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STOL TACTICAL AIRCRAFT INVESTIGATION–EXTERNALLY BLOWN FLAP

Volume VI

Air Cushion Landing System Trade Study

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Approved for public release; distribution unlimited

FOREWORD

This report was prepared for the Prototype Division of the Air Force Flight Dynamics Laboratory by the Los Angeles Aircraft Division, Rockwell International. The work was performed as part of the STOL tactical aircraft investigation program under USAF contract F33615-71-C-1760, project 643A0020. Daniel E. Fraga, AFFDL/PTA, was the Air Force program manager, and Garland S. Oates, Jr., AFFDL/PTA, was the Air Force technical manager. Marshall H. Roe was the program manager for Rockwell.

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This technical report has been reviewed and is approved.

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ABSTRACT

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The basic objective of the work reported herein was to provide a broader technology base to support the development of a medium STOL Transport (MST) airplane. This work was limited to the application of the externally blown flap (EBF) powered lift concept.

The technology of EBF STOL aircraft has been investigated through analytical studies, wind tunnel testing, flight simulator testing, and design trade studies. The results obtained include development of methods for the estimation of the aerodynamic characteristics of an EBF configuration, STOL performance estimation methods, safety margins for takeoff and landing, wind tunnel investigation of the effects of varying EBF system geometry parameters, configuration definition to meet MST requirements, trade data on performance and configuration requirement variations, flight control system mechanization trade data, handling qualities characteristics; piloting procedures, and effects of applying an air cushion landing system to the MST.

From an overall assessment of study results, it is concluded that the EBF concept provides a practical means of obtaining STOL performance for an MST with relatively low risk. Some improvement in EBF performance could be achieved with further development - primarily wind tunnel testing. Further work should be done on optimization of flight controls, definition of flying qualities requirements, and development of piloting procedures. Considerable work must be done in the area of structural design criteria relative to the effects of engine exhaust impingement on the wing and flap structure.

This report is arranged in six volumes:

Volume I - Configuration Definition

Volume II - Design Compendium

Volume III - Performance Methods and Takeoff and Landing Rules

Volume IV - Analysis of Wind Tunnel Data

Volume V - Flight Control Technology

  Part I - Control System Mechanization Trade Studies
  Part II - Simulation Studies/Flight Control System Validation
  Part III - Stability and Control Derivative Accuracy Requirements and Effects of Augmentation System Design

Volume VI - Air Cushion Landing System Trade Study

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LIST OF SYMBOLS

A_C = cushion area, ft^2
A_L = theoretical cushion leakage area, in.^{2}
ACLS = air cushion landing system
BPR = bypass ratio
c = cushion perimeter, ft.
CBR = California bearing ratio
EBF = externally blown flap
fps = feet per second
ft^2 = square feet
ft/sec = feet per second
g = acceleration due to gravity, ft./sec^2
lb = pounds
lb/in = pounds per inch
lb/sec = pounds per second
M_n = Mach number
MST = military STOL transport
P_c = cushion pressure, psig
P_T = trunk pressure, psig
P_{tf} = trunk pressure, front, psig
P_{tr} = trunk pressure, rear, psig
PR = pressure ratio
psig = pounds per square inch, gage
rpm = revolutions per minute
SHP = shaft horsepower
SIL = speech interference level
STOL = short takeoff and landing
t = theoretical cushion height, in.
W_a = airflow weight, lb/sec
W_f = airflow weight, front, lb/sec
W_r = airflow weight, rear, lb/sec
ΔP = incremental pressure, psig
θ = airplane flight angle, degrees
μ_R = rolling resistance

SECTION I

INTRODUCTION

1.1 BACKGROUND

The air cushion landing system (ACLS) under development by AFFDL, references 1 through 5, is based on the "ground effect machine" principle. The conventional shock strut landing gear is replaced by inflatable expanding trucks (skirts) incorporating a distributed jetflow pattern at the ground tangent. Inward flow from the jets fills the cavity between the ground and the vehicle with air at a pressure above atmospheric. This air, sealed around the periphery by the truck, is called the air cushion and supports the weight of the vehicle. The continuing flow of air at the low pressures provides a film of air that enables the aircraft to operate over surfaced runways, semiprepared strips, ice, snow, mud, and even water. As demonstrated by the LA-4 tests, references 3 and 4, obstacles such as rocks, tree stumps, and ditches are readily transversed as the flexibility of the material and the air film allows the trunk to flow over all proturbances.

Initial development tests were conducted by Bell Aerospace on an LA-4 Lake amphibian aircraft modified to incorporate an ACLS landing system. A rubberized nylon trunk encircled the bottom of the aircraft and incorporated six pillow brakes to provide ground control. Air was supplied to the trunk by a two-stage fan driven by a McCulloch two-cycle, air-cooled, aircraft engine rated at 92.5 horsepower. The cushion area proved to be 41.67 feet^2, which required a pressure of 60 pounds/foot^2 to support the aircraft. The operating trunk pressure was 140 pounds/foot^2. Many takeoff and landing tests were conducted over a wide variety of surfaces, from concrete to water, that successfully demonstrated the ACLS concept.

In a continuing development process, a DeHavilland C-8 Buffalo is now being modified to incorporate an ACLS landing system in a joint USAF-FDL and Canadian effort. This modification will use two PT-6A turboshaft engines to power the fans supplying air to the rubberized nylon trunk that encircles the bottom of the fuselage. With the trunk fully inflated, hard structure is over 32 inches from the ground, which should provide sufficient depth to satisfactorily demonstrate landing impact absorption and rough terrain handling capability. Operational tests of this larger CC-115 ACLS system should begin in early 1973.

1.2 STUDY OBJECTIVE

The objective of this trade study is to compare the landing characteristics and performance capability of the MST equipped with an ACLS and with a conventional landing gear. Results should be presented so that the procuring and/or using agency can be fully cognizant of the penalties (or advantages) of requiring the MST to operate from soft, unprepared, forward air bases. No new ACLS concepts should be invented. The cushion system shall be a direct application of that being developed by the AFFDL, Mechanical Branch, Vehicle Equipment Division.

SECTION II

SUMMARY

2.1 STUDY METHODOLOGY

To obtain the objectives of the previous section, two ACLS installations were designed and analyzed, along with three conventional landing gear sizes. With this approach, a wide spectrum of landing performance capability could be studied and compared. The same configurations were also compared for a constant cruise performance capability. Takeoff performance for an ACLS and conventionally geared MST were compared for the distance required to clear a 50-foot obstacle.

2.2 STUDY RESULTS AND CONCLUSIONS

As a result of this ACLS/conventional gear trade study, several conclusions can be made, as follows:

1. The ACLS appears promising for this application.
2. The cushion area should be made as large as possible to minimize cushion air supply requirements.
3. The ACLS is more efficient than a conventional gear for a wide range of CBR values. For 200 passes at CBR 6, the ACLS can save up to 6,000 pounds airplane gross weight, compared to a conventional gear. Savings are even greater at lower CBR values.
4. The ACLS takeoff performance over a 50-foot obstacle from soft ground is about equal to a conventionally geared airplane; from hard surfaces, the conventional gear is about 8 percent shorter than the ACLS.
5. Because of a higher braking friction factor, the ACLS landings can be as good or shorter than with conventional gear.
6. For level landings, the ACLS has excellent load attenuation characteristics at all sinking speeds. Sharply reduced attenuation capability of the cushion at large noseup angles may limit the permissible sinking speed for these attitudes.

7. Having dual cushion air supply engines, considerable capability exists to withstand extensive damage to the trunk without affecting cushion operating characteristics.

8. Similar to a ground effect machine, low-speed maneuverability of an ACLS aircraft is highly sensitive to crosswinds and slope of the ground surface.

9. The Buffalo CC-115 ACLS modification should be carefully monitored to verify operational suitability and validity of inputs to this trade study.

SECTION III

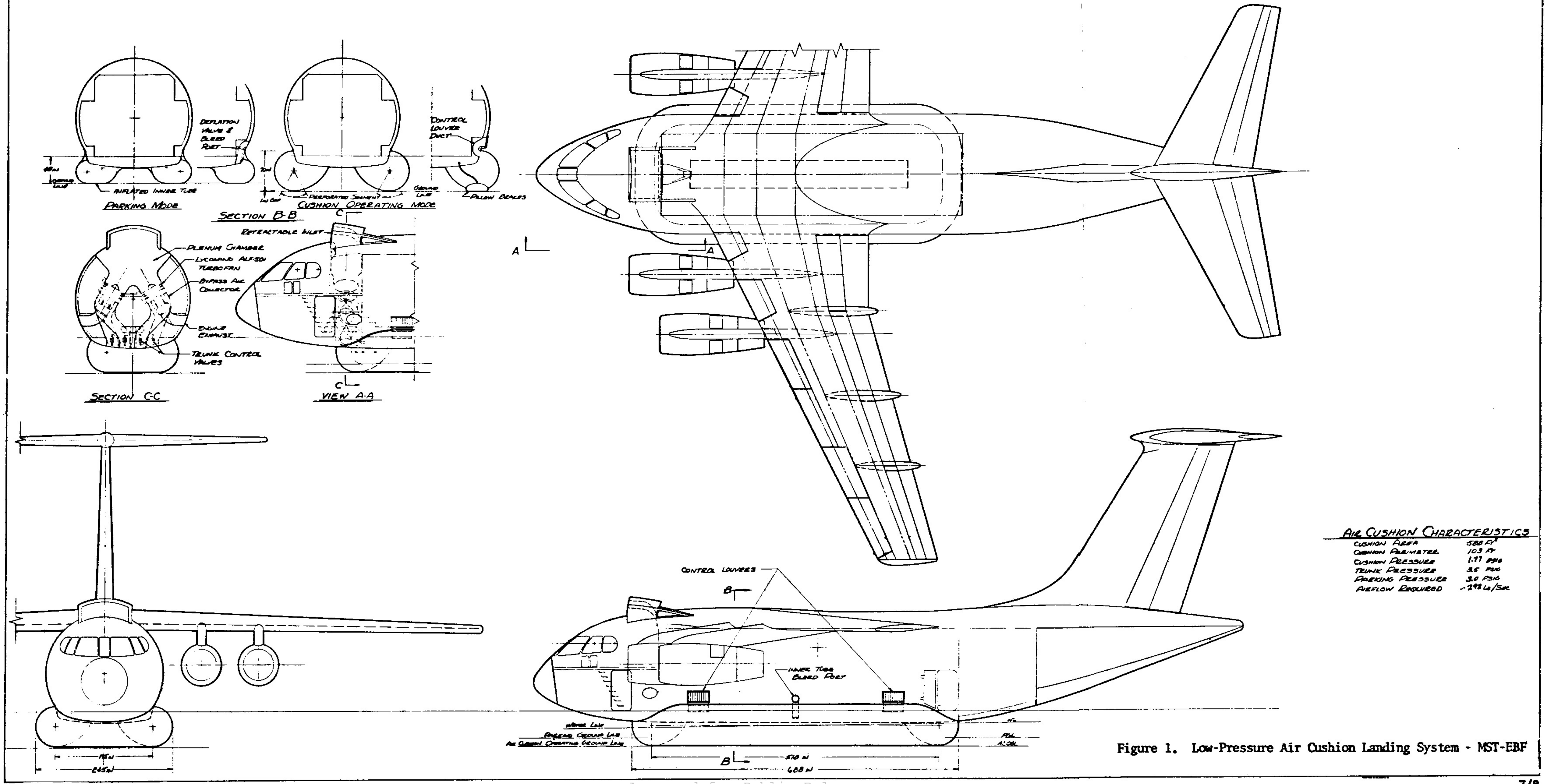
AIR CUSHION LANDING SYSTEM

3.1 DESIGN CONCEPT

The primary objective of this trade study is to directly install the air cushion landing system (ACLS) as developed by the Flight Dynamics lab, in the MST configuration and compare it with a conventional landing gear. The initial ACLS design was for as large a cushion area as practical. Direct performance comparisons with conventional gear at the same CBR or field rating proved to be difficult with this size cushion. It was decided to try a second ACLS design with four times the cushion pressure of the initial concept. These concepts are called low- and high-pressure ACLS designs, respectively.

3.1.1 LOW-PRESSURE ACLS DESIGN

In the low-pressure ACLS design, as shown in figure 1, a single compartment trunk encircles as large a portion of the fuselage as possible. Overall cushion dimensions are 20.5 feet wide by 57 feet long, which provides a tanget point cushion area of 588 square feet and a perimeter of 103 feet. To support the aircraft at 150,000 pounds gross weight, the required cushion pressure is 1.77 psig. As determined from the LA-4 application, the trunk pressure should be about 3.5 psig. To assure adequate single-engine pumping capability, dual pumps will supply air at this pressure, with an airflow of about 292 pounds per second. The most compact engine/pump arrangement with this capacity appears to be two Lycoming ALF-501 turbofans. The engines can be located in the unused space between the flight crew and the forward end of the cargo bay. (See figure 2.) Air can be drawn into a large plenum chamber with a single, top centerline, retractable inlet. Each engine draws air from the plenum chamber. Air that passes through the engine core is separately ducted overboard. The bypass air is collected and ducted to the forward crossover portion of the trunk. Control valves at this point will automatically close for engine start, or with a single-engine failure, and prevent truck pressure from escaping through the shutdown engine. The pressurized air causes the trunk to inflate to its operating configuration. The air then flows through thousands of small inward slanting holes located in the lower segment of the trunk - some to be captured by the air cushion, the remainder to provide a lubricating film that prevents actual trunk-to-ground contact.



