement of nozzle plugs or perturbations in the lift engine/fan performance around the 4100 rpm and 200 ft^3/sec nominal output at the test full throttle reference.

Detailed examination of the data taken tend to confirm that observed decreases in braking effectiveness (deceleration ~ g's) are primarily a result of changes in the number of nozzle plugs in the trunk. A comparison of Table 3 and Figure 6 shows temporary gains after replacement of lost nozzle plugs. The presentation of nozzle plugs remaining and deceleration versus accumulated taxi time illustrate that a dependent relationship is probable.

The time histories of the tests where significant levels of braking were attained have similar characteristics with repeatable relationships of peak to average deceleration and velocity decrease. At higher speeds, since the activation time on the test suction braking system is limited to approximately 6 seconds due to the capacity of the nitrogen bottle, the cushion pressure partially recovers resulting in lower deceleration and flattening of the velocity trace prior to stopping (0 ground velocity). Since the limited duration is peculiar to the test vehicle, the average deceleration attained can be used to compute a corrected stopping distance.

A typical time history of the significant parameters is presented in Figure 11.

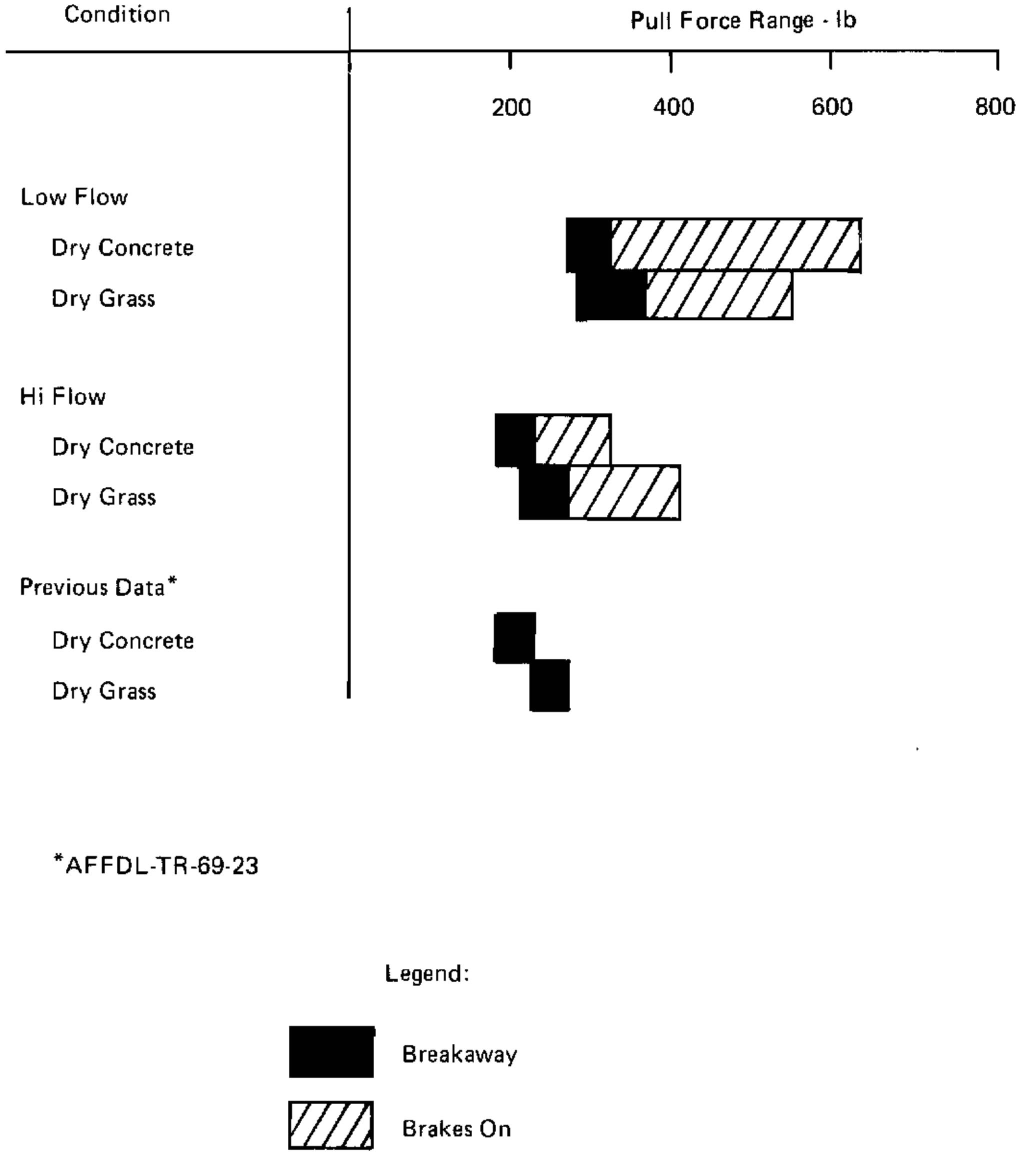

Figure 10. Measured Pull Forces

TABLE 3
BRAKING TEST DATA

Operations Number	Trunk Pressure (psf)	Trunk Flow (cfs)	Crab Angle (deg)	Maximum Longitudinal Acceleration (g's)	Minimum Cushion Pressure (psf)	Minimum Vertical Acceleration (g's)	Suction Fan Flow (cfs)	Suction Time (sec)	Suction Application Speed (mph)	Notes
T6-0407	139	165.6	-	0.24	-18	0.17	64.4	0.5	7.8	No stop — wet concrete
T8-0411 B1	152	175.0	-	0.15	12	-	52.2	2.7	7.0	3.0 sec. to stop — dry concrete
B2	144	167.9	5.9	0.12	12	-	52.2	3.0	6.7	2.5 sec. to stop — dry concrete
B3	144	167.9	3.0	0.50	-18	-	57.1	2.6	8.9	1.3 sec. to stop — dry concrete
T9-0414	111	147.0	-12	0.44	-13	0.2	64.3	2.3	11.8	1.3 sec. to stop — grass
T10-0415B1	144	167.9	-12	0.06	0	-	51.2	3.6	11.8	1.3 sec. to stop — dry concrete
B2	139	165.5	-	0.10	-10	0.14	52.2	6.6	39.2	11 sec. to stop — dry concrete
B3	161	181.0	-	0.04	0	-	52.2	7.0	32.5	No stop — dry concrete
T11-0417 B1	127	159.0	-	0.15	0	-	54.3	5.0	20.2	6 sec. to stop over grass
B2	127	159.0	-	0.22	-3	-	60.8	5.0	29.4	6.2 sec. to stop over grass
T12-0418	139	165.5	-	0.21	0	-	54.6	3.7	6.2	2.2 sec. to stop wet pavement
T-14 0528	140	166.4	-	0.06	0	-	54.5	5.0	15.0	No stop — wet concrete

B - Braking run during taxi test

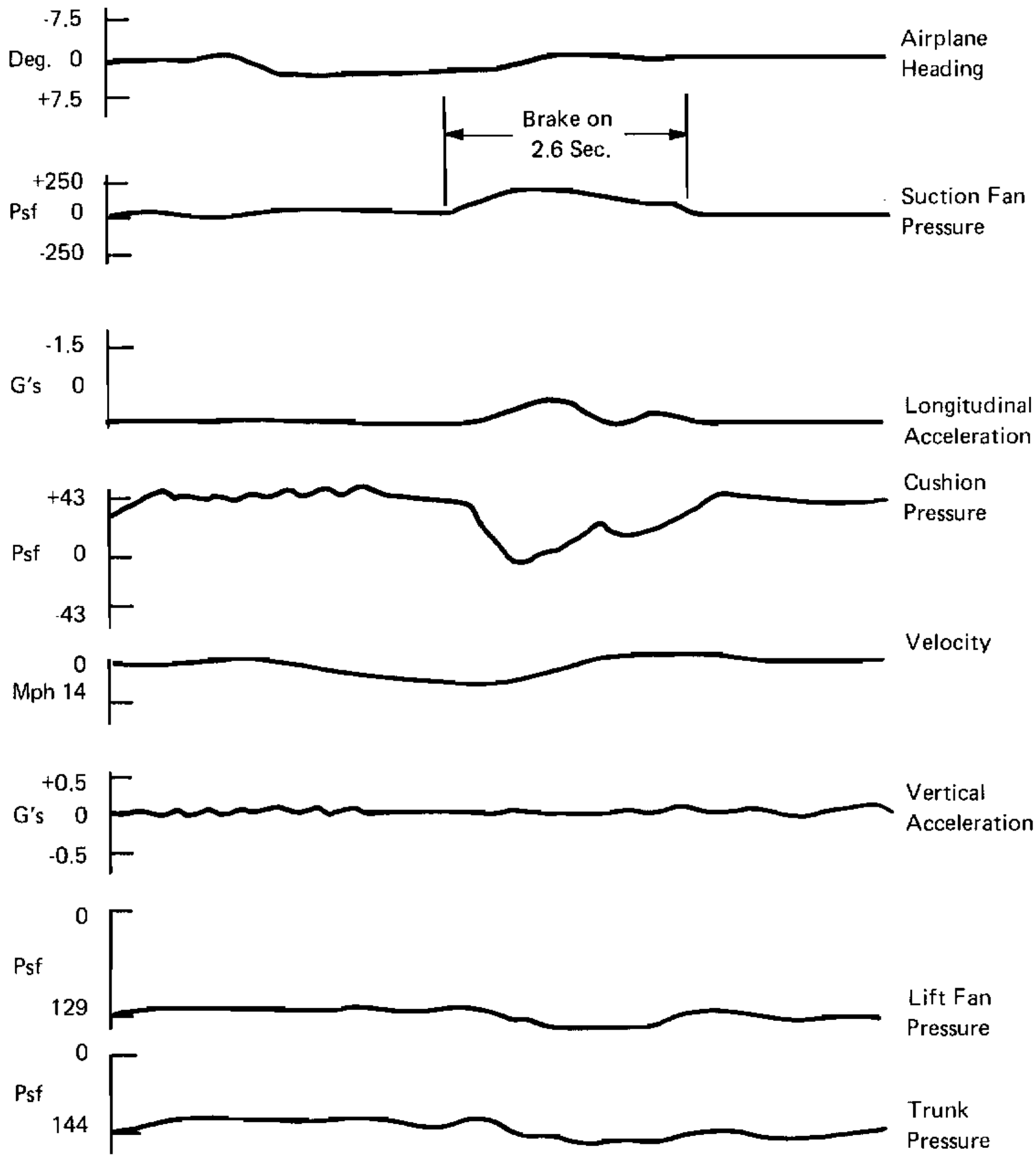

Figure 11. Typical Braking Time History

Comparison With Pillow Braking

Meaningful comparisons of suction braking results with pillow braking results are difficult to make for the following reasons:

1) Scarcity of data points

2) Widely diverse test conditions such as thrust level and wind velocity and direction

3) The effect of wing lift with increasing speed which causes variations in braking acceleration level for a given cushion pressure

4) Suction pressures and deceleration ratio vary during braking runs

5) The difficulty of wear plug retention in the suction tests, the loss of which affected braking ability.

Several approaches to correlation of the suction braking test data were made with the following giving the best results.