AIR CUSHION CHARACTERISTICS	
CUSHION AREA	588 FT²
CUSHION PERIMETER	103 FT
CUSHION PRESSURE	1.77 PSIG
TRUNK PRESSURE	3.5 PSIG
PARKING PRESSURE	3.0 PSIG
AIRFLOW REQUIRED	~298 LB/SEC

Figure 1. Low-Pressure Air Cushion Landing System - MST-EBF

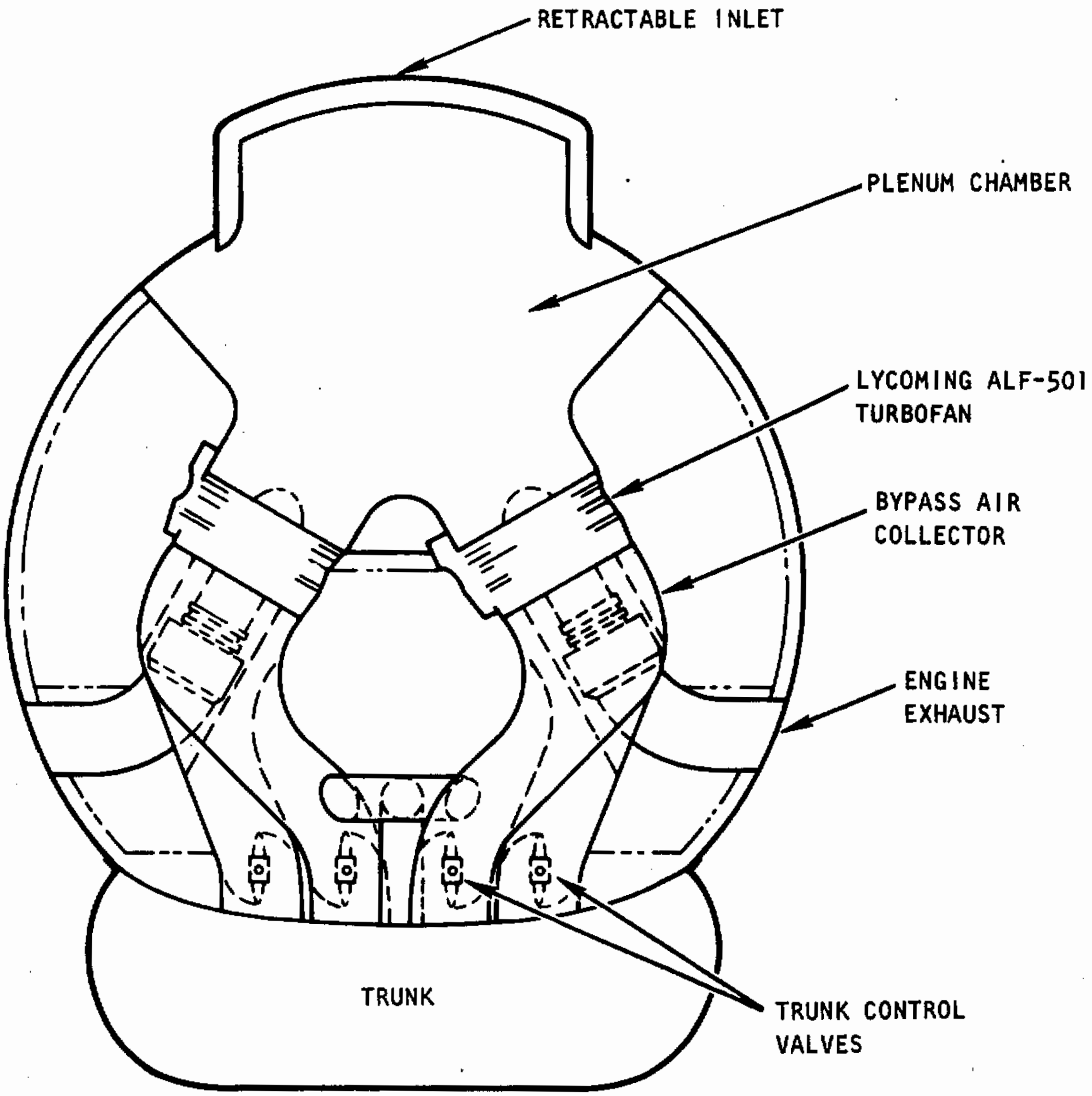


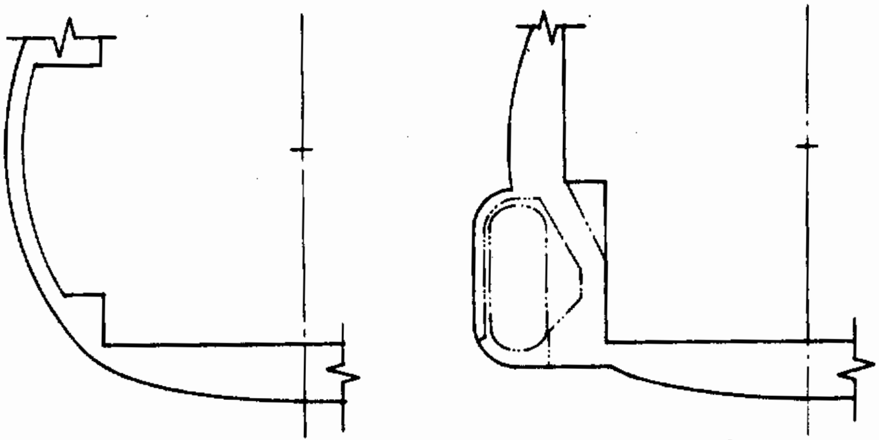
Figure 2. ACLS Air Supply System

The basic trunk material of the Buffalo ACLS modification consists of a four-ply single-stretch nylon fabric with natural rubber layers between the plys and an outside coat of neopreme. The weight of this material is 180 ounces per square yard. This same type of material can be used for the MST application, with the unit weight increased to 200 ounces per square yard to account for the higher pressures required. The inflated perimeter must be limited to 2.5 times the stowed or relaxed condition. Because of this requirement, the lower fuselage corners are slightly enlarged to provide this relaxed perimeter. (See figure 3.)

With the air cushion in the operating mode, little or no friction to any motion is apparent. Thus taxiing and takeoff should have less resistance than a conventional gear. Once airborne, the auxiliary air cushion turbofan can be shut down and the trunk will then automatically collapse to its stowed position, hugging the fuselage contour. At the six pillow brake locations, the folded tread extends 2 to 3 inches beyond the trunk contour and will add slightly to the cruise drag. Upon engine shutdown, the top centerline inlet is retracted to further reduce the cruise drag. After reaching the desired destination, the aircraft is slowed down and flaps deflected to an intermediate position. The auxiliary inlet is placed in the open position, and the cushion air supply engines are started. When trunk is fully inflated and airflow equilibrium is established, final approach and landing can be made. The trunk provides large energy absorption capability and is expected to withstand sinking speeds up to 15 feet per second with no difficulty.

The braking system consists of three pillow brakes on each side of the trunk (figure 4) that can be inflated with an engine compressor bleed system controlled by the pilot to provide a braking surface. Differential braking, together with differential engine thrust, can be applied to provide aircraft directional control while taxiing. Another control method proposed by NR (figure 5) is to provide four separately operated exhaust louvers that bleed air from the trunk, with each port capable of supplying a force up to 1,800 pounds. It may be possible to move the aircraft with just these maneuver jets and meet the MST requirement of moving the airplane without the main engines running. On a flat surface, these jets alone can react the force generated by a side wind as high as 18 knots.

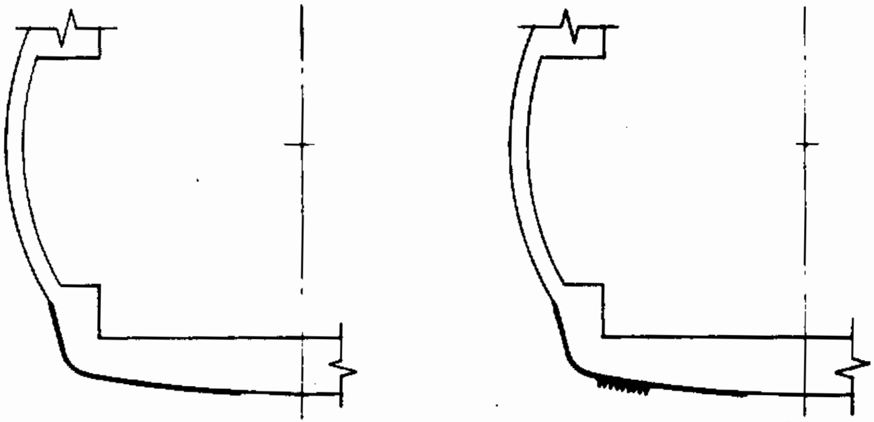
The Buffalo ACLS will have a six-segment inner bladder system to test a lightweight parking method. All segments are simultaneously filled; then intersegment valves are closed to isolate each segment. Thus, a puncture of one segment will not deflate any other, and a measure of safety is attained. It is assumed that this parking system can be directly adapted to the MST. The desired floor height of 48 inches can be achieved by controlling the amount of air pumped into the bladder system. Also, should pitching of the



BASIC

WITH GEAR

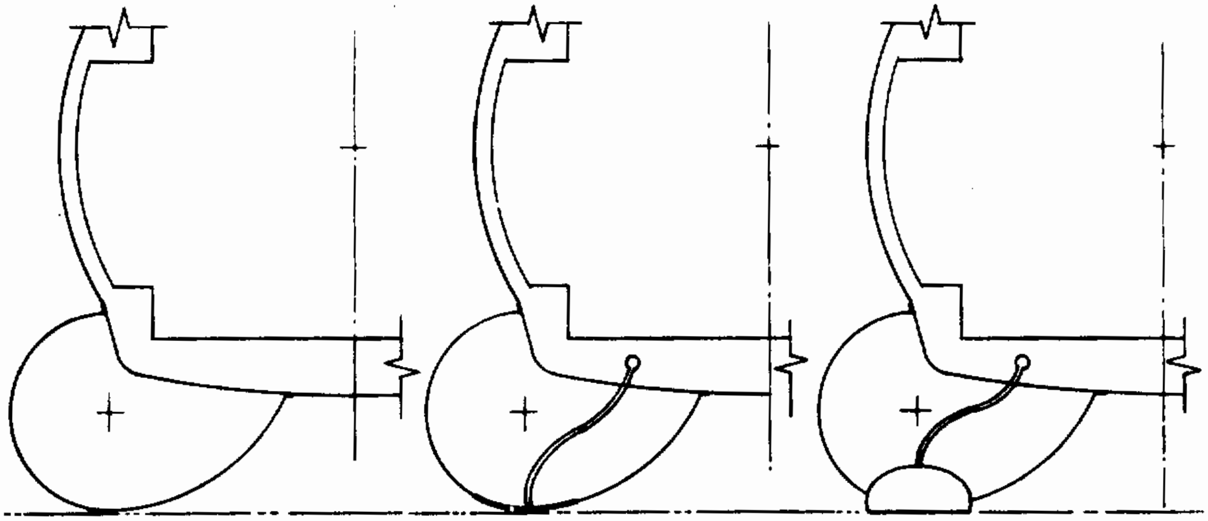
MST CONVENTIONAL GEAR



BASIC

BRAKE LOCATION

ACLS DEFLATED CONDITION



BASIC

BRAKE OFF

BRAKE ON

BRAKE LOCATION

ACLS INFLATED CONDITION

Figure 3. Fuselage Sections

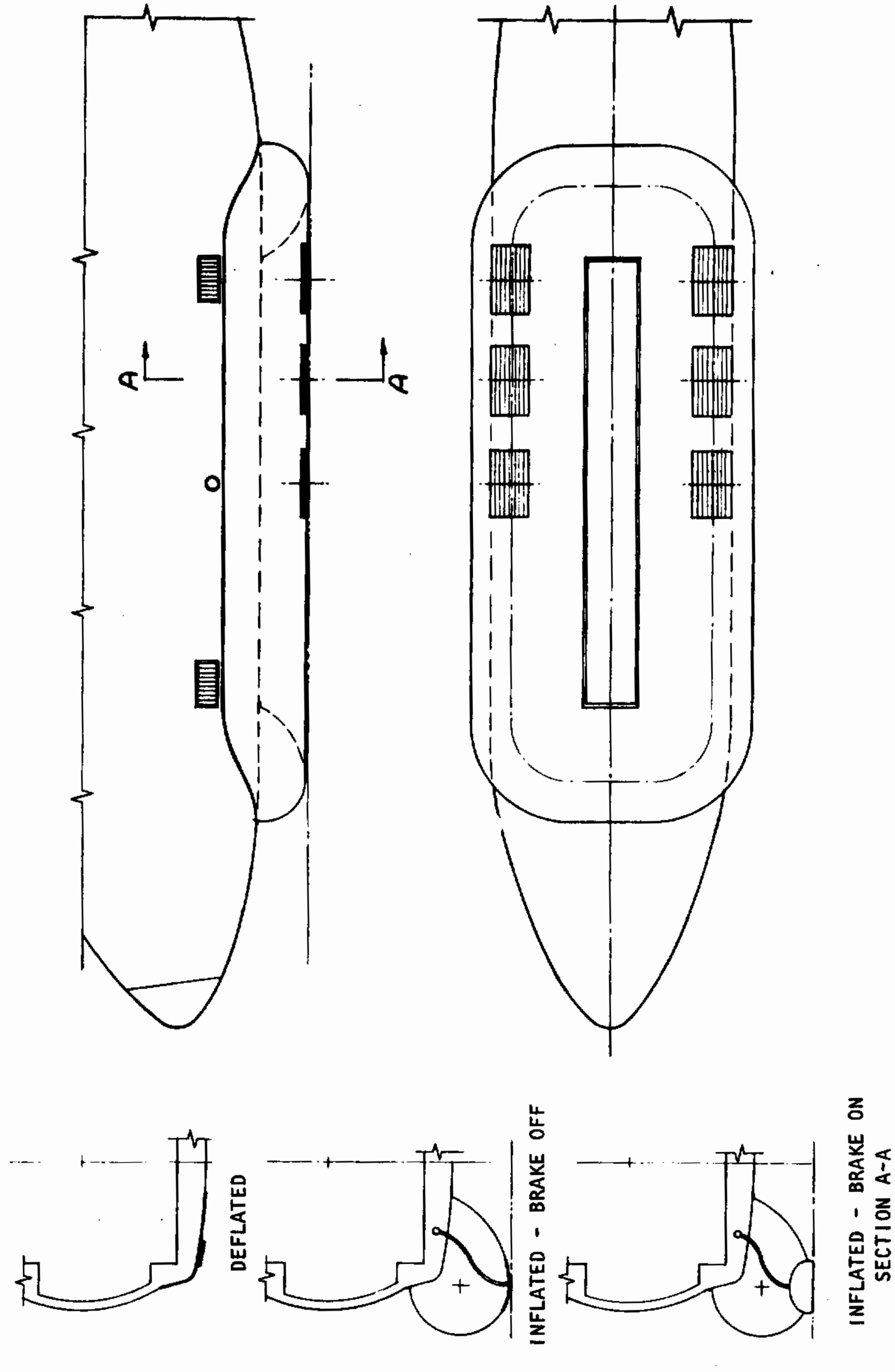
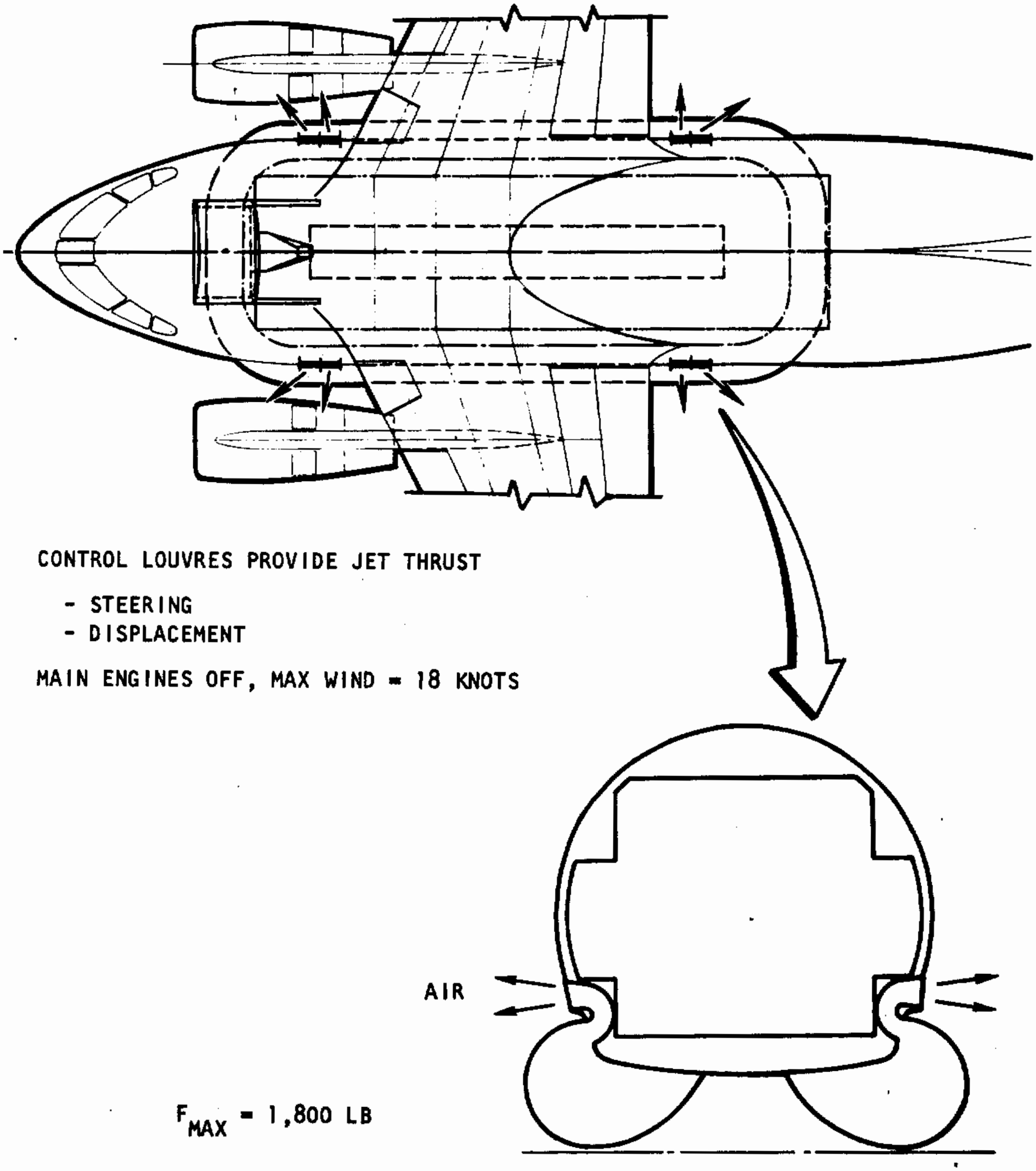