As noted previously, the tests were conducted by bringing the airplane up to speed then applying the cushion suction without changing throttle setting. From pull tests, the thrust required once breakaway has been accomplished, is about 200 lb. The accelerations of Table 3 were corrected by the equivalent acceleration due to this force or 0.0715 and plotted versus cushion pressure in Figure 12. The points for wet concrete and high speed were ignored in fairing the curve because the wet concrete apparently has a much lower friction coefficient than the other cases and the points at high speed had insufficient suction time available. The suction expired while there was still sufficient lift on the wings to reduce the maximum decelerations.

The point at 41 psf cushion pressure represents zero suction, or the 0.0715 g's discussed above.

Figure 12 was used to calculate stopping distances as functions of cushion pressure and initial velocity again assuming constant rates of deceleration. The results are plotted in Figure 13. Superimposed are pillow braking data points from previous LA-4 tests for velocities of 45 and 60 mph. It is significant that the points for macadam surface all lie near a constant suction cushion pressure for suction braking. The pillow brake tests did not have suction, only venting. From these data it can be inferred that pillow braking is equivalent to suction braking with the cushion pressure sucked down to about 12 from the normal of about 40 psf. The data point for grass is also shown for pillow brake tests. The greater stopping distance on grass must be due partly to lower friction.

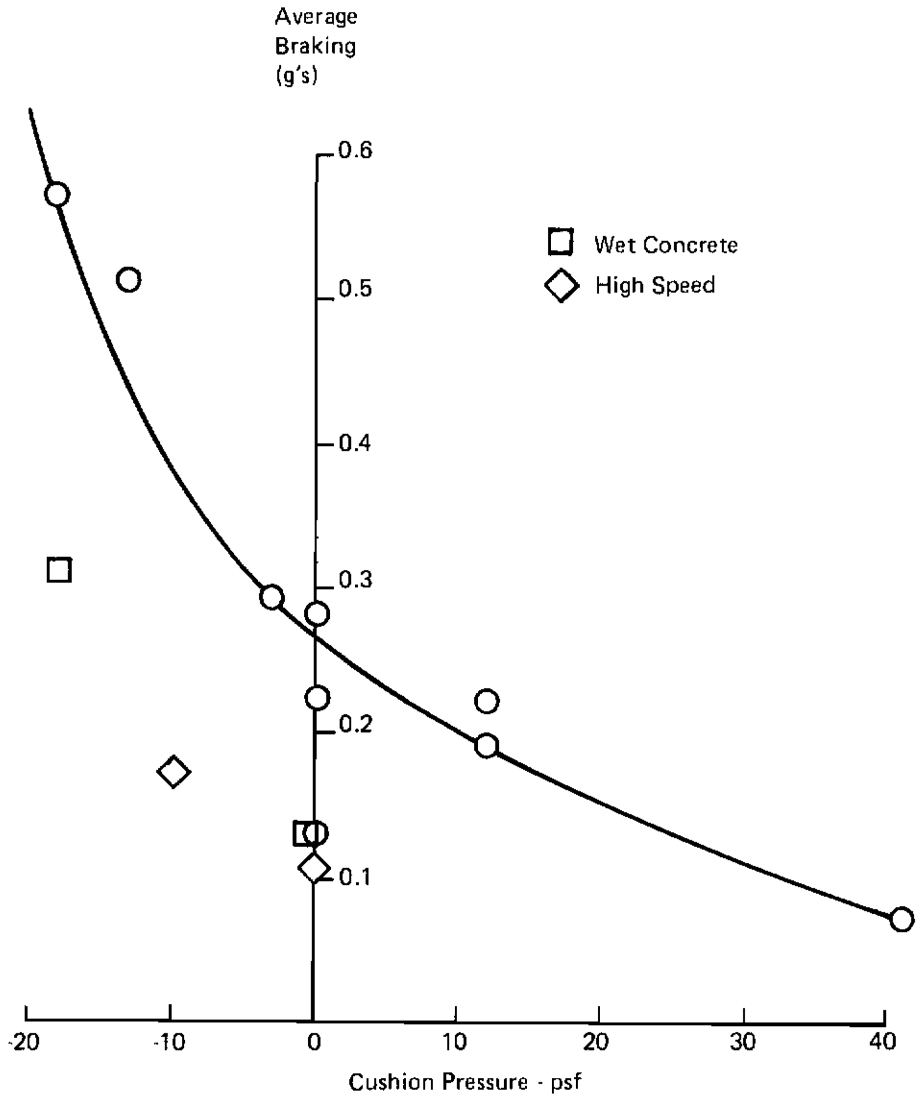

Figure 12. Effect of Cushion Pressure on Suction Braking

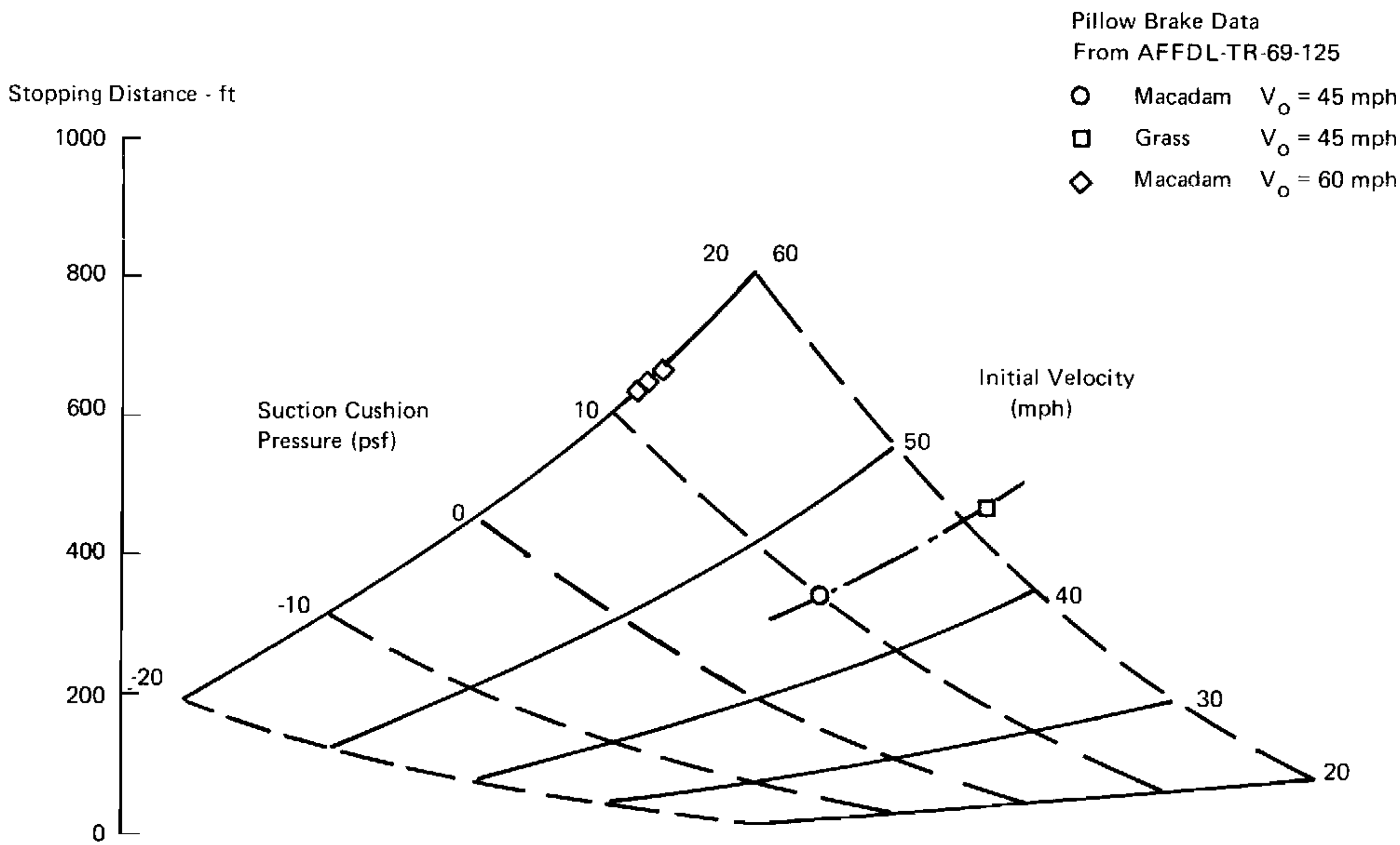

Figure 13. LA-4 Pillow and Suction Braking Comparison

EXTRAPOLATION OF SUCTION BRAKING TO THE C-130, JINDIVIK AND XC-8A

C-130 ACLS

One possible configuration for a C-130 with ACLS is illustrated in Figure 14. This embodies a wide, egg shaped planform for improved roll stiffness, as compared to the XC-8A configuration, and was selected for this analysis because it maximizes the base area for suction.

The basic characteristics of the C-130 ACLS are as follows:

Airplane Gross Weight, lb	155,000
Cushion Area, sq. ft.	589
Cushion Pressure, psf	263
Trunk Pressure, psf	488
Trunk Flow at 1-g, cfs	1,400

Figures 15 and 16 illustrate the lubrication concept. A narrow swath around the trunk ground tangent contains a hexagonal pattern of jet nozzles in the trunk with a solid wear plug in the center of each of the hexagons. These plugs protect the trunk area that has the most contact with the ground from wear. This area at the aft end of the trunk is generally in contact during normal taxiing due to the location of the airplane center of gravity aft of the cushion center of pressure. The nozzles around the wear plugs permit lubrication flow when the wear plugs are in contact with the surface. They are not closed off as would be the case with nozzles in the plugs themselves. The width of this area varies from 6 inches at the forward end of the trunk to 10 inches at the aft end.

Outboard of the above area, there are solid wear plugs but no jet nozzles. The wear plugs extend a distance of 18 inches from the ground tangent to protect the trunk from wear during landing and braking.

Inboard is a pattern of nozzle plugs for the same radial distance. This nozzle area primarily provides the required cushion flow to maintain cushion pressure. However, when suction braking is applied and the nozzle plugs come in contact with the surface, the nozzles are closed off, reducing the cushion flow and thereby reducing the suction flow that would otherwise be required.

A typical variation in cushion and footprint widths with cushion pressure and ground height is shown in Figure 17 for one longitudinal station. The decrease in cushion area with suction and stroke indicates the desirability of a wide cushion relative to the trunk cross-section size to minimize the percentage reduction in effective suction area as suction is applied.

To determine the suction requirements for the C-130 airplane, the results from the LA-4 tests were plotted as the ratio of cushion pressure with suction to cushion pressure without suction versus the ratio of suction flow to cushion flow as shown in Figure 18. Due to the different lubrication nozzle patterns wherein the LA-4 nozzles were approximately equally distributed inboard and outboard of the ground tangent but the C-130 has no nozzles outboard, it was assumed that the LA-4 trunk flow was equally divided between the cushion and to the outside. Since the data points were clustered within a small area of Figure 18 due to the suction fan limits, a straight line variation was assumed from the zero suction point through the data points to the point representing a negative suction pressure equal to the normal cushion pressure. This suction pressure should provide ample braking.

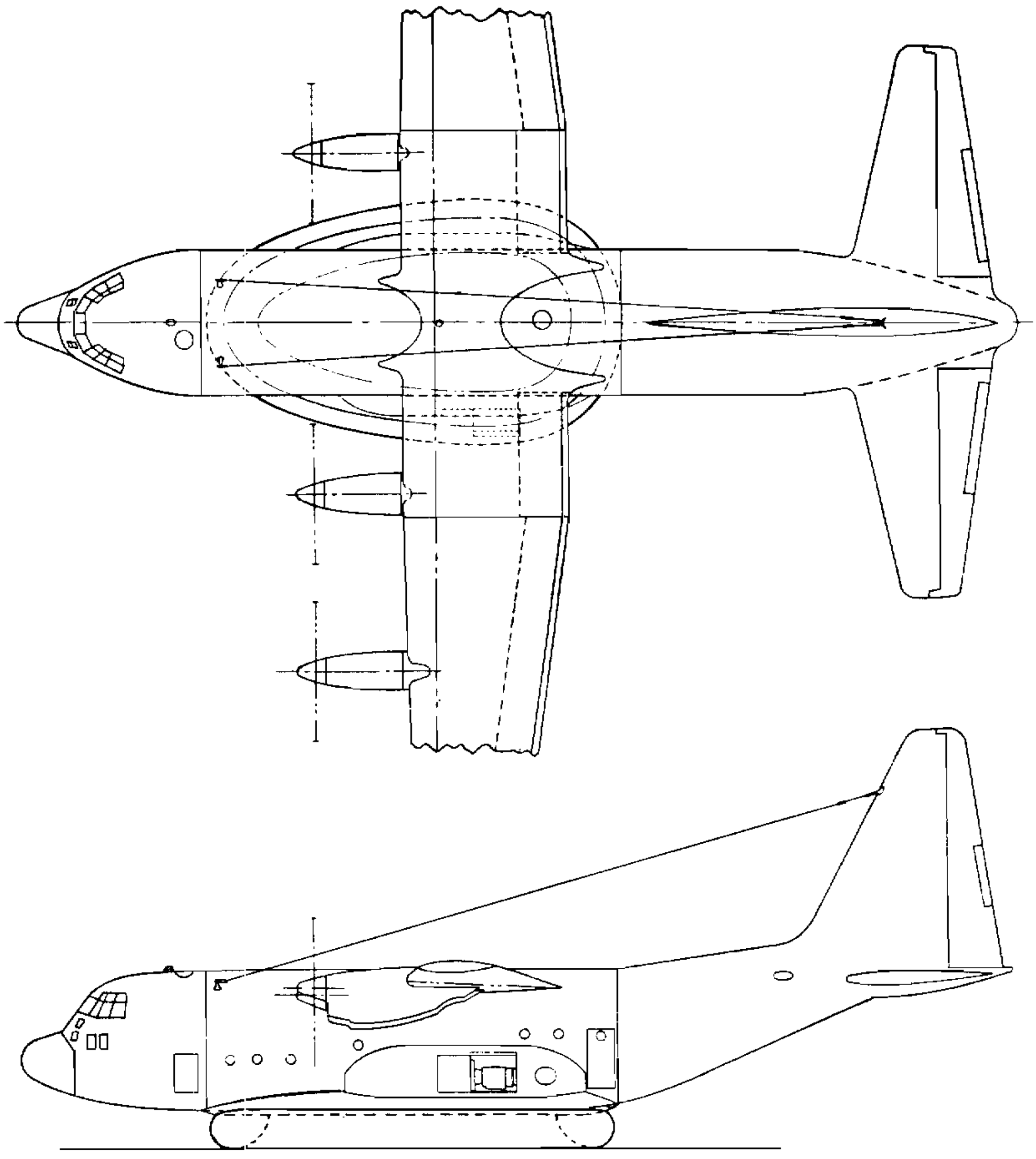

Figure 14. C-130 ACLS Configuration

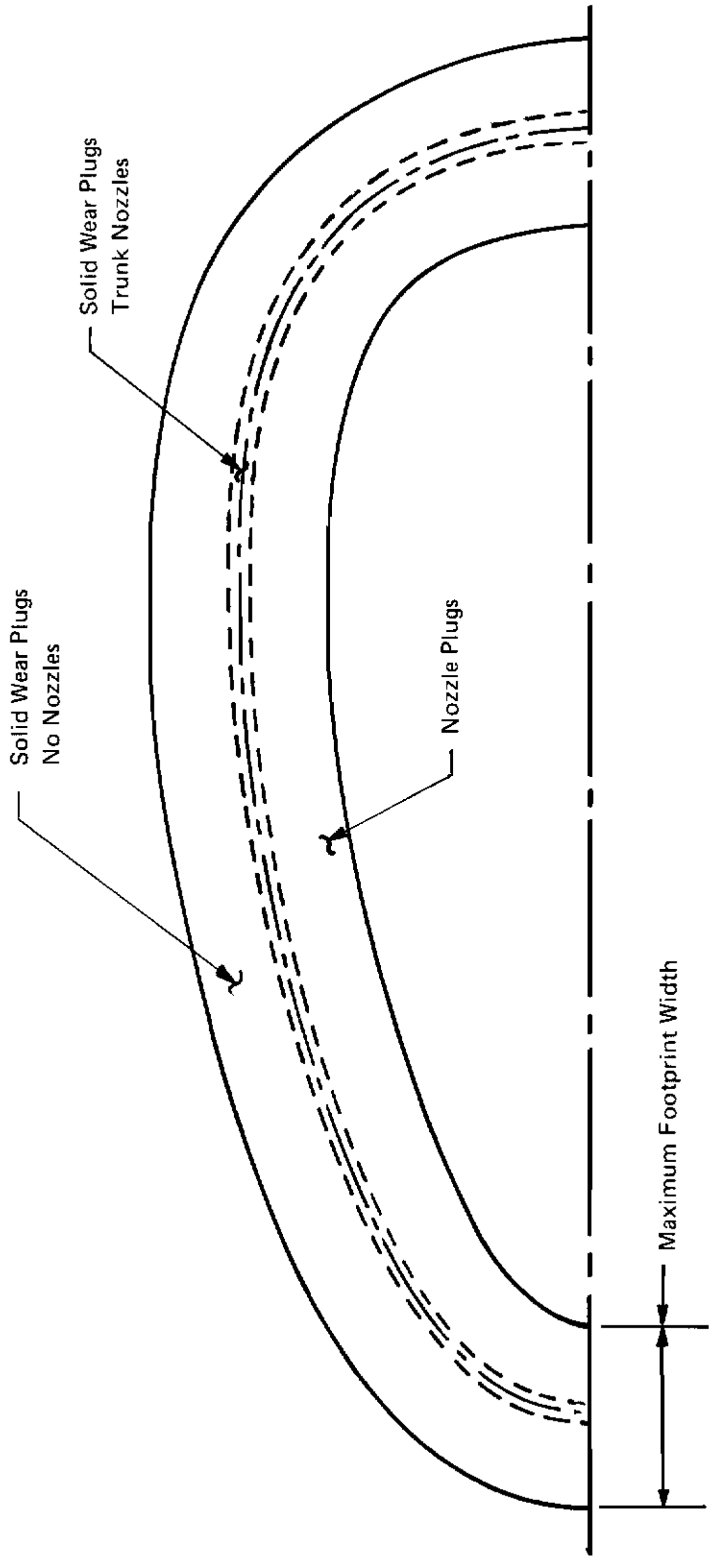

Figure 15. C-130 ACLS Lubrication Pattern

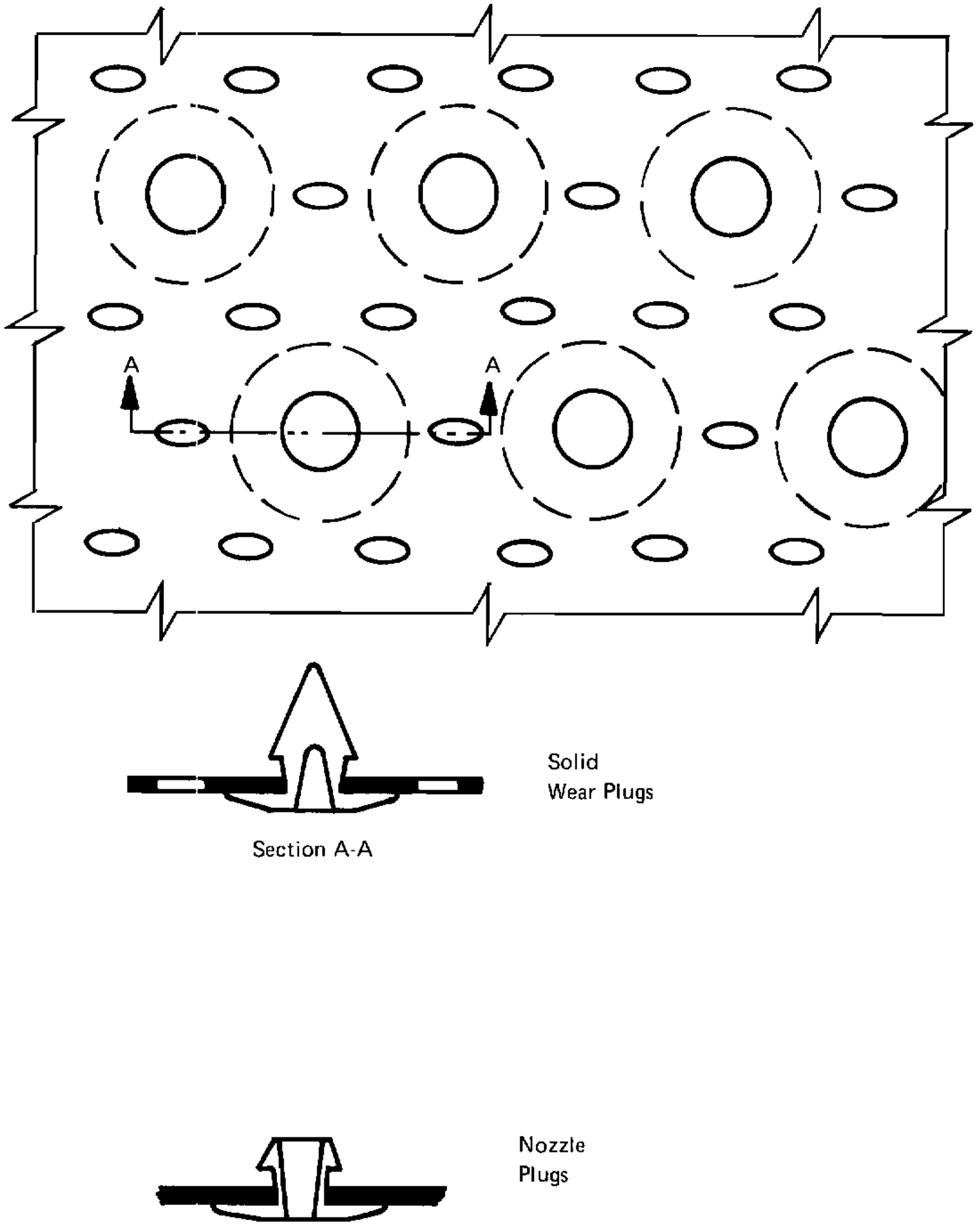

Figure 16. C-130 Lubrication Nozzle Details

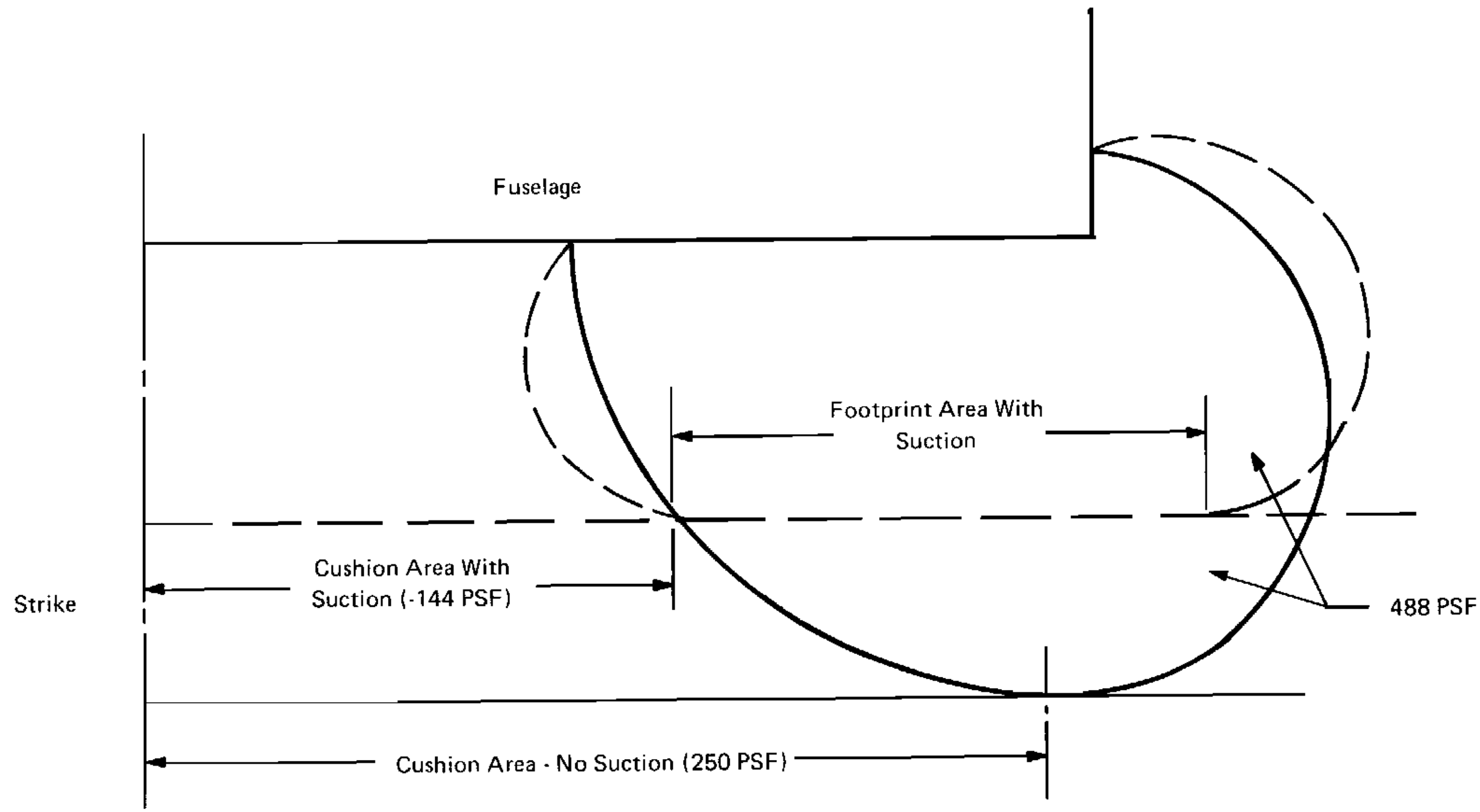

Figure 17. Cushion Geometry Variation with Suction

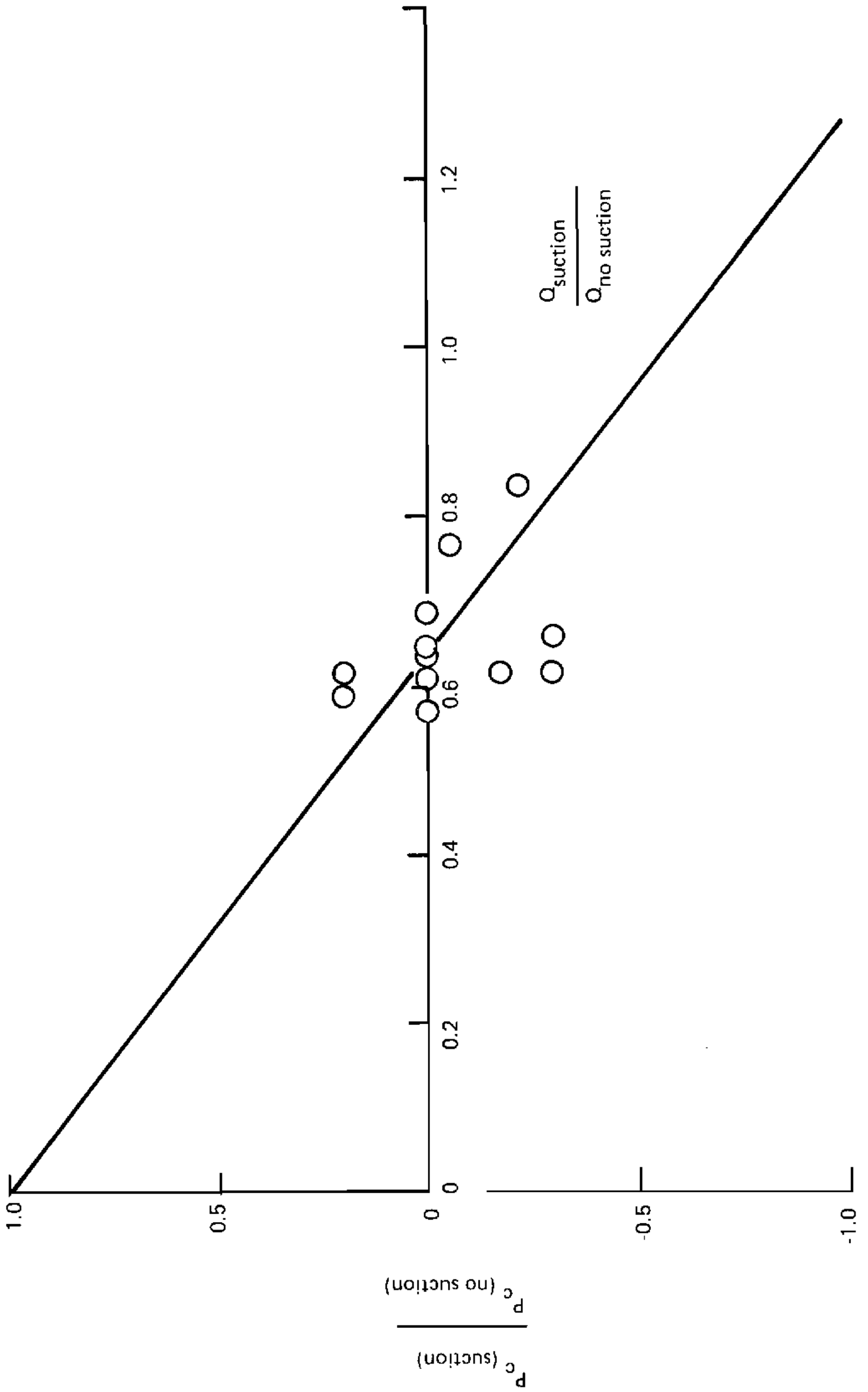

Figure 18. LA-4 Suction Braking Results

To determine the cushion flow, a level airplane attitude was assumed and equilibrium conditions were calculated for variations in stroke. That is, at a given stroke the cushion pressure was varied, the resulting footprint determined and the vertical forces summed. From cross plots of stroke and cushion pressure, at a given trunk pressure, the equilibrium conditions for a specified weight are obtained. This is illustrated in Figures 17, 19 and 20. Figure 17 illustrates the determination of footprint width. This was done for several locations around the trunk perimeter. Figure 19 illustrates a typical footprint. It is for a 20-inch stroke and trunk and cushion pressures of 488 psf and -144 psf respectively. The vertical forces are as follows:

$$F_{total} = P_t \times S_{fp} + P_c \times S_c$$

$$= 488 \times 440 - 144 \times 366.5 = 161{,}944 \text{ lb}$$

$$F_{footprint} = P_t \times S_{fp}$$

$$= 488 \times 440 = 214{,}720 \text{ lb}$$

Plots of the vertical reactions versus cushion pressure at fixed stroke are made as shown in Figure 20. Airplane equilibrium is the point where the total vertical force is equal to the airplane weight. Thus, for example, at a stroke of 20 inches and an airplane weight of 155,000 