Figure 4. ACLS Pillow Brake System



CONTROL LOUVRES PROVIDE JET THRUST

- STEERING
- DISPLACEMENT

MAIN ENGINES OFF, MAX WIND = 18 KNOTS

F_{MAX} = 1,800 LB

Figure 5. ACLS Maneuver Control System

aircraft during loading be a problem, the separate bladder segments could be separately controlled with an automatic leveling system to provide the required air pressure. Since the bladder is made of very thin rubber, it is highly elastic and will completely fill the trunk cavity. Bladder and trunk mounting must be collocated or immediately adjacent to each other. To prevent air blockage during normal cushion operation, special screens or bladder cutouts must be provided at the air inlets and the control louver bleed ducts.

3.1.2 HIGH-PRESSURE ACLS DESIGN

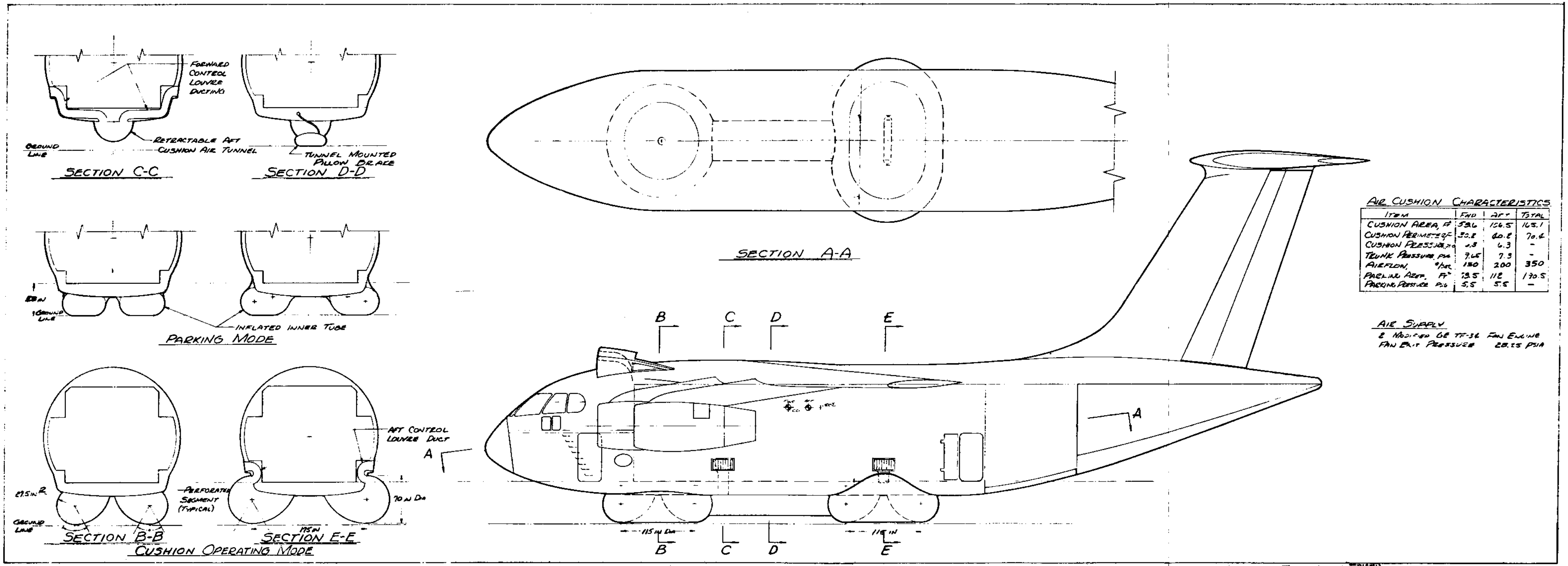
The high-pressure ACLS design was generated (figure 6) to provide a second ACLS data point and, perhaps, provide a field performance more directly comparable to conventional landing gear. The goal was a cushion pressure of 7 psig - four times that of the low-pressure ACLS concept. A dual-cushion arrangement appeared to be the only method to obtain sufficient pitch stability. To retain some lateral stability, the width of the aft cushion is the same as the low-pressure system. With these cushion criteria, the smallest area appeared to be 165 square feet with a perimeter of 70 feet. Cushion pressure turns out to be 6.3 psig, instead of the desired 7.0. To keep the trunk from becoming too hard, the trunk pressure is increased only 1.5 psi above the cushion pressure. Assuming that the air supply system will be located forward as in the low-pressure system, a retractable tunnel is provided to supply air to the aft trunk.

Calculation of the required cushion air supply reveals that a higher airflow is necessary for the same ground clearance as for the low-pressure system. The greater pressure and airflow require a larger power source. The closest fan engine proves to be the TF34-GE-2, which must be modified.

The key characteristics of both the low- and high-pressure ACLS concepts are directly compared in table I.

TABLE I. ACLS OPERATING CHARACTERISTICS

Item	Low-Pressure ACLS	High-Pressure ACLS
Cushion area (ft^2)	588	165
Cushion perimeter (ft^2)	103	70
Cushion pressure (psig)	1.77	6.3
Trunk pressure (psig)	3.5	9.65 (fwd) 7.8 (aft)
Airflow required (lb/sec)	292	350



AIR CUSHION CHARACTERISTICS

ITEM	FWD	AFT	TOTAL
CUSHION AREA, FT²	58.6	106.5	165.1
CUSHION PERIMETER, FT	30.2	40.2	70.4
CUSHION PRESSURE, PSIG	6.3	6.3	-
TRUNK PRESSURE, PSIA	7.65	7.3	-
AIRFLOW, #/SEC	150	200	350
PARKING AREA, FT²	58.5	112	170.5
PARKING PRESSURE PSIG	5.5	5.5	—

AIR SUPPLY

2 MODIFIED GE TF-34 FAN ENGINE

FAN EXIT PRESSURE 28.25 PSIA

Figure 6. High-Pressure Air Cushion Landing System - MST

3.1.3 ALTERNATE AIR SUPPLY CONCEPTS

Several alternate air supply concepts and locations were investigated prior to the selection of the primary design. Some concepts attempted to mount the fan engines horizontally below the crew compartment. With this arrangement, a retractable inlet is more difficult to design and ingestion of debris or water is more likely. Crew compartment access and side crew boarding door location also become problems. Should a drive-through or front cargo loading capability be required, the selected air supply location would not be acceptable. A promising location for the air supply system with the front cargo loading requirement is the upper fuselage shoulder behind the rear spar, as shown in figure 7. Some bulging of the mold line is required, but its favorable location should minimize drag effects. A retractable inlet could be used to reduce cruise drag. The fan air can be collected and piped downward by three 18-inch ducts to the air cushion trunk. Some restriction or limitation of in-flight crew passage may be necessary at the duct location.

3.2 AIR SUPPLY SYSTEM

3.2.1 CONCEPT

The basic requirement for the air supply system is that a source of air at sufficient flow and pressure to maintain a reasonable air-to-ground clearance must be delivered to the air cushion. The basic approach selected to supply this air is a concept that collects the bypass air from a turbofan engine and ducts the air to the air cushion. An alternate concept is to obtain the air supply from a separate air compressor driven by a turboshaft engine. The turbofan concept appears to be the most suitable source, as it is a self-contained unit that can supply air having the required flow characteristics. A detailed analysis of the system was made using a Lycoming turbofan engine. A separate air compressor-shaft engine arrangement was reviewed only to the extent necessary to provide trade-off data with the turbofan concept.

3.2.2 AIR SUPPLY SYSTEM ANALYSIS

3.2.2.1 Low-Pressure Air Cushion

The low-pressure air cushion concept is shown in figure 1. The cushion air supply analysis for this concept is based on the principles described in reference 1. The primary controlling parameter in the analysis is the theoretical cushion height, which is defined as 1.0 inch but provides an actual height of approximately 0.7 inch, as indicated by data in reference 1.

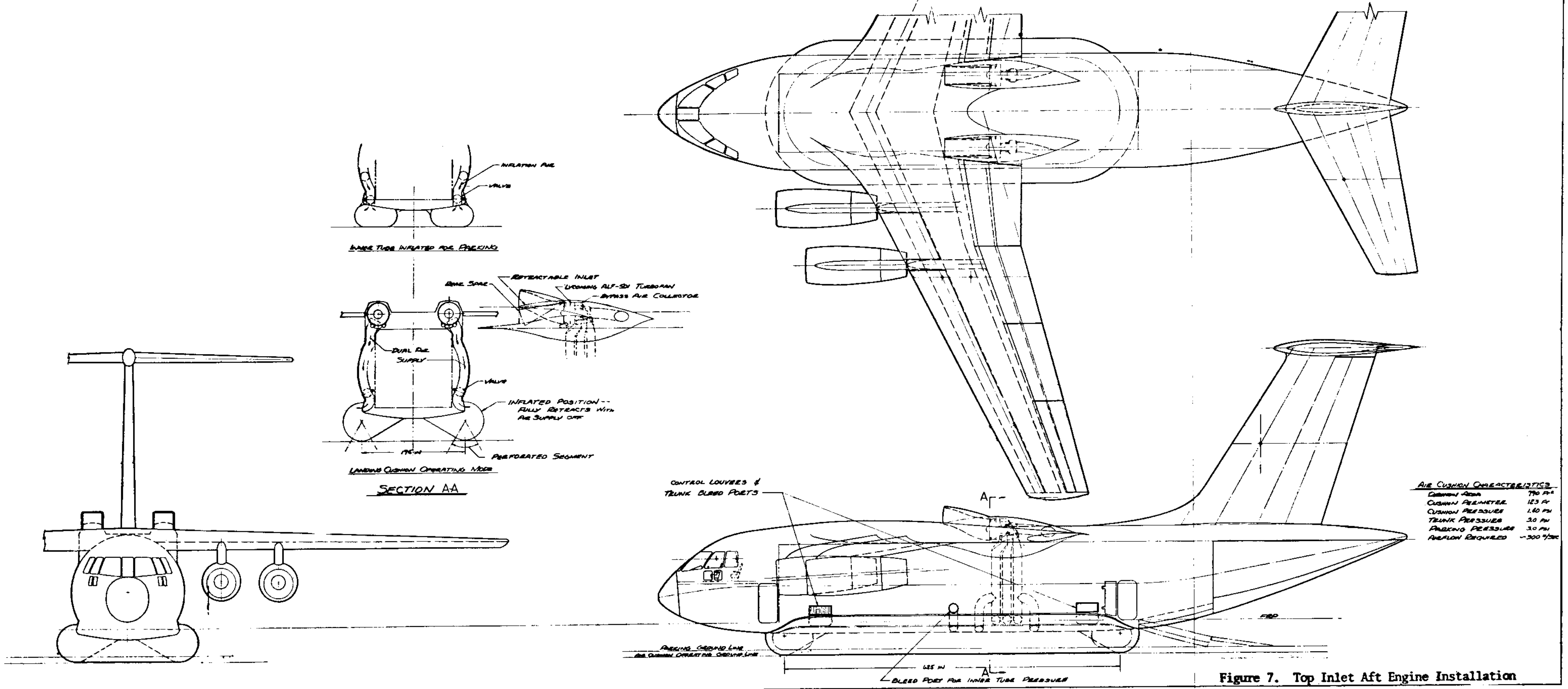


Figure 7. Top Inlet Aft Engine Installation

Since the design approach for the NR ALCS concept is to use two engines to supply cushion air, an engine failure will reduce this actual height to about 0.46 inch, which should be sufficient to provide a safe landing at reduced sinking speeds.

The air supply flow rate for the two engined vertically mounted configuration shown in figure 1, is calculated as follows:

Cushion area (A_C) = 588 sq ft

Cushion perimeter (c) = 103 ft

Required cushion pressure (P_C) $= \dfrac{\text{Aircraft max gross weight (lb)}}{\text{Cushion area (sq ft x 144)}}$

$P_C = \dfrac{150{,}000}{588 \times 144} = 1.77$ psig

Cushion trunk pressure (P_T) $= 2 \times P_C = 3.5$ psig

Theoretical cushion height (t) = 1 in. (assumed)

Theoretical cushion leakage area (A_L) $= (c) \times \dfrac{\text{in.}}{\text{ft}} \times (t) = 103 \times 12 \times 1 = 1238$ sq in.