lb, the cushion pressure is -157 psf and moving vertically to the footprint reaction, as shown by the dotted lines, it is seen to be 212,000 lb. Equilibrium points are determined for the range of strokes and plotted as in Figure 21, which presents footprint load versus cushion pressure. The footprint patterns generated above determine the extent of nozzles on the cushion side of the trunk that permit flow to the cushion.

To be conservative in estimates of fan flow requirements, the flow in the center "race track" area of trunk nozzles with solid wear plugs was assumed to vary with the square root of the pressure difference between the trunk and cushion regardless of the strokes; the nozzle plugs in contact with the ground completely closed off the flow; and the inboard nozzle plugs not in contact with the ground provided flow as a function of the trunk-to-cushion pressure difference. The resulting cushion flow and cushion pressure ratio used with the LA-4 data of Figure 18 determines the suction pressure and flow required. The calculations of flow for a cushion pressure of +100 psf are as follows:

Trunk area covered with trunk nozzles = 66.0 sq. ft.
Trunk area covered with nozzle plugs = 115.5 sq. ft.

At P_c = 100 psf, the equilibrium stroke is 9 inches and the total footprint area is 175 sq. ft. The nozzle plug area in contact (and closed off) is 175-66 = 109 sq. ft. Thus the nozzle plug trunk area passing flow is 115.5 - 109 = 6.5 sq. ft.

The jet area is then:

$$0.034 \times 66 + 0.023 \times 6.5 = 2.394 \text{ sq. ft.}$$

where 0.034 and 0.023 are the respective porosities of the trunk nozzle area and the nozzle plug area.

Assuming a discharge coefficient of 0.6, the following is the cushion flow:

$$Q = 2.394 \times 0.6 \times 29 \sqrt{488-100} = 820 \text{ cfs.}$$

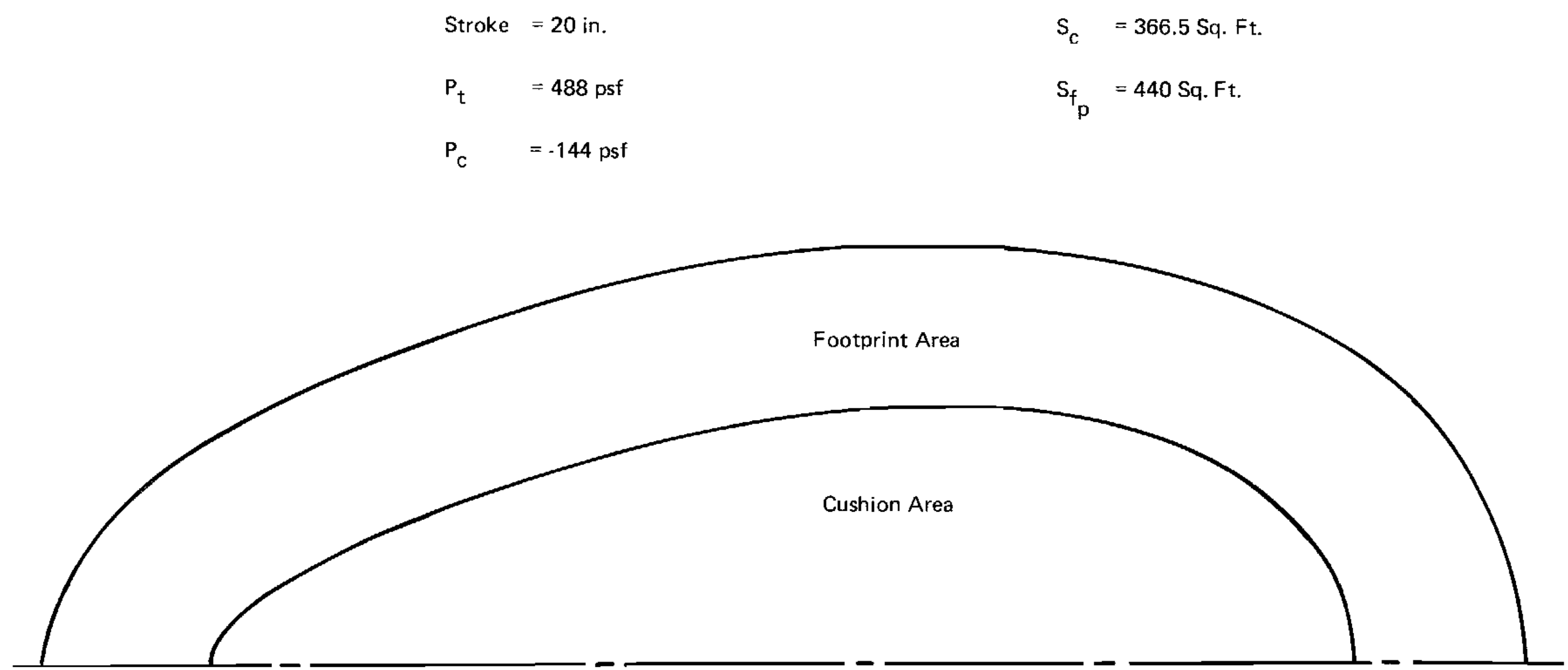

Figure 19. Typical Footprint with Suction

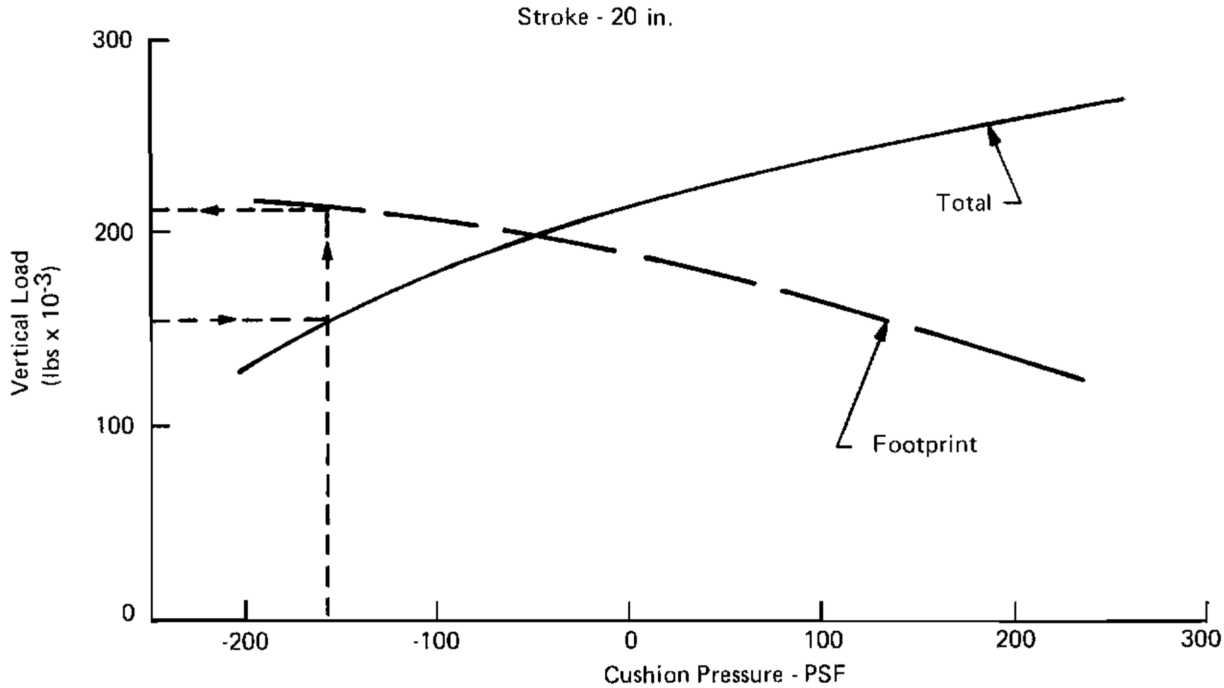

Figure 20. C-130 Vertical Reactions

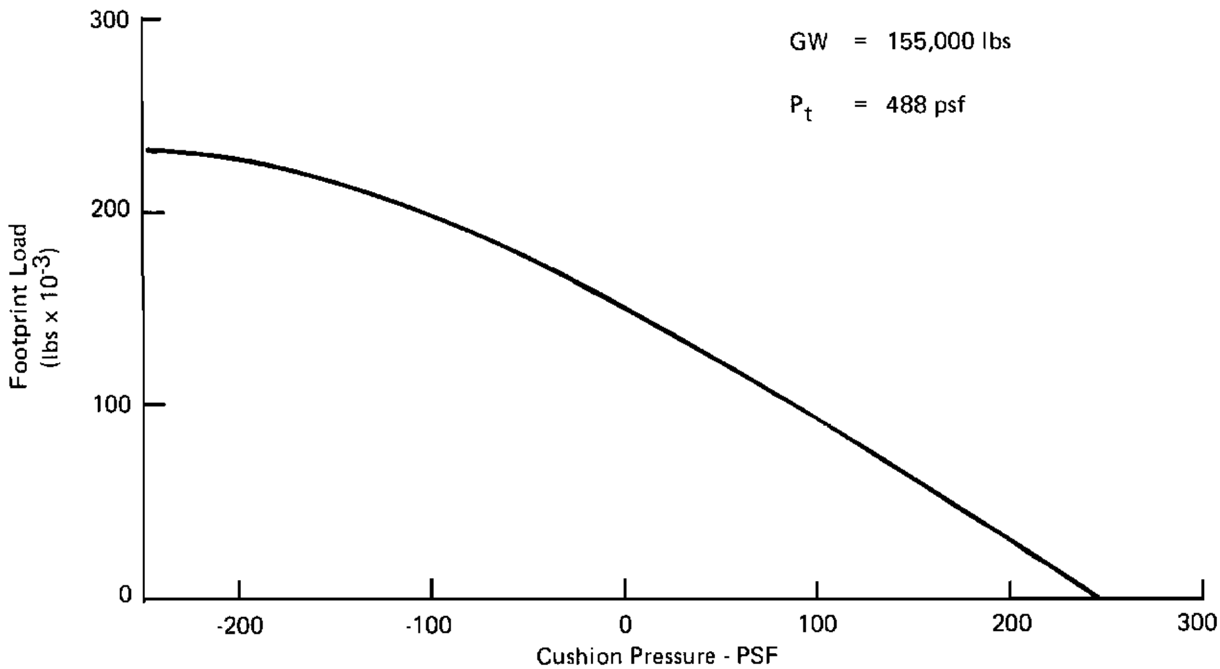

Figure 21. C-130 Air Cushion Vertical Reaction

Then using the suction factor from Figure 18 at a $P_{c(suction)}/P_{c(no\ suction)} = \frac{100}{263} = 0.38$, the suction required is

$$Q_{suction} = 820 \times 0.38 = 312 \text{ cfs.}$$

The results are presented in Figure 22 as suction fan total head rise versus flow rate. The positive region is where the cushion pressure is above ambient and the negative is below ambient. The normal trunk flow is 1400 cfs. Above a head rise of 0 the footprint width is sufficient that all nozzle plugs are closed off. The maximum suction air HP, which is calculated from QΔP/550, is approximately 641 compared with 1800 for the baseline air cushion system.

To determine the braking performance, a friction coefficient is applied to the vertical load of Figure 20. A coefficient of 0.8 yields the following maximum deceleration due to the ACLS alone:

$$\frac{0.8 \times 272{,}000}{155{,}000} = 1.4 \text{ g's}$$

The variation of g's with suction requirements is shown in Figure 23. This is, of course, attenuated by wing lift which has been assumed to be zero in this analysis and will also be less on those sorts of rough surfaces which do not effectively close off the jet nozzles and, in addition, permit more inflow to the cushion from the outside. However, such surfaces will produce a higher basic drag due to irregularities contacting the trunk.

The effect of suction braking on C-130E stopping distance as compared to wheel gear distance was estimated for 155,000 lb weight. The following assumptions were made:

$$C_{L_{max}} = 2.4$$

$$C_{L_{ground\ roll}} = 0$$

$$V_{touchdown} = 1.1\ V_{stall}$$

From Reference 1, the wheeled ground run is 3150 feet.