Cushion pressure ratio $= \dfrac{14.7 + 1.77}{14.7} = 1.12$

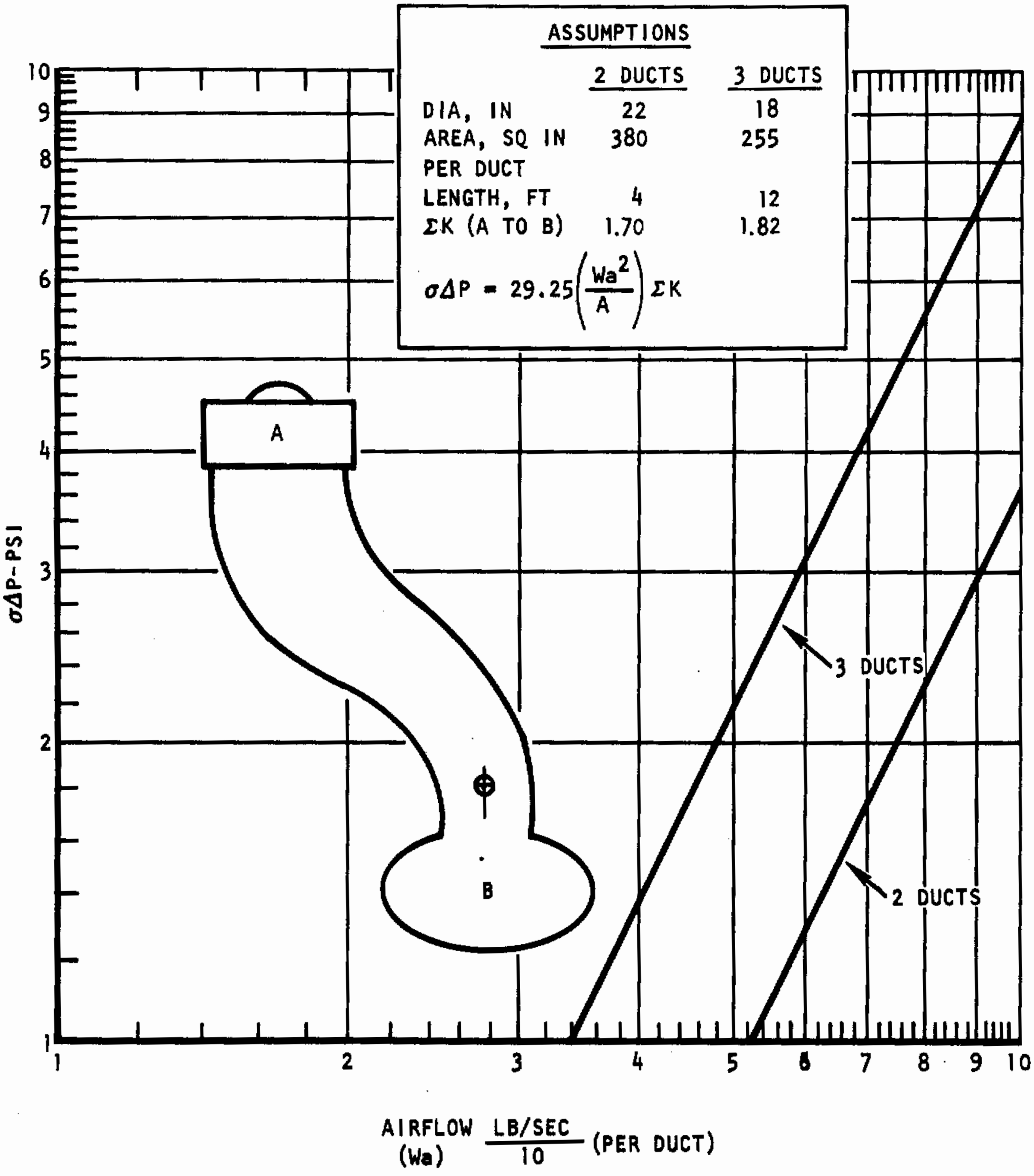
Cushion airflow exit M_N = 0.41 (thermo handbook)

Flow function $\dfrac{W \sqrt{\theta_t}}{A \; \delta_t}$ = 0.221 (thermo handbook)

Cushion weight flow (W) (flow function) $= \dfrac{0.221 \times 1{,}238 \times 1.12}{\sqrt{575/520}} = 292$ lb/sec

3.2.2.2 Ducting System

The pressure loss through the ducting system (the fan plenum to the cushion trunk) is shown in figure 8. The data are for one engine feeding into two ducts 22 inches in diameter, or three ducts, 18 inches in diameter. The two-duct system is for the vertical-mounted engine installation. (See figure 1.) The three-duct system is for a horizontally mounted engine installation used in initial studies. (See figure 7.)



ASSUMPTIONS

	2 DUCTS	3 DUCTS
DIA, IN	22	18
AREA, SQ IN PER DUCT	380	255
LENGTH, FT	4	12
ΣK (A TO B)	1.70	1.82

$$\sigma \Delta P = 29.25\left(\frac{Wa^2}{A}\right)\Sigma K$$

Figure 8. ACLS Air Supply Duct $\sigma\Delta P$
Fan Plenum to Cushion Trunk

3.2.2.3 Fan Discharge Requirements

1. Flow Rate

The total system flow rate requirement is 292 lb/sec, as calculated in paragraph 3.2.2.1. For a system using two engines, the flow rate required for normal operation on each engine is 292/2 = 146 lb/sec. In the event of one engine out, only one-half the flow would be available. To provide a reasonable margin for operation with one engine, the flow rate should be increased to about 190 lb/sec. This results in an actual cushion height of

$$\text{Actual cushion height} = 0.7 \times \frac{190}{292} = 0.46 \text{ inch}$$

This height should be reasonable for the emergency condition, since reference 1 indicates 0.25 inch is suitable for operational use.

$\therefore$ Maximum flow rate required = 190 lb/sec (per engine)

2. Discharge Pressure

The discharge pressure requirement is the total system pressure drop which is:

Fan discharge pressure required = supply duct ΔP + cushion trunk pressure (psig) + ambient pressure = 3.0 + 3.5 + 14.7 = 21.2 psia (at 190 lb/sec)

$\therefore$ Discharge pressure required at maximum flow rate = 21.2 psia or fan pressure ratio of 21.2/14.7 = 1.44

3.2.2.4 High-Pressure Air Cushion

The minimum size cushion system is represented by the dual system shown in figure 6. The analysis of this system shows the following results:

Rear cushion area (A_C) = 106.5 sq ft
Rear cushion perimeter (c) = 40.2 ft
Required cushion pressure (P_C) $= \frac{150{,}000}{165.1 \times 144} = 6.3$ psig

Rear cushion trunk pressure (P_{t_r}) = 6.3 + 1.5 = 7.8 psig

Rear cushion pressure ratio $= \frac{6.3 + 14.7}{14.7} = 1.43$

Rear cushion airflow exit M_N = 0.735 (thermo handbook)

Rear cushion flow function $= \frac{W\sqrt{\theta}_t}{A\ \delta_t} = 0.32$ (thermo handbook)

Rear cushion airflow (W_r) $= \frac{0.32 \times 40.2 \times 12 \times 1.43}{\sqrt{1.217}} = 200$ lb/sec

ΔP, front cushion to rear cushion (3-duct system) = 1.85 psi

Front cushion pressure (P_C) = 6.3 psig

Front cushion trunk pressure (P_{t_f}) = 7.8 + 1.85 = 9.65 psig

Front cushion airflow (W_f) $= \frac{30.2}{40.2} \times 200 = 150$ lb/sec

Total system airflow (W_{TOT}) = 200 + 150 = 350 lb/sec

ΔP, fan discharge to front cushion = 3.45 psi

Emergency airflow $= \frac{190}{292} \times 350 = 228$ lb/sec

Total system ΔP = 7.8 + 1.85 + 3.45 = 13.1 psig

$\therefore$ Fan discharge pressure required = 14.7 + 13.1 = 27.8 psia

3.2.3 ALTERNATE AIR SUPPLY CONCEPTS

Two concepts for providing the air supply for the air cushion landing system have been considered. One concept involves the direct use of airflow developed from turbofan bypass air. The other concept relies on mechanical linkage via shaft and gearbox to an engine for fan operation.

The concepts of an integral system over a nonintegral system approach were reviewed and a preliminary analysis was made, to determine their design effects, availability, installation, and operational merits.

Conclusions derived from this preliminary analysis has shown that the turbofan appears to offer the best solution to the air supply problem. Turbofan engine candidates, selection, performance summary, and discussion on turboshaft alternate approach are given in the following paragraphs, followed by a review of the operational design considerations that are to be considered in the detail design of the air cushion landing system.

3.2.3.1 Turbofan Engine Candidates

The turbofan engine candidates considered in the study are listed in table II. These engines were selected on the basis that they were capable of supplying the air requirements and were existing, or could be derived from, engines currently being developed in a weapon system application. It was felt that it would not be economically desirable to develop and qualify an engine for the ACLS. While this approach would not necessarily provide an optimized configuration, it was found that several candidate engines were available that appear to be suitable. In accordance with system requirements, only high bypass ratio turbofans with a fan pressure ratio of at least 1:4 and airflow of at least 180 pounds per second were considered. Data are for sea-level static, standard day, maximum power setting.

TABLE II. TURBOFAN ENGINES

			Fan		
Manufacturer	Model	BPR	Wa (lb/sec)	PR	Spec wt (lb)
Lycoming General Electric	ALF 501 TF34-GE-2	6.04 6.2	190 289	1.45 1.50	1,080 1,421
Weights shown do not include engine oil system changes necessary for vertical operation.					

There are no "off-the-shelf" engines available that exactly meet the requirements for the ACLS. The two derivative engine candidates considered are listed. The General Electric TF34-GE-2 engine would be suitable as is, except the fan pressure ratio (FPR) is too low for the airflow available. The engine could be modified to a lower bypass ratio derivative to provide the desired combination of airflow and FPR.

The Lycoming ALF 501, which uses the T55-L-11 gas generator, is chosen for purposes of this study, since it meets the ACLS requirements (table III). This engine, or a version of the possible production ALF 502 engine, have airflow and fan pressure ratios in the desired range.

TABLE III. SYSTEM DESIGN PERFORMANCE SUMMARY - LYCOMING ALF-501 ENGINE

	Flow Rate (lb/sec)	Fan Discharge Pressure (psia)
Required (emergency condition)	190	21.2
Available (max power) setting	190	21.3

The engine performance quoted is for uninstalled conditions. No corrections were made for inlet or exhaust system losses, since they are not expected to be significant.

The Lycoming engine installed as shown in figure 2 would require modification to the oil scavenging system to permit engine operation in the semi-vertical attitude shown.

3.2.3.2 Turboshaft Engine Candidates

The alternate concept studied that would be suitable as a power system providing the air supply for the ACLS is the combination of a shaft engine driving an air compressor. The most suitable arrangement is one in which the shaft engine would directly drive the compressor, using off-the-shelf components. The candidate engines (table IV) are selected on the basis of being in the range of SHP required for the ACLS system. However, none of the candidates have operating speeds that match available compressors, and a gearbox will be required to reduce the output speed to that of the compressor.

Turboshaft engine candidates are limited to those in the range of 4,500 to 6,000 SHP output.

TABLE IV. TURBOSHAFT CANDIDATE ENGINES

Manufacturer	Model	SHP	Output (rpm)	Dry Weight (lb)
Pratt & Whitney	T73-P-700	4,800	9,000	981
Lycoming	LTC4B-12	4,600	16,000	680
General Electric	TF34/S1A	6,150	7,100	1,082
Rolls Royce	RTy20	5,440	15,250	1,742
Allison	501-M45	5,100	13,820	933

On coordination of the requirements with the engine manufacturers, Pratt & Whitney responded with preliminary data on their FT4 engine compressor, which can be used as a representative unit to be driven by the P&W T73-P-700 turboshaft engine. (Refer to table V.)

TABLE V. FT4 AIR COMPRESSOR

Engine	Compressor Stages	Wa	RPM	Press, Ratio	SHP Reqd	Weight (lb)	Length/Diameter
P&W FT4	4th & 5th	160	5,190	1.38	3,260	375	14/40
P&W FT4	4th & 5th	182	5,920	1.48	4,530	375	14/40
P&W FT4	4th & 5th	188	6,120	1.51	5,050	375	14/40

The SHP values are based on a compressor efficiency of 88 percent and a gearbox efficiency of 95 percent. The compressor unit dimensions include a front bearing support, inlet and exit guide vanes and hubs, and rear bearing support. The system estimated dry weight (engine + gearbox + compressor) =

981 + 200 (assumed) + 375 = 1,556 lb

3.3 ACLS GROUND PERFORMANCE CAPABILITY

The performance data contained in this section of the report are limited to the ground capability of the low-pressure ACLS design. Cruise performance and takeoff capability are presented in the last part of the report, where direct comparisons with a conventionally geared aircraft can be made.

3.3.1 COCKPIT NOISE LEVEL

The proximity of the air cushion turbofans to the crew compartment will require installation of acoustical material to keep the cockpit noise level to reasonable limits. Cockpit noise is defined in terms of speech interference level (SIL). Without acoustic treatment, the SIL noise level is expected to be 114 in the cockpit with cushion engines operating. The acceptable limit is 103 for a 15-minute exposure, per MIL8806. The noise level as a function of acoustic treatment is estimated in figure 9. As indicated, approximately 150 pounds of material will be required to attenuate the engine noise to the acceptable 103 SIL level. Total material thickness for this reduction is 3 inches.

The installation area is estimated as requiring 1,000 square feet of acoustic treatment material, which establishes the baseline area from which the weights shown in figure 9 are derived. The material will be applied to the crew compartment floor, the fore and aft bulkheads, and the left and right side structure of the engine compartment. The installation thickness can be increased to further reduce the SIL noise level if operational requirements so dictate.

3.3.2 RATE OF SINK AT TOUCHDOWN

To provide a steep approach path and minimum touchdown distance, a high rate of descent for a military STOL aircraft is required. For these high sink speeds, the energy absorption capability of the air cushion must be investigated. Bell Aerospace has found that experimental testing provides the only reasonable evaluation of this capability. However, the contractor desired to scope the problem and see if some meaningful analysis could be accomplished using simplifing assumptions. At the maximum airplane attitude of 8 degrees nose up, the cushion footprint was estimated for various amounts of cushion deflection. Assuming no increase in trunk pressure nor any buildup of cushion pressure, the maximum energy the cushion can absorb before impacting hard structure proves to be from a 5.5 fps rate of sink. Some additional absorption can be expected from an increase in trunk pressure, a backflow of air through the fan, a buildup of cushion pressure, and airplane rotation; however, to achieve a four-fold increase in absorption to double the allowable sink speed may prove difficult. As the airplane noseup attitude is reduced, a greater trunk footprint is obtained and, thus, more energy can be absorbed. The extreme case is for zero degrees where the airplane is level at touchdown. The full cushion area can be considered acting, as well as the trunk. Also, the proximity of the ground causes the attenuation to begin nearly