From the above assumptions the stall speed is calculated to be 176 ft/sec and the touchdown speed is 193.6 ft/sec. Neglecting the time from touchdown through rotation to nose wheel contact and brake application, and considering the entire ground run as an average deceleration, the equation:

$$S = V^2/2a$$

yields an average deceleration of

$$a_{avg} = \frac{V^2}{2s} = \frac{193.6^2}{2 \times 3150} = 5.95 \text{ ft/sec}^2$$

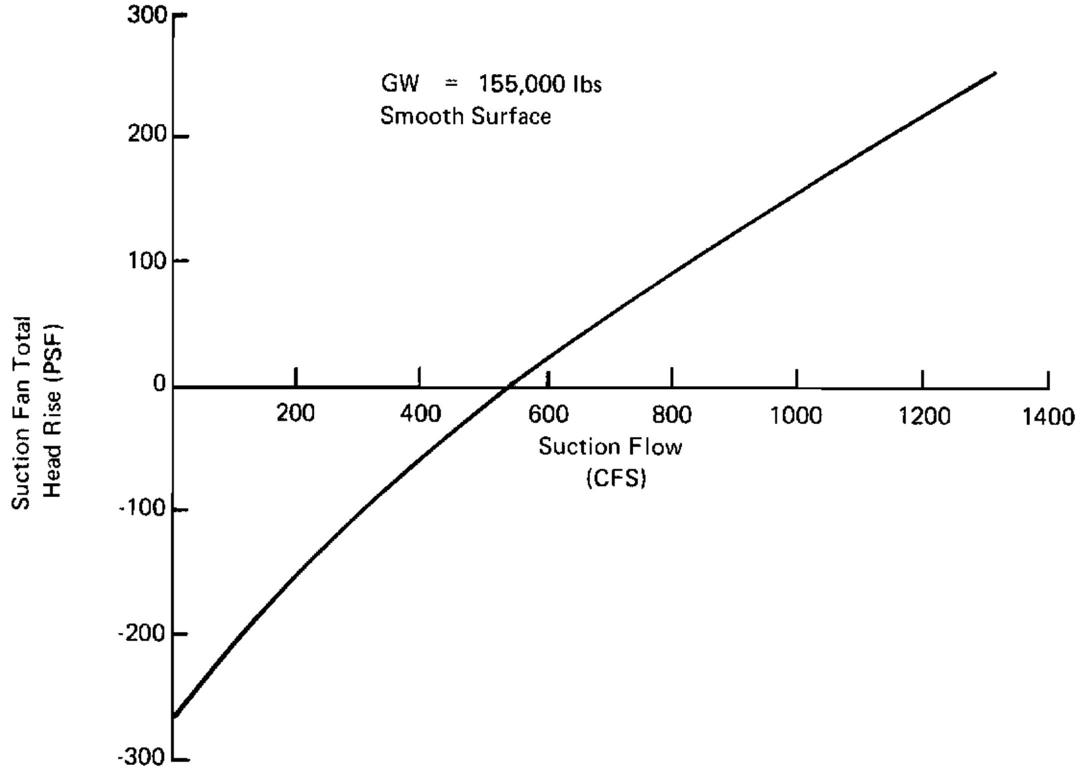

Figure 22. C-130 Suction Requirements

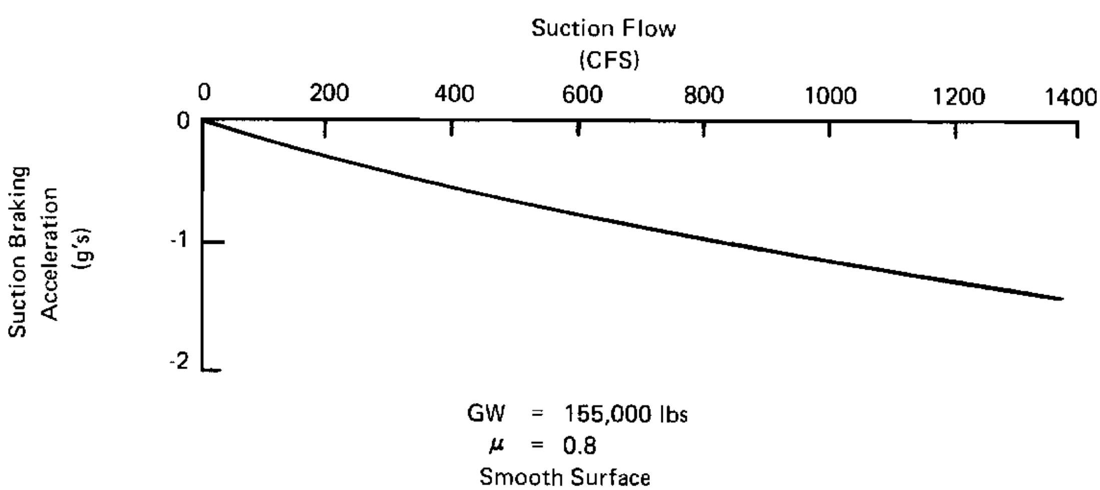

Figure 23. C-130 Braking Performance

From F = ma, the average decelerating force is:

$$\frac{155{,}000}{32.2} \times 5.95 = 28{,}641$$

The footprint load with suction, from Figure 21, is 233,000 lb thus the increase in retarding force for an assumed friction coefficient of 0.8 is:

$$F = -(0.107 \times 155{,}000) + 0.8 \times 233{,}000 = 169{,}815 \text{ lb}$$

where 0.107 is the attainble friction coefficient for the wheeled C-130 at 155,000 lb (From reference 2).

The stopping distance with suction braking is then:

$$3150 \times \frac{28{,}544}{(169{,}815 + 28{,}641)} = 453 \text{ ft.}$$

Cushion suction for braking on the C-130 can be accomplished by the use of tip turbine fans as used on the LA-4 but driven by airplane and ACLS engine bleed or, more simply, by opening the cushion to the ACLS fan inlet with controllable doors that can be modulated with the normal inlet doors to provide the required suction as illustrated schematically in Figure 24.

In such an arrangement, the total head rise across the fan must be sufficient to provide normal trunk pressure as well as suction; in this C-130 case 488 and 263 = 751 psf (neglecting losses). In the unbraked case, e.g., in landing, fan operation will then be far from stall, and it is probable that the total system can be operated to avoid fan stall even in hard landings.

For the C-130 airplane, the kinetic energy and rate of energy dissipation in landing are sufficiently high that pillow brakes will be marginal and a braking system with lower contact pressure on the landing surface will be desirable. Suction braking can provide this. The use of wear plugs as described for the C-130 trunk, will eliminate trunk wear and the "race track" of solid plugs surrounded by trunk nozzles will minimize plug wear.

It is expected that use of suction braking would provide approximately neutral or slightly negative directional stability during braking which may be controllable with rudder, ailerons and β-control. Differential braking for directional control is not available. It should be remembered that the airplane yaw attitude can divert from the ground track with the ACLS without signficiant consequences.

Consideration has been given to the weight for suction braking equipment on the C-130. Difinitive estimates are not feasible without more extension system design. However, it appears that if suction braking was designed into the system from the start and the cushion fan was designed for the suction case, the incremental weight compared with pillows would be small.

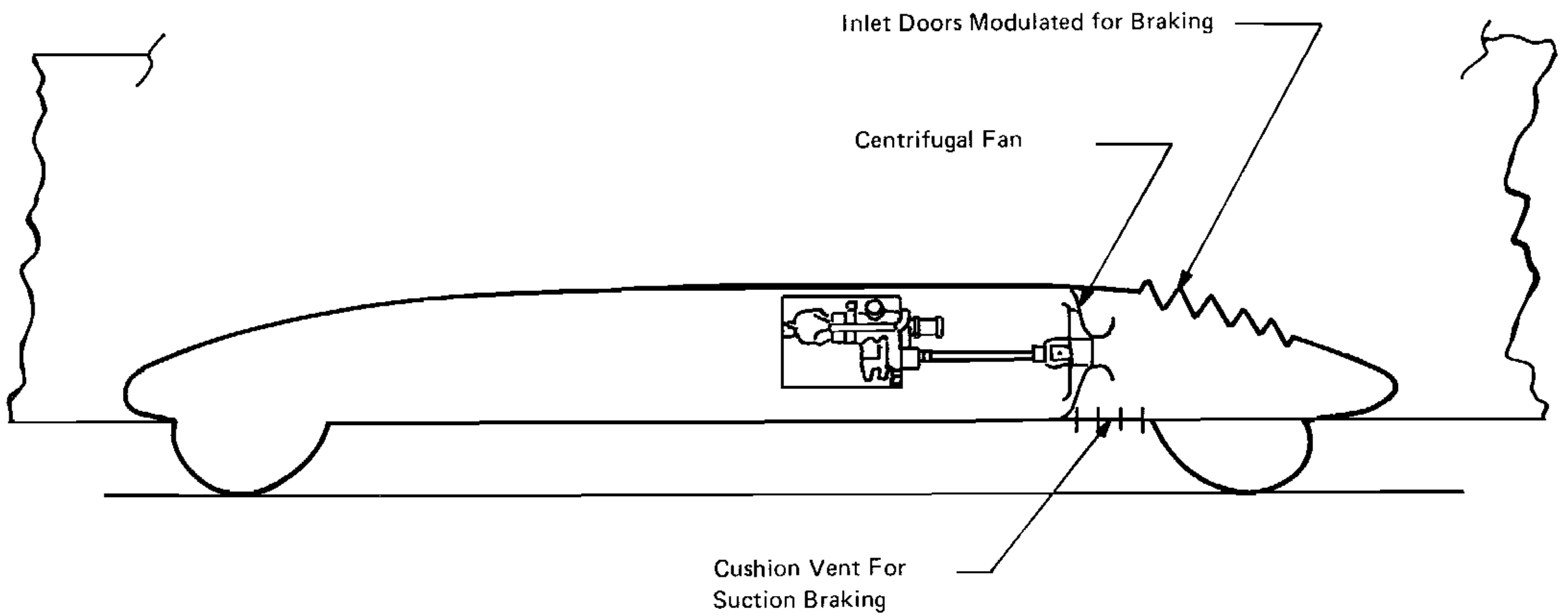

Figure 24. Air Cushion Power and Braking

For extrapolation to the Jindivik, the configuration of Reference 3 was used. The trunk flow was assumed constant at 1.4 lb/sec regardless of footprint size although the referenced report states that it decreases as would be expected with a smooth trunk undersurface that would permit the flow to be partially closed off as the trunk contacts the surface. A further discrepancy in flow occurs because the LA-4 data of Figure 18 is based on the use of wear plugs which reduce this throttling effect and this curve was applied to the Jindivik.

As in the previous extrapolations, the trunk cross-sections were calculated and the equilibrium footprint load calculated for a gross weight of 2470 lb. Here a phenomenon occurred which illustrates the disadvantage of a small cushion cavity and can cause a large discrepancy in calculated and actual braking data at high suction pressures as shown subsequently. The discrepancy is that in the trunk geometry calculations, no lateral friction is assumed between the trunk and the ground and as the cushion pressure is reduced, the trunk is free to rotate and slide in toward the center of the vehicle. The effect of this is such that, because of the narrow cushion width of Jindivik, the suction area is too small to provide additional suction effectiveness beyond a cushion pressure of -100 psf. In actuality, as suction is applied, the vehicle loses height first and the degree to which the trunk reaches the calculated equilibrium depends on the distance the vehicle moves forward after the suction is applied. In the tests of Reference 3, this distance may not have been sufficient for final equilibrium to be reached.

The calculated footprint load versus cushion pressure is presented in Figure 25 and the flattening of the curve at -100 psf is evident.

The curve of Figure 18 was used to obtain the suction requirements as presented in Figure 26.

From the footprint load versus flow, a coefficient of friction of 0.8 produces the braking decelerations of Figure 27 which show a maximum of 0.87.

The tests of Reference 3 were made on smooth plywood which has a fairly low coefficient of friction. Therefore a friction coefficient of 0.35 was assumed for a comparison of calculations with Figure 29 of Reference 3 as shown in Figure 28. Correlation is good at low suction and the figure illustrates the divergence at high suction pressures.

Due to the differences in flow conditions previously discussed, there is no correlation with Figure 30 of Reference 3.

The stopping distance was calculated for a touchdown speed of 130 knots, zero lift and thrust during braking, and a suction cushion pressure of -100 psf with a friction coefficient of 0.8.

$$S = \frac{V^2}{2a}$$

$$S = \frac{(130 \times 1.69)^2}{2 \times 0.87 \times 32.2} = 861 \text{ ft.}$$

Reference 4 indicated the desirability of having greater friction aft of the c.g., than forward to improve the directional stability during braking. Although the air cushion system design was dif-

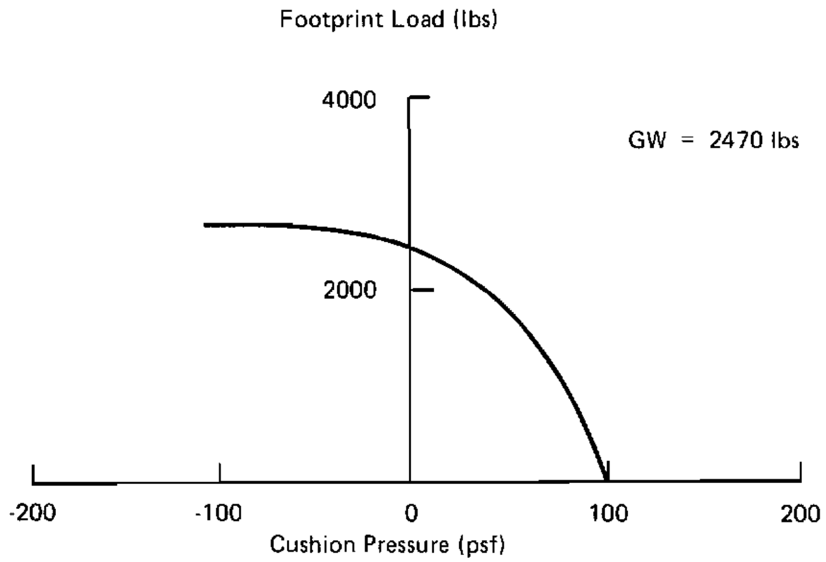

Figure 25. Jindivik Vertical Load

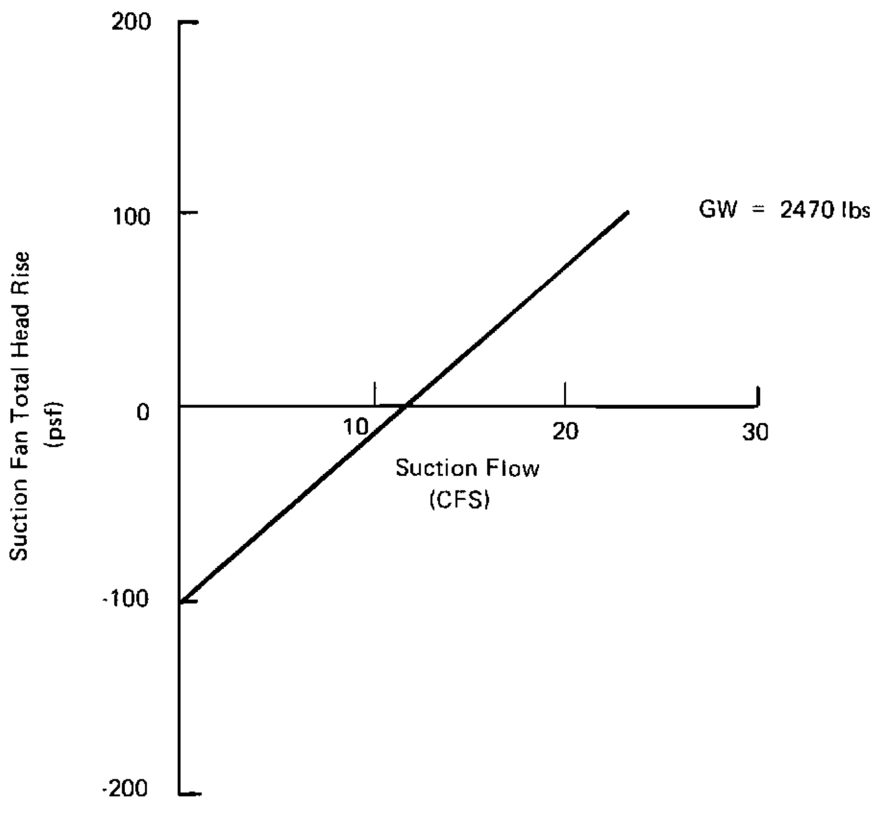

Figure 26. Jindivik Suction Requirements

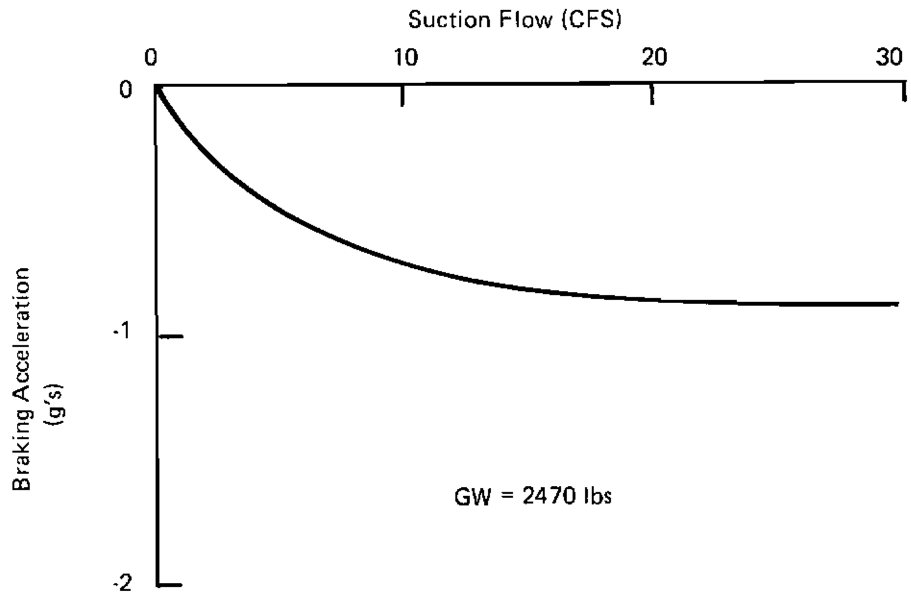

Figure 27. Jindivik Braking Performance

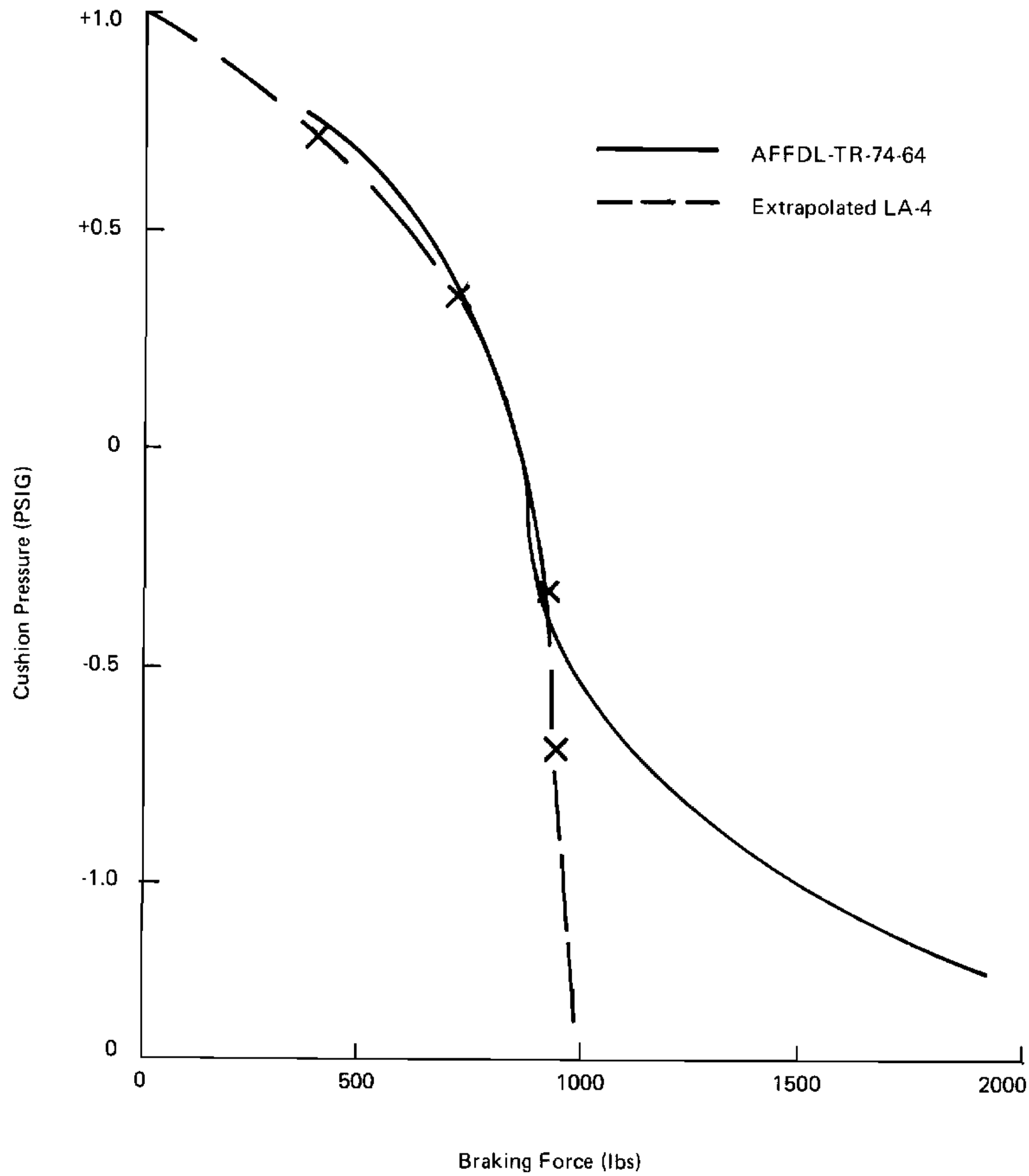

Figure 28. Jindivik Suction Braking Comparison

ferent than that of Reference 3, the general conclusions should apply. Reference 4 does not indicate the effect of longitudinal cg-cp relation but it is assumed they are similar to Reference 3. Thus it is expected that landing ground runs can be kept within 50 feet of the landing area centerline but if the friction coefficient is greater than 0.5, large yaw excursions are possible.

Reference 6 indicated that a suction braking system for RPVs using an ejector and stored gas can be designed for short brake durations for about 10 lb.

XC-8A Suction Braking

A suction braking system for the XC-8A airplane with its present ACLS system requires careful consideration because of the potential for stalling the ASP-10 fans and the resulting stall characteristics and the fact that the system presently provides considerable excess airflow. The system controls and logic should be changed so that the trim ports remain closed to reduce suction requirements to reasonable levels, and the flow diverter vanes modulated to by-pass flow during suction braking to prevent fan stall. Consideration should be given to operating with only the ASP-10 to reduce the suction flow requirement and thrust due to diverted flow. During braking, the vane modulation can be such as to permit the trunk pressure to increase beyond its normal value to reduce the heave dipping tendency when suction is applied. However, in the following analysis, trunk pressure is assumed constant.

Using the above technique, the same approach to nozzle plug and trunk nozzle distribution as outlined for the C-130 is used with trunk No. 3 which is also provided with pillow brakes. No changes to the trunk are assumed other than the distribution of wear plugs in the existing hole pattern as shown in Bell drawing 7396-185084. The wear plug distribution is as follows.

The racetrack around the ground tangent is selected to be 6 inches wide ahead of the brake pads, 8 inches wide between the brake pads and 10 inches wide aft of the pads. All but the aft end have nozzle plugs in every other jet hole and the aft section has a solid plug pattern such that each plug is surrounded by six jet holes. Nozzle plugs are used in the above areas as opposed to solid plugs as for the C-130 to permit adequate flow in the non-braking condition to prevent fan stall without vane modulation. Inside the above racetrack, all holes contain nozzle plugs.