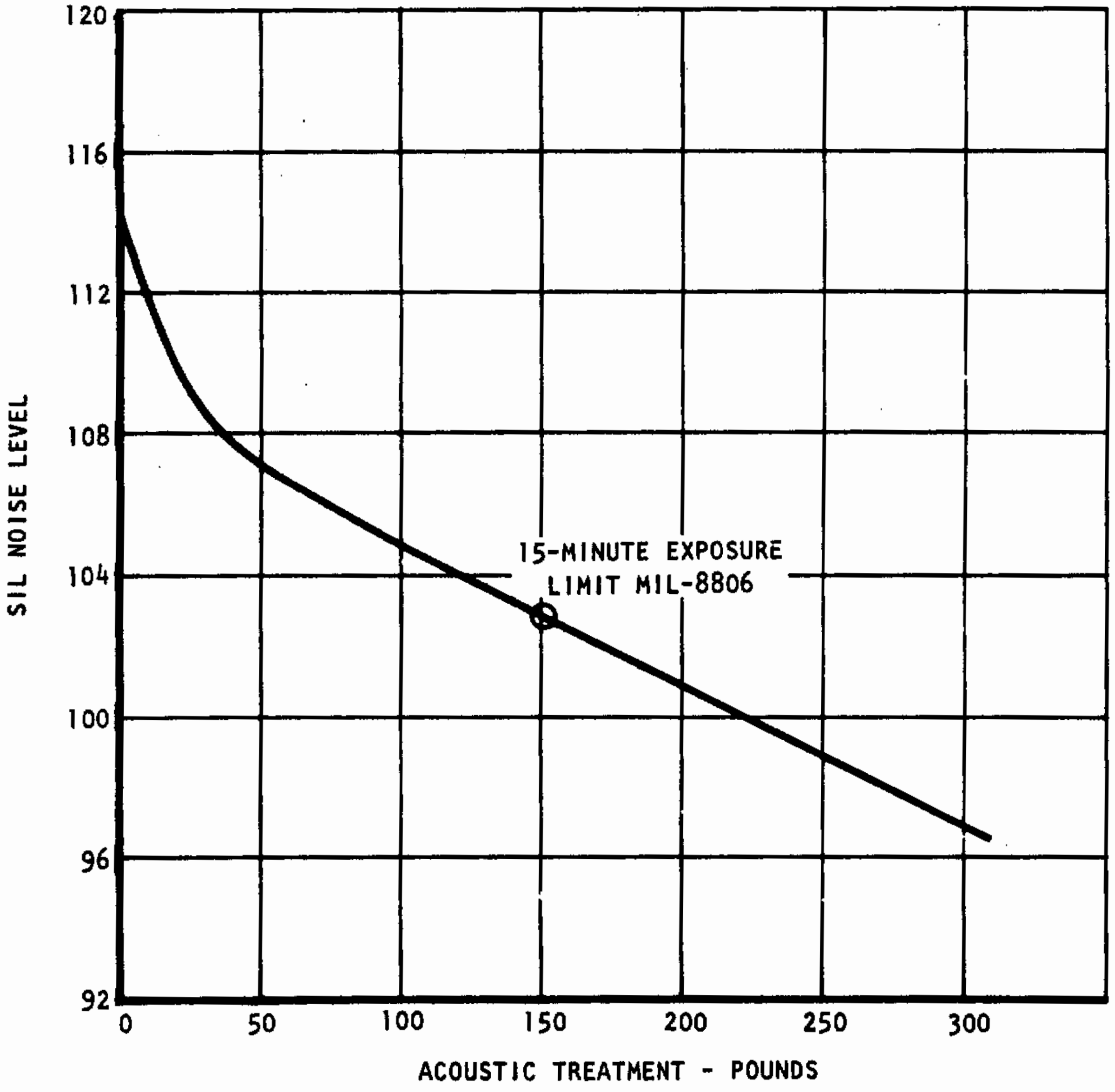


Figure 9. Internal Noise Level, Air
Cushion Operation

15 inches prior to actual ground contact. For this attitude, early Bell data indicate that a 25 fps sink rate can be absorbed, with over 15 inches clearance still remaining to hard structure. Both these cases are plotted in figure 10 as a function of attenuation distance. Unpublished data from the Flight Dynamics Lab indicate that the Buffalo CC-115 ACLS modification will absorb about a 12-1/2 fps drop at a 12-degree cushion attitude prior to impacting hard structure. These data provide a point close to the desired capability of figure 10 and give an indication of the probable conservatism of the initial noseup calculation. It can be concluded that there may be a problem at high sink rates and large noseup attitudes. However, solutions can be readily attained. Perhaps the simplest approach is to install the wing at a greater incidence angle to reduce or eliminate the possibility of high noseup attitude at touchdown. Another approach is to compartment the air cushion by adding a cross-ship trunk some 15 feet forward of the normal aft cross-ship trunk. A buildup of aft cushion pressure would then be possible, and a significant improvement in shock-absorbing capability would exist.

3.3.3 LANDING LOAD FACTOR

In analyzing the cushion energy-absorption capability, it was realized that the load/stroke curve for an air cushion system can be far different from that of a conventional landing gear oleo. Normally, a relatively flat load/stroke curve is desired, as the attenuation force can then be constant. In a conventional oleo system, the metering pin is experimentally modified so that the desired load/stroke curve is easily attained. The flexibility of the cushion in the air cushion system causes high peaks in the similar load/stroke curve that may prove difficult to flatten out. Using early experimental Bell data, a landing load factor versus rate of sink variation has been estimated for the subject ACLS design. (See figure 11.) Normal MIL specification requirements for a cargo aircraft are for a limit sink speed of 10 fps. If this sink speed is used for design, the landing load factor is nearly the same as the flight limit load factor. However, the steep descent and short field operation planned for the MST have resulted in a 15 fps sink speed requirement. This high rate may generate landing load factors as high as 5, which is a significant amount above the flight load factor. High weight items such as engines and cargo loading points may cause critical structural loads for this condition. Total wing down-bending loads will be more critical for -1 g flight than during this high sink landing condition. Unpublished data from the Buffalo ACLS conversion indicate that a slightly more optimum load/stroke curve is apparently available, as the landing load factor is only 3.3 at a sink speed of 12-1/2 fps.

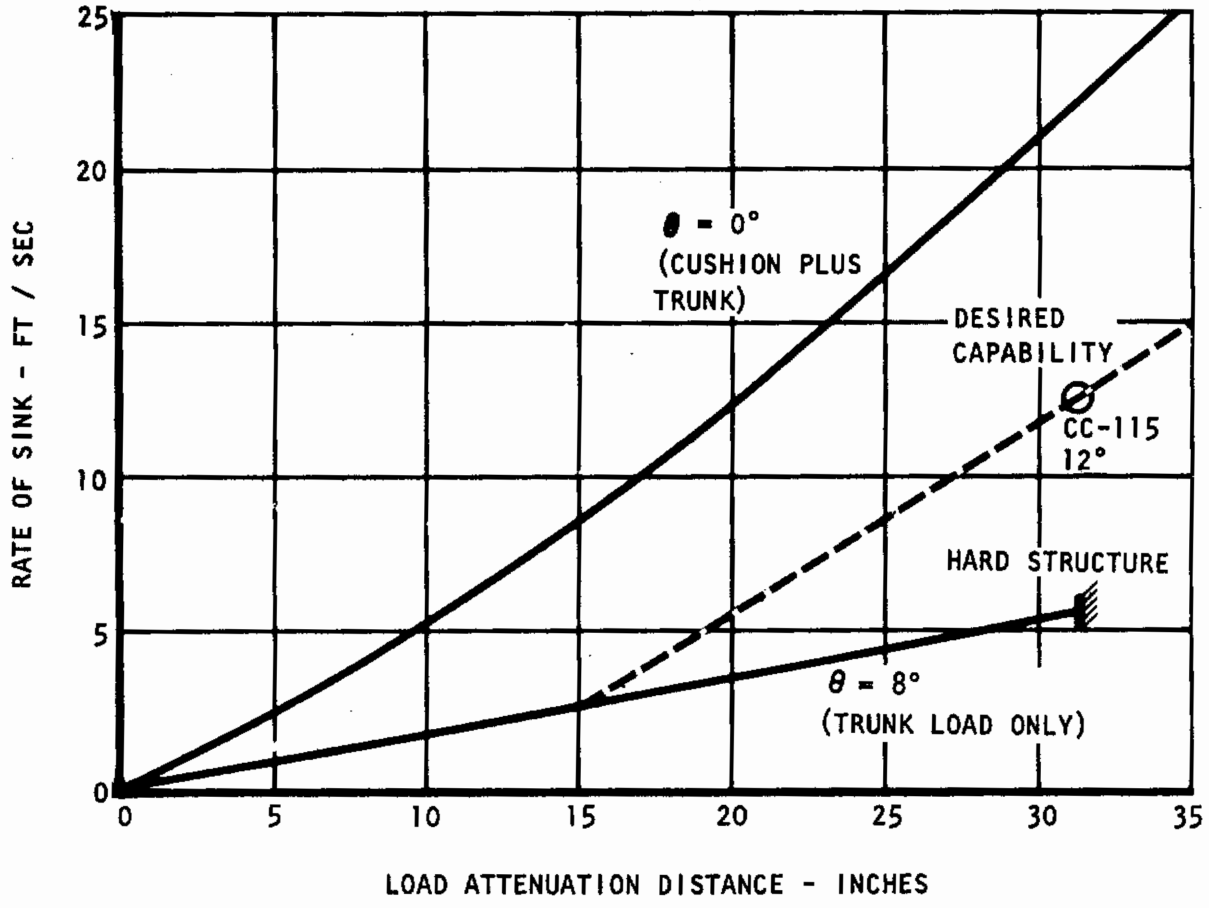


Figure 10. Rate of Sink Versus Load Attenuation Distance

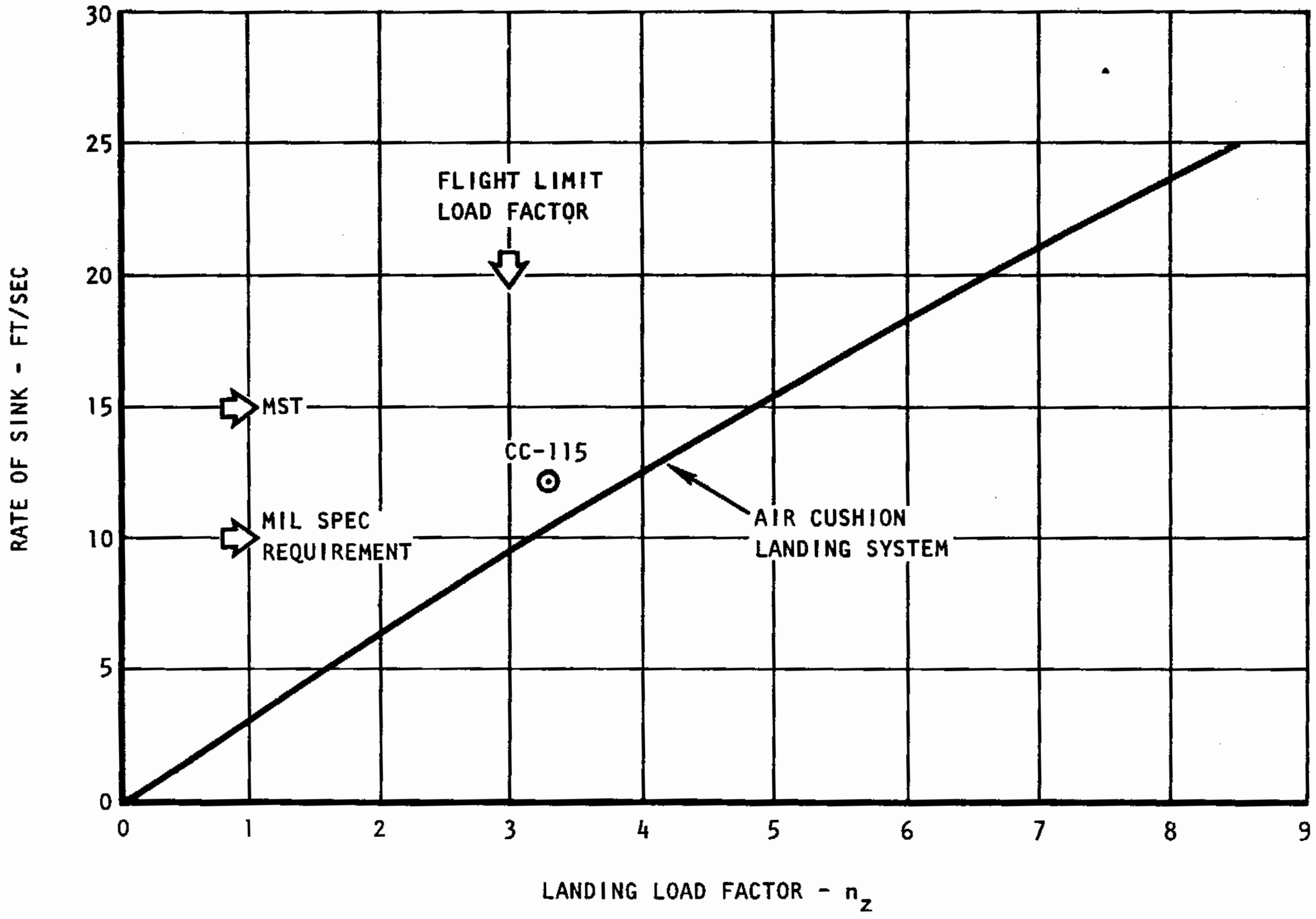


Figure 11. Rate of Sink Versus Landing Load Factor

3.3.4 PITCH STIFFNESS IN PARKING MODE

In the parking mode, sufficient cushion stiffness must be available to preclude a pitching mode problem or an excessive cushion deflection at high cargo loads. A brief analysis of this problem has been made and is included in this section.

The air cushion landing gear incorporates an internal lightweight elastic bladder which, when inflated, provides a sealed pneumatic cushion to support the aircraft while parked. The compartmented bladder is inflated to a pressure which provides a cargo floor height of 48 inches above ground level. At this height and pressure, the trunk and bladder cross section must be such that the hoop tension forces are in balance with the pressure load. The bladder and trunk perimeter must also be such that the elastic forces due to material elongation are the same as the required hoop tension forces. The selected design condition requires a footprint load of 75 pounds per inch of trunk length.

In order to arrive at an economical first-order estimate of pitch stiffness, it was necessary to substitute a simplified model for the actual trunk geometry, and to utilize some simplifying assumptions to reduce the bulk of calculations. The simplified model is described in figure 12. The method and assumptions used are as follows:

1. Establish material dimensions and strength/elastic properties required to produce design operating shape at 3.5 psig trunk pressure. For the selected geometry, the membrane running load is 122.5 pounds per inch. For a design extension equal to 240 percent of unloaded length, the material must produce a load 1.75 times the value used in figure 31, reference 1. The corresponding unloaded perimeter is 42 inches.

2. Find inflation pressure required to produce 75 pounds per inch footprint load at a cargo floor height of 48 inches. The parking bladder is assumed to increase the elongation load by 10 percent.

   Three cross-sectional geometries were analyzed. Each satisfied the 48-inch floor height, but had differing perimeter, radius, and footprint width. The pressure necessary to balance the material tension (resulting from the selected perimeter) was determined and is plotted in figure 13. The point on this curve where the product of pressure by contact width equals 75 pounds per inch defines the design pressure (and corresponding radius) for the static parking case. The pressure is 2.85 psig, and the radius is 26.3 inches.

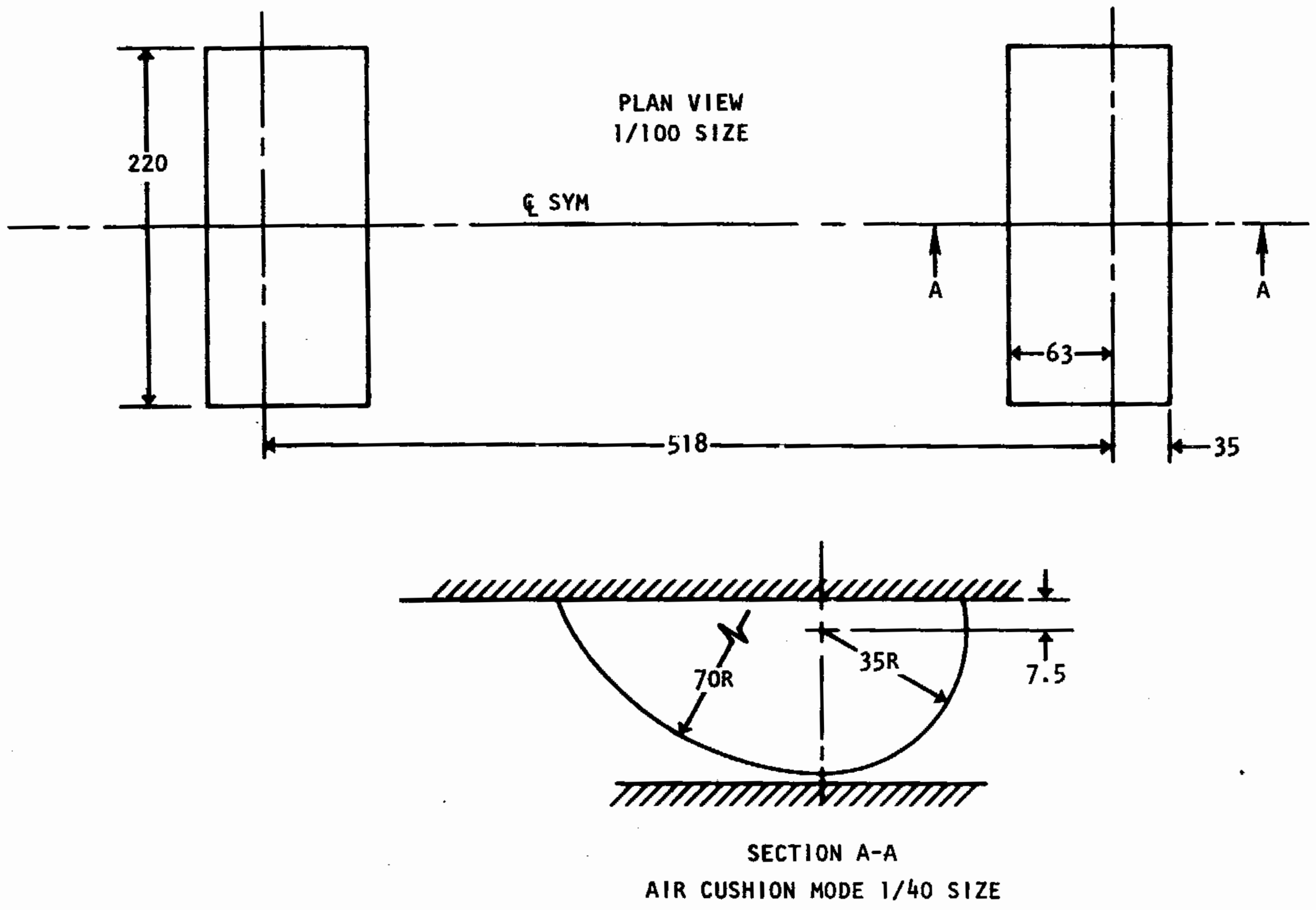


Figure 12. Simplified Model, Trunk Parking Mode Pitch Stiffness

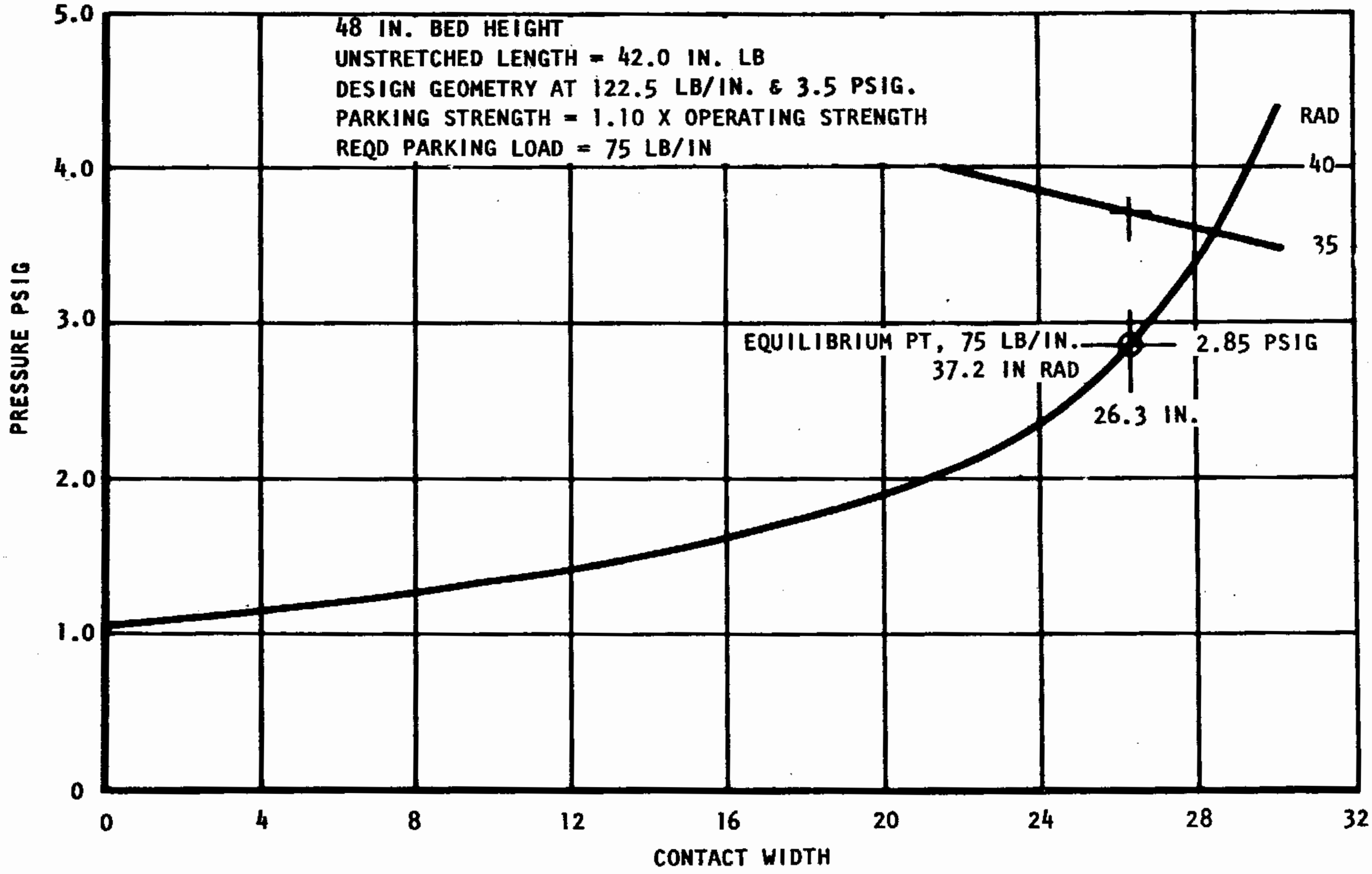


Figure 13. Pressure Versus Footprint Width, Parking Mode

3. Determine resulting trunk geometry when ground contact load is removed.

   Four geometries were examined. The pressure required to balance the material elongation load was determined for each geometry.

   The pressure available was determined for each geometry by computing the volume ratio with respect to the parking geometry.

   The pressure required and available was plotted (figure 14), and the intersection defines the desired trunk geometry and pressure. The corresponding trunk height was determined by interpolation. (See figure 15.)

4. Establish an angular spring rate for the simplified model.

   One compartment was assumed to have the design static deflection, and the other was at zero ground load; i.e., just clear of the ground. The resulting angular deflection was computed, as was the corresponding moment about the center of the cushion. Applying this result as a linear spring rate permitted calculation of vertical deflections of the aft end of the cargo bay as a result of applying various loads at that point. The results are plotted in figure 16.

The preceding method neglects the contribution of the longitudinal cushions to the pitch stiffness and assumed linear load/deflection characteristics for the end compartments.

Additional analysis incorporates a third point at an even greater parking mode deflection that reveals the nonlinear loading characteristics of the trunk. (See figure 17.) This increasing stiffness adds further conservatism to the preceding load deflection analysis. The 50,000-pound load example of figure 16 would cause a deflection closer to 8 inches.

3.3.5 TAXI TURNING RADIUS

On a purely theoretical basis, the vehicle on an air cushion would normally not be able to swing a turn, as no side force vector is usually available. The ACLS version of the MST as proposed in this report has maneuvering ports that can be differentially opened to provide side jet force. Each port can develop a reaction of 1,800 pounds. Since sufficient air is supplied by a single cushion engine to support the vehicle, the remaining air is