Following the same analysis as for the C-130 in calculating the footprint equilibrium conditions for different suction pressures, the footprint load is as shown in Figure 29 for a gross weight of 41,000 lb and the corresponding suction requirements are as shown in Figure 30. The deceleration capability due to suction braking only and assuming zero wing lift is shown in Figure 31, and shows a maximum of 1.04 g's for a cushion pressure of -170 psf and a weight of 41,000 lb, and a friction coefficient of 0.8. Again, this will vary with landing surface smoothness and friction coefficient.

For a landing distance comparison, the following data were used from Reference 5:

Touchdown speed = 70 knots
Ground run = 640 ft.

from which the average deceleration is 3.828 ft/sec^2 and the average decelerating force is 4874 lb.

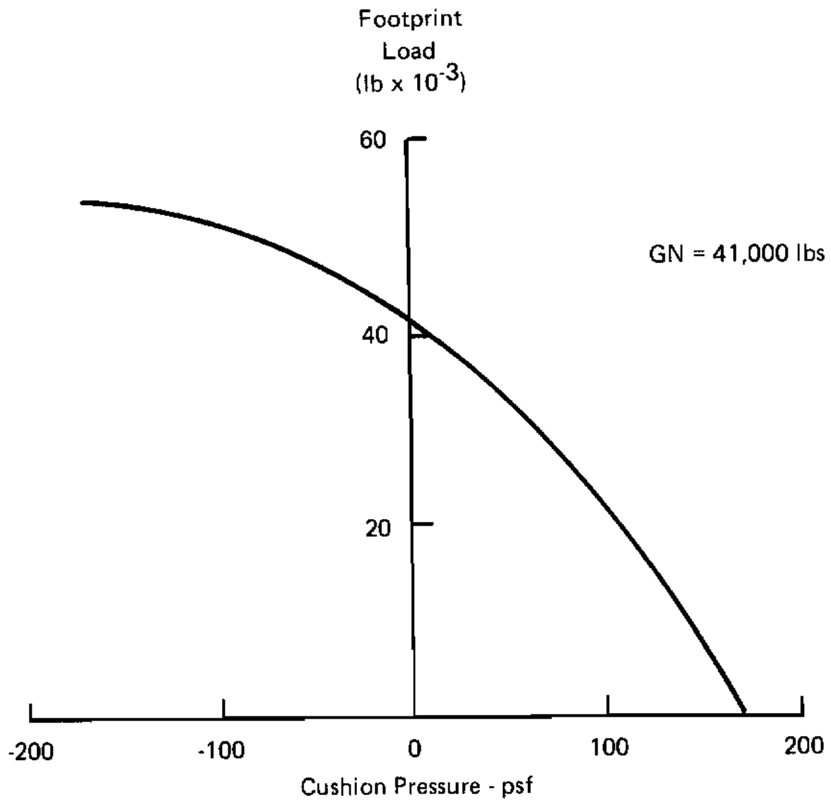

Figure 29. XC-8A Footprint Load

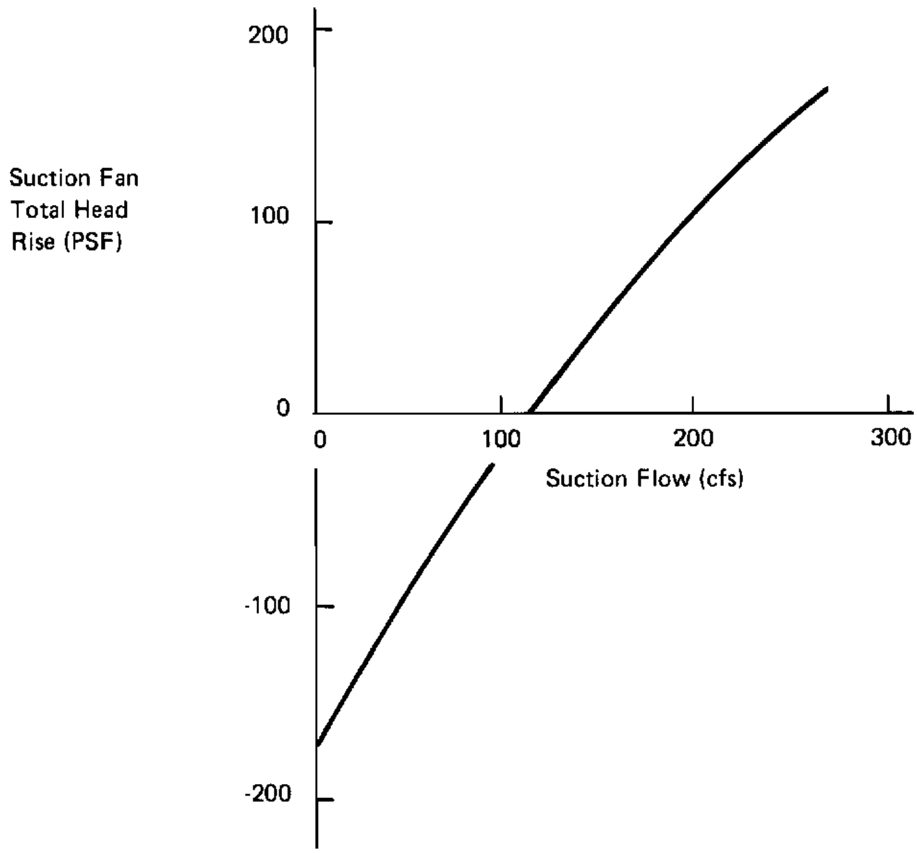

Figure 30. XC-8A Suction Requirements

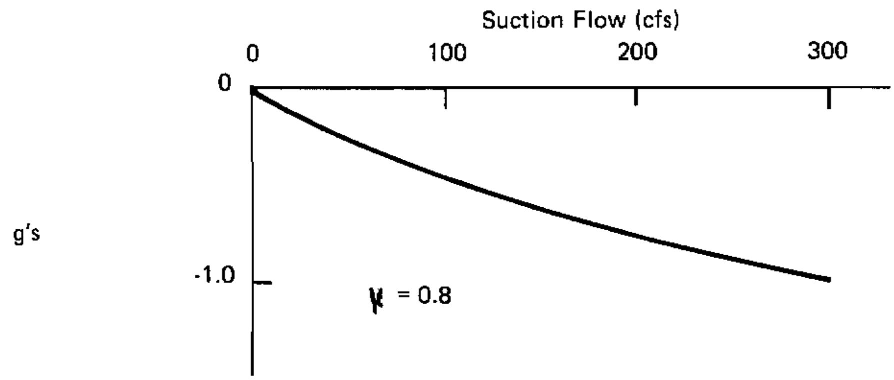

Figure 31. XC-8A Braking Performance

The footprint load with maximum suction is, from Figure 29, 53,500 lb. Assuming zero lift during braking, the coefficient of friction of 0.25 from Reference 4 wheel braking, the increase in retarding force due to suction is:

$$F = 0.8 \times 53{,}500 - 0.25 \times 41{,}000 = 32{,}550 \text{ lb}$$

assuming a friction coefficient of 0.8 for ACLS braking.

The stopping distance with suction providing a cushion pressure of -170 psf is:

$$640 \times \frac{4874}{4874 + 32{,}550} = 83 \text{ ft.}$$

The application of suction braking to the XC-8A airplane will require some means of applying suction. With the present design, the use of the ASP-10 fans is impractical. Auxiliary tip driven fans could be used such as the Tech Development Model 875 of which three are required to provide adequate flow for a negative cushion pressure of 170 psf. However, they would require a drive flow of about 7.5 lb/sec which is more than that available from the airplane engines, even at maximum power, and a storage tank would be required. The direct bleed available from two T-64 engines at maximum reverse thrust used with two model 875 fans would be adequate to produce a cushion pressure of about -50 psf and a corresponding deceleration due to suction of about 0.75 g's.

The weight penalty for three fans and adequate storage gas for 20 seconds of braking is estimated to be as follows:

	Weight (lb)
2 - 24.5 in the 3000 psi tanks	220
3 - model 875 fans	75
1 - pressure regulator	80
Installation, plumbing and controls	45
Total	320 lb

It is assumed the pillow brakes would remain unchanged.

The directional stability during braking based on the assumption of zero pitch attitude would be slightly destabilizing to the XC-8A. However, with the c.g. aft of the cushion c.p. as is the case, this destabilization would be somewhat nullified by the greater drag at the aft end of the trunk.

The use of suction braking would not induce trunk wear since sacrificial wear plugs are used. There are no weight penalties to the trunk itself; however, larger wear plugs may be necessary for acceptable replacement frequency.

CONCLUSIONS AND RECOMMENDATIONS

1. The results of the test program support the theory that very effective braking is achievable by suction. Substantial negative pressure was reached in the cushion cavity for a suction flow much less than cushion flow.

2. The maximum deceleration achieved was 0.5 g. Ultimate levels achievable were not realized in the test because of deficiencies in the configuration - failure to retain nozzle plugs and a non-optimum plug configuration.

3. Based on the flow required for suction generation and applying known air lubrication and friction parameters, a deceleration potential of 1.4 g can be predicted for a C-130, 0.87 for Jindivik and 1.04 for an XC8A designed for suction braking ACLS, in a realistic configuration. This is in the order of two to three times that which can be produced with wheel brakes.

4. Repeat tests are recommended to establish that the developed theory can be proven. In such repeat tests, the optimum plug geometry should first be specified and suitable retention should be established. Brake skids should be eliminated in favor of an overall uniform plug distribution. Additional suction (a second identical fan) should be provided and fan control improved. Full deceleration potential should then be realized.

5. Suction braking can be applied to ACLS systems at weight savings over pillow brakes.

REFERENCES

1. C-130E Hercules Operational Planning Data Book, AER300B, 1 December 1964, Lockheed Georgia Company.

2. C-130E Aerodynamic Data, ER7357, Lockheed Georgia Company.

3. Laboratory Tests of an Air Cushion Recovery System for the Jindivik Aircraft, AFFDL-TR-74-64, April 1974.

4. Design of an Air Cushion Recovery System for the Jindivik Drone Aircraft, AFFDL-TR-74-38, March 1974.

5. DHC-5 Performance - Volume II - Landing, AEROC 5.2.G.1, DeHavilland Aircraft of Canada, October 1963.

6. A Study of Air Cushion Landing Systems for Recovery of Unmanned Aircraft, AFFDL-TR-72-87, July 1972.

LIST OF SYMBOLS

a	=	acceleration (ft/sec^2)
C_L	=	lift coefficient (L/q S)
F	=	force (lbs)
g	=	acceleration (dimensionless "g's" normalized by acceleration of gravity, 32.174 ft/sec^2)
L	=	aerodynamic lift (lbs)
P	=	pressure (psf)
q	=	dynamic pressure (psf)
Q	=	flow rate (cfs)
s	=	distance (ft)
S	=	area (sq ft)
V	=	speed (ft/sec)
μ	=	coefficient of friction

Subscripts

c	=	cushion
fp	=	footprint
t	=	trunk

☆ U. S. GOVERNMENT PRINTING OFFICE: 1976 — 657-630/537