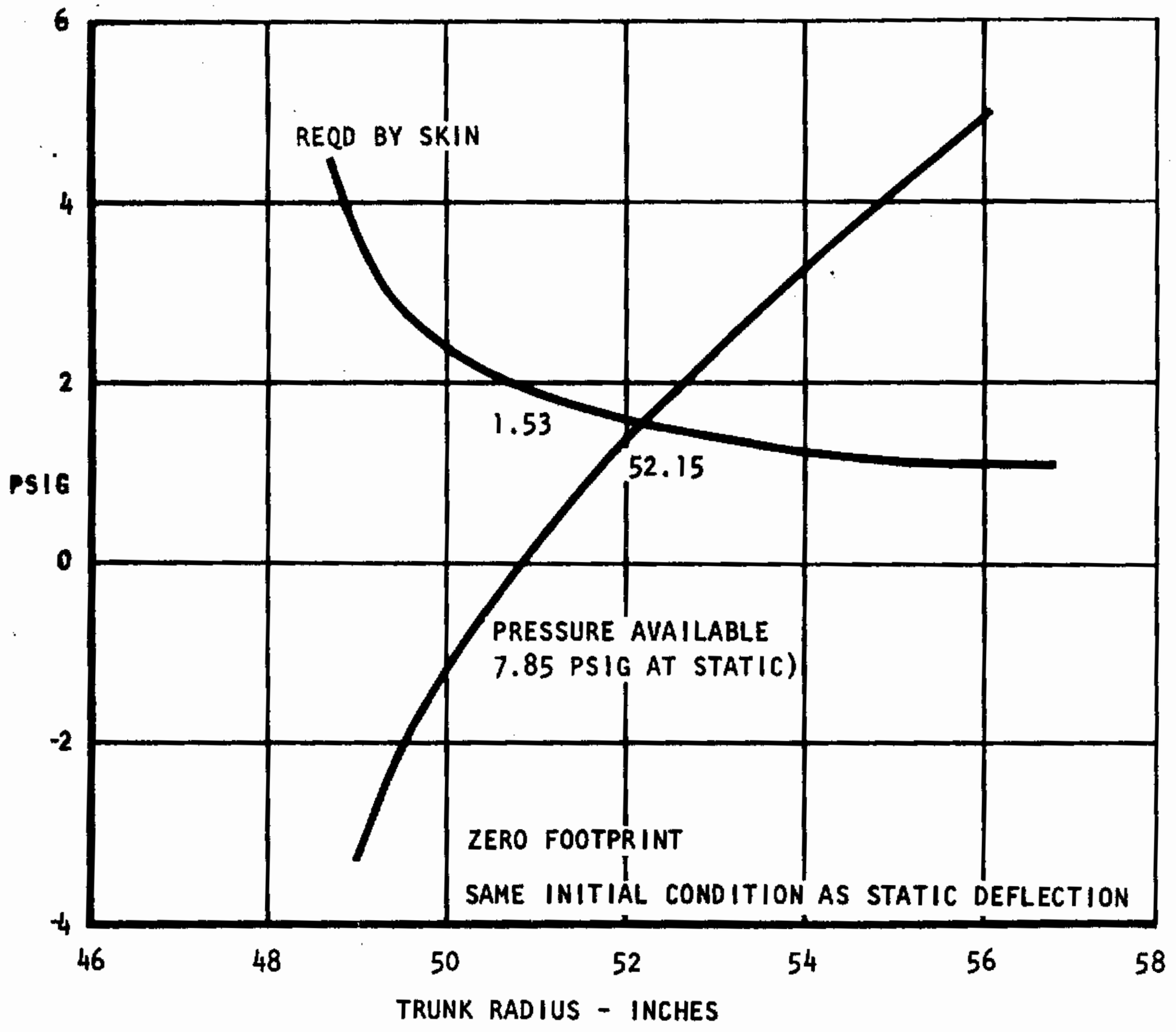


Figure 14. PSIG Required and Available Versus Trunk Radius

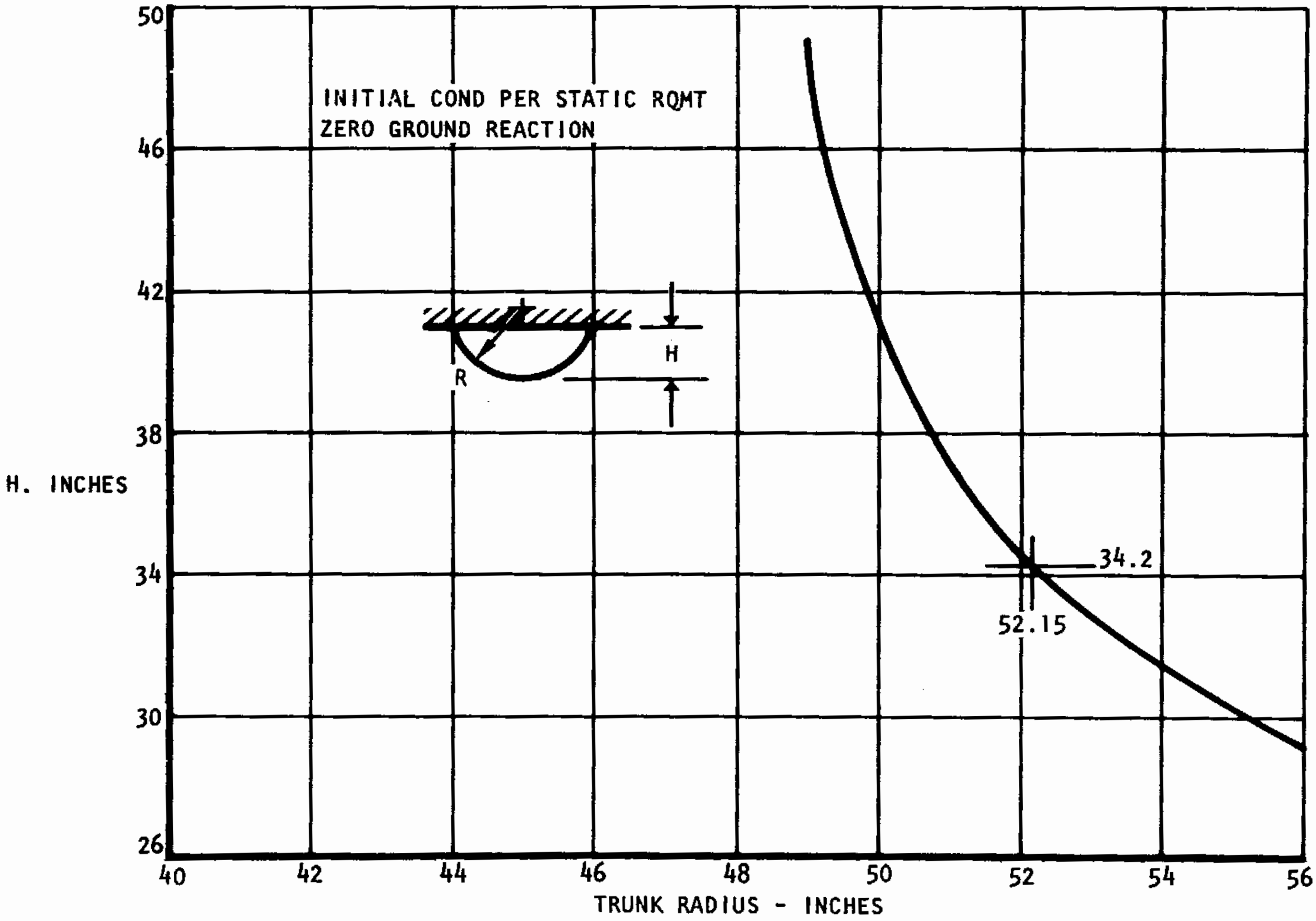


Figure 15. Height Versus Trunk Radius

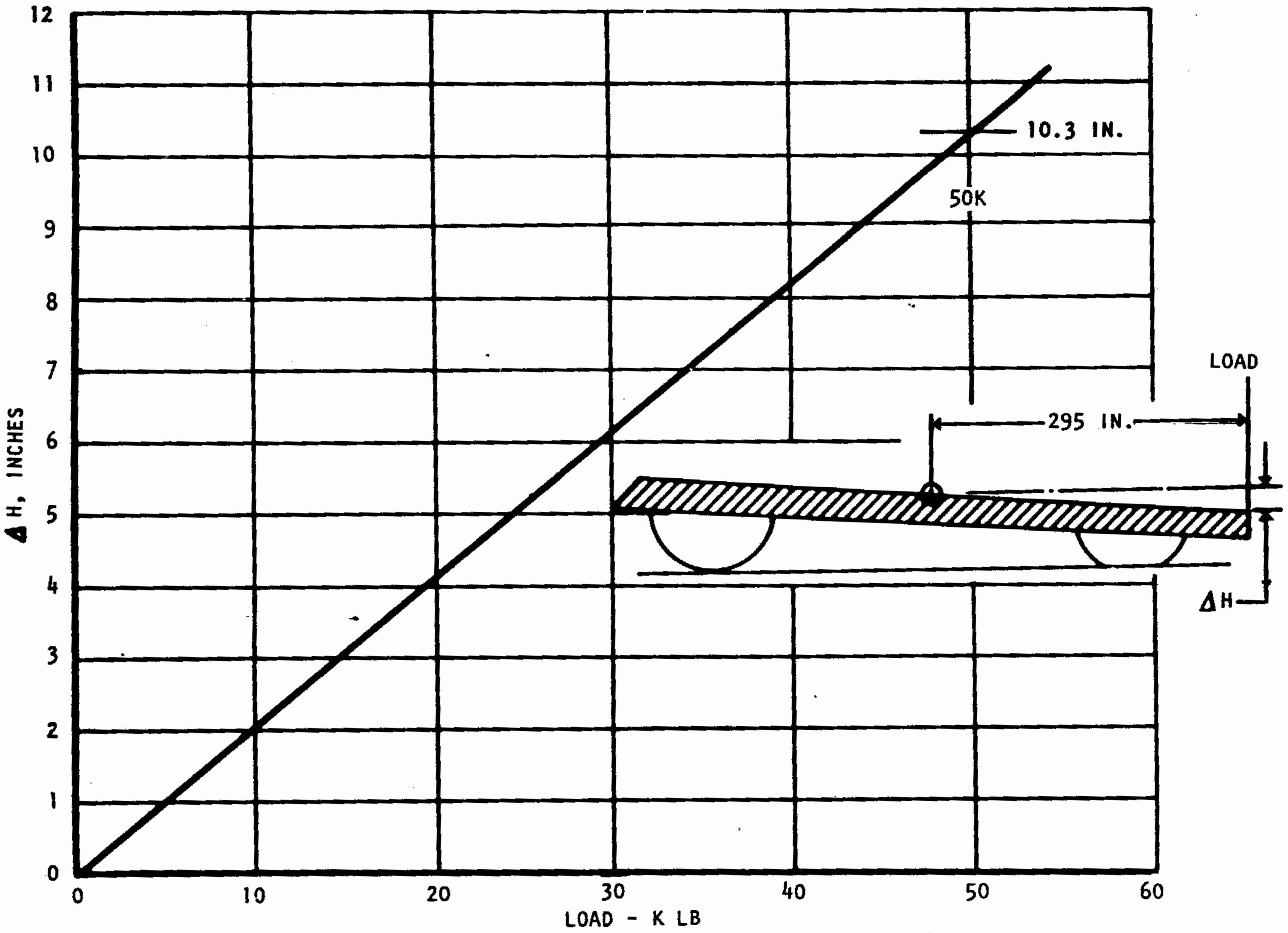


Figure 16. Load Versus Deflection, Parking Mode

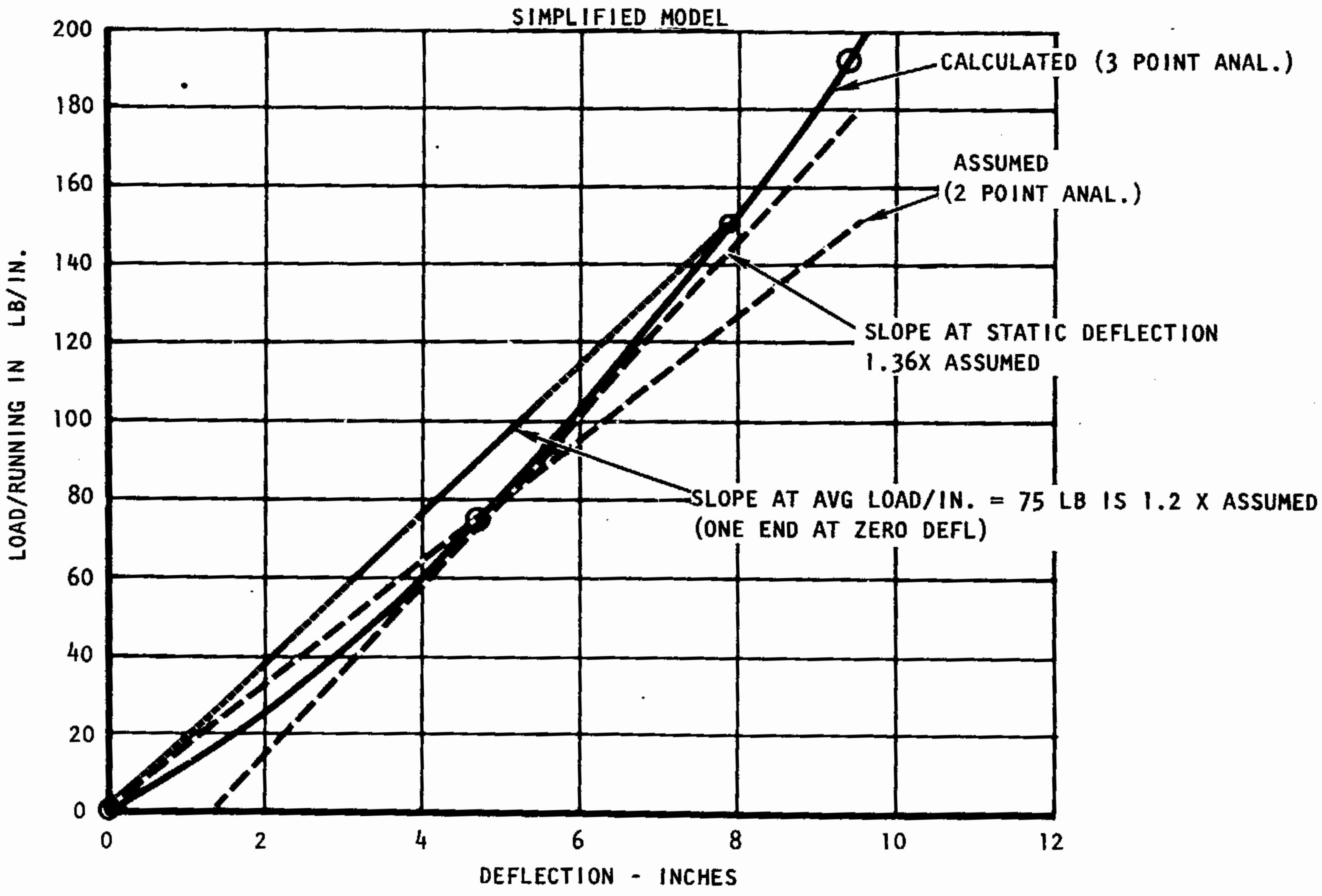


Figure 17. Load/Inch Versus Deflection, Parking Mode

available for a continuous supply of maneuvering control air. The turning radius that this reaction force can exactly balance is shown as a function of airplane taxi velocity in figure 18. The actual turn radius will normally be better than that shown, as other procedures will also be used to generate favorable forces such as airplane yaw, differential thrust, and differential braking.

3.3.6 AUXILIARY WING FLOAT CHARACTERISTICS

Should an auxiliary wing float be required to maintain lateral stability while on water, the design of figure 19 shows a possible approach for design studies. The design shown is sized for approximately 4,500 pounds of static buoyancy. This size is perhaps one-third to one-fourth that provided on earlier Navy seaplane designs, but the greater width of the cushion may provide greater stability when compared to the central seaplane hull. The approximate turning radius, assuming all rolling force absorbed by the outboard float, is plotted as a function of taxi velocity. (See figure 20.)

3.4 ACLS OPERATIONAL CONSIDERATIONS

The primary purpose of this study is to compare an ACLS with a conventional landing gear applied to a military STOL cargo aircraft. The intent is to install directly the ACLS as developed by FDL, with only modifications considered where dictated by configuration details. However, in studying the ACLS system, it appears that some operational problems may exist; these are briefly discussed in this section, with possible solutions suggested.

3.4.1 RESIDUAL EXHAUST THRUST

With the dual-engine air supply system, normal operation could be with both engines set at part power (146 pounds per second airflow each) to conserve fuel, provide longer engine life, and minimize noise and exhaust effects. In the event of one engine out, the operative engine is set at full power, which will provide a reasonable air cushion thickness for emergency operation. The flow rate and temperature of the hot-gas generator exhaust and residual thrust are minimized by selection of a high bypass turbofan or turboshaft engine. The hot-gas thrust from the turbofan and turboshaft is in the range of 700 to 1,200 pounds. This side load during single-engine operation may be undesirable. There are several possible approaches to the problem, such as enlarging the exhaust exit area to reduce the exit thrust, pointing the exhaust up or down, or rematching the engine to minimize the residual thrust. Further study would be required to establish the best approach to this problem.

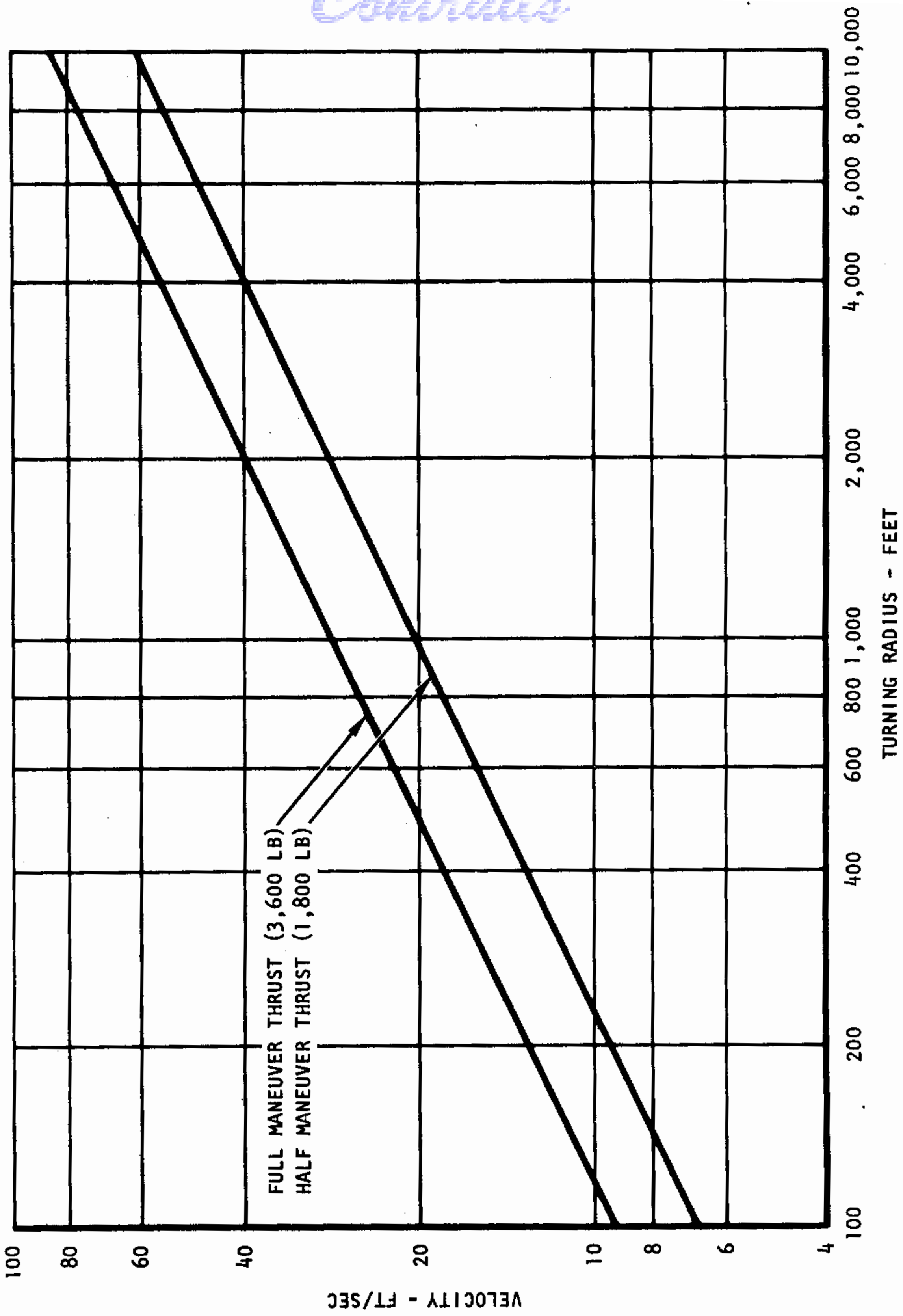


Figure 18. Turning Radius Versus Velocity, Maneuver Thrust Ports

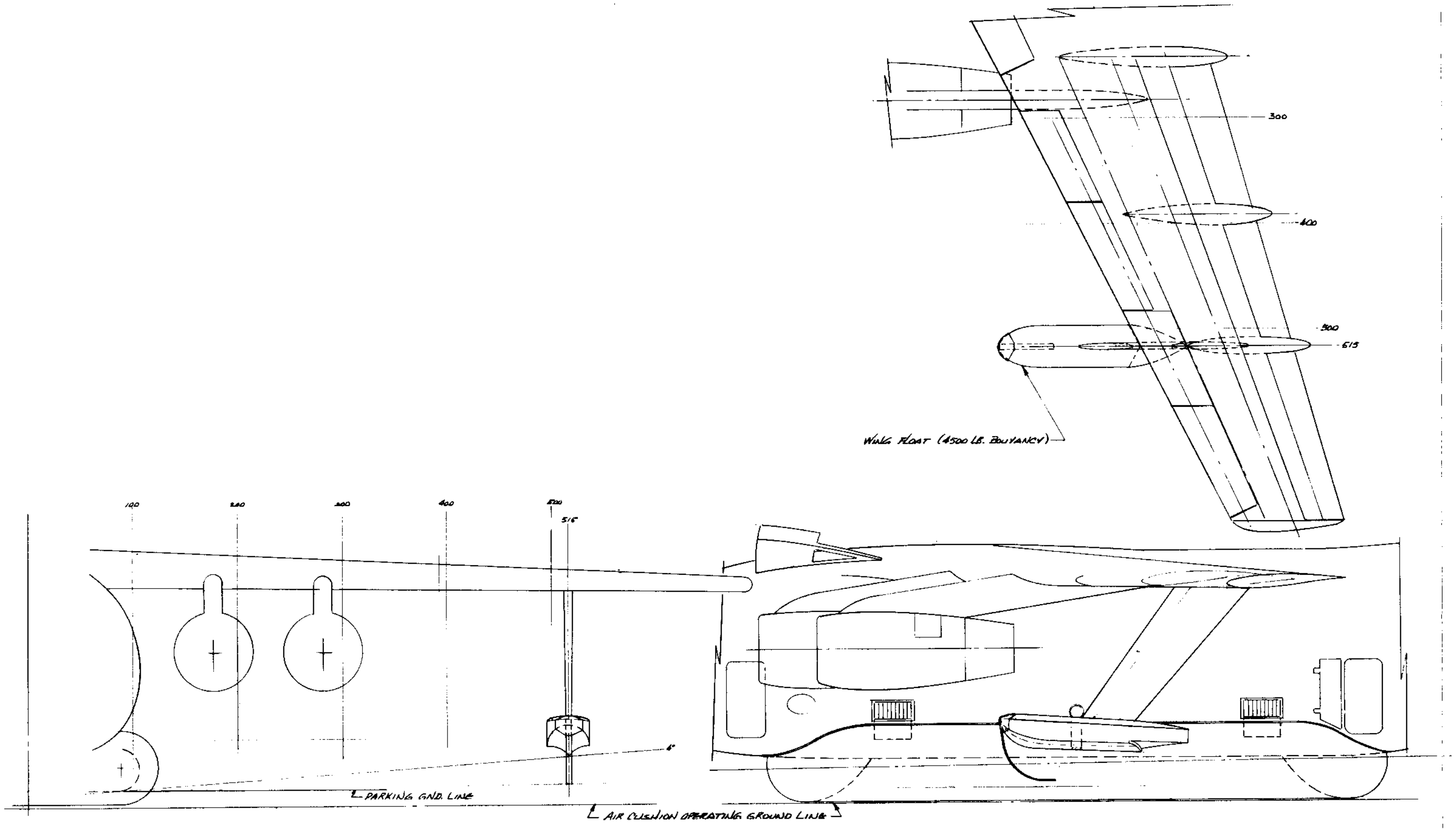


Figure 19. Wing Float Study - MST Air Cushion Landing System

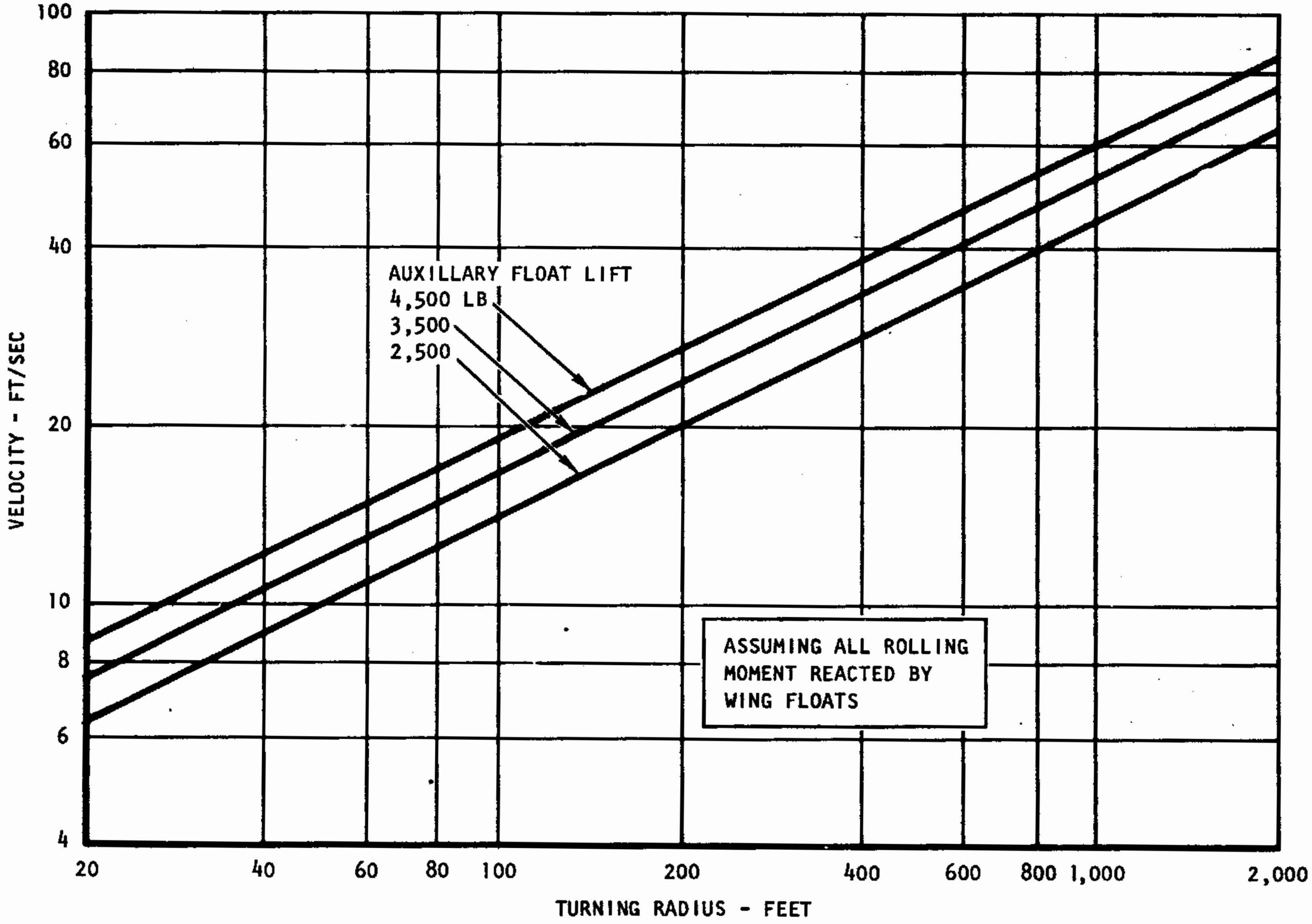


Figure 20. Turning Radius Versus Velocity, Auxiliary Wing Floats

3.4.2 EXHAUST EXIT LOCATION

The initial ACLS design incorporated a concept where the exhaust from the air cushion turbofan was directed aft and outboard behind the crew boarding door. When in the operating mode, the height of this exhaust would be about 6 feet above the ground level - possibly an undesirable situation for ground crew or deplaning passengers. Several alternative designs have been considered to improve this situation. (See figures 21 and 22.) The most reasonable approach appears to redirect the exhaust so that it is deflected more upward, as in figure 21. Some internal space is lost which will make in-flight passage from the forward crew compartment to the cargo bay walkways slightly more difficult.

3.4.3 TRUNK OPERATING VULNERABILITY

Because of the potential frontline and rough field operation planned for the MST, some concern has been expressed about the vulnerability of the operating air cushion. The cushion trunk has thousands of small holes built in that provide the exit orifices for the normal airflow. Since the system airflow is predicated on an engine-failure condition, considerable excess airflow is available when both air supply engines are operating. For example, it is estimated that up to 10 holes 8-1/2 inches in diameter could be sustained by the trunk without appreciably affecting normal landings and takeoffs. In the Bell LA-4 ACLS taxi demonstration, the cushion sustained a 15-inch-long rip, with little operating difference noted by the pilot. Other LA-4 tests indicated that the ACLS is far more forgiving than a conventional gear, in terms of rough field operation, inadvertent drops, or poor pilot techniques. In summary, it is believed that the air cushion system is less vulnerable to rough field handling and small-arms fire than a conventional landing gear.

3.4.4 PARKING SYSTEM VULNERABILITY

The initial concept for the ACLS parking system consisted of a single inner bladder within the trunk that would be inflated to about 3 psig to support the aircraft when the cushion air supply engines were shut down. A single-cell system would be adversely vulnerable to a single puncture. Discussion with the CC-115 Buffalo ACLS project engineer indicated that a similar concern led to a six-cell bladder concept that will be demonstrated on the CC-115. A single-cell puncture will not affect the adjacent cell. The

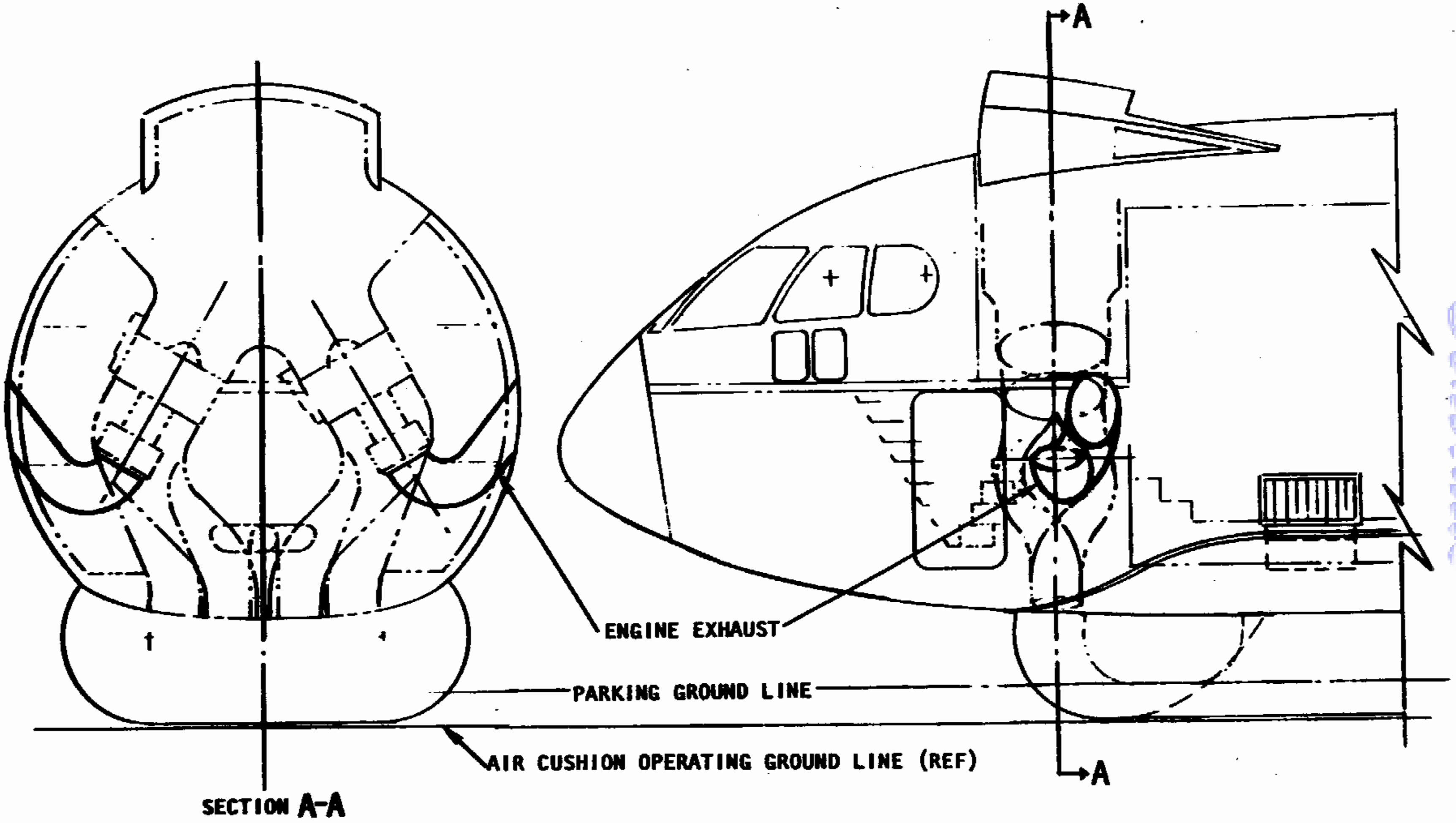


Figure 21. Cushion Engine Exhaust, Alternate No. 1

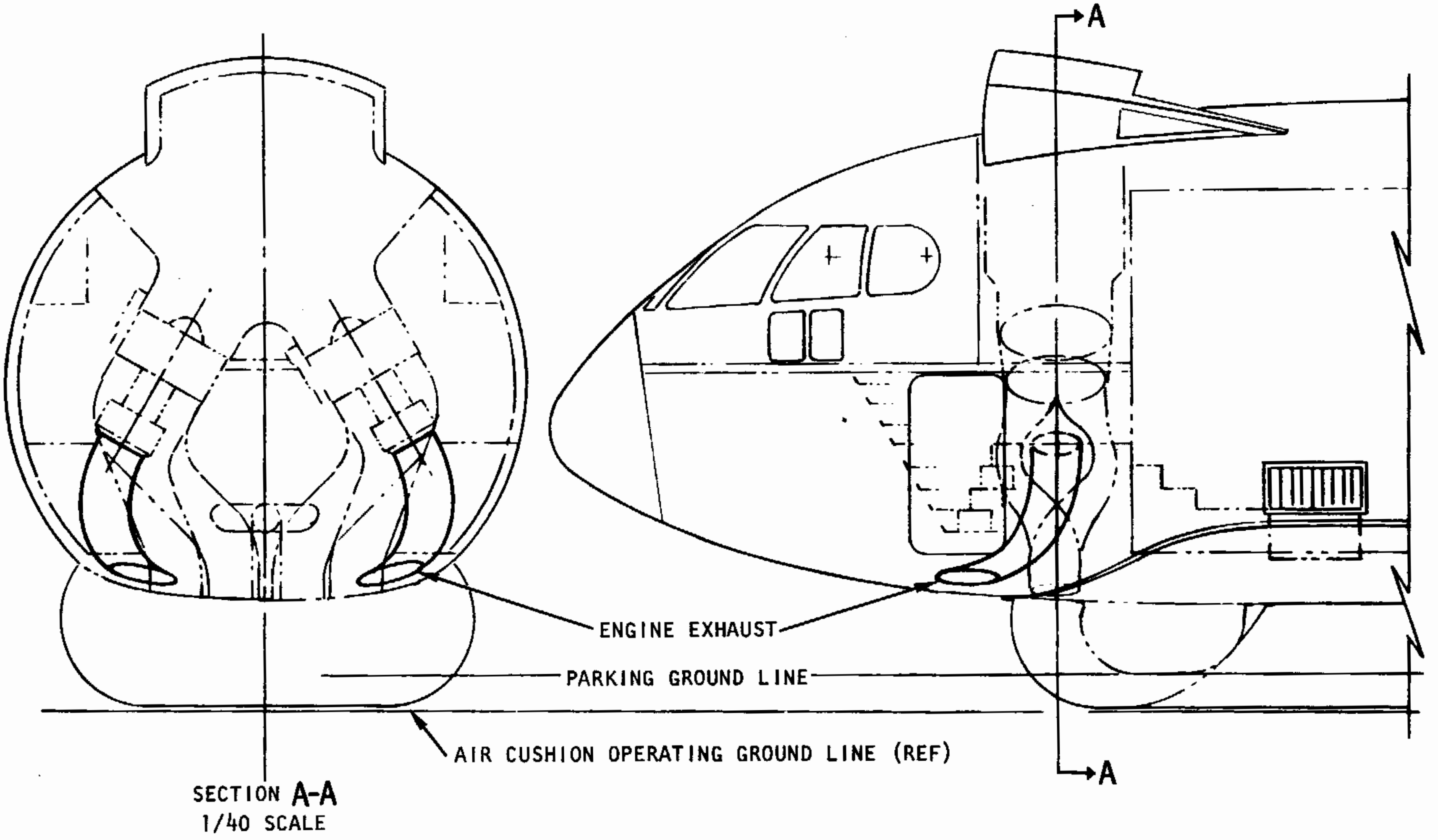


Figure 22. Cushion Engine Exhaust, Alternate No. 2

CC-115 parking cells are interconnected for inflating pressure. If each cell were separately controlled, a method to maintain a level floor during loading operations could be easily obtained.

3.4.5 CUSHION ROLLING STIFFNESS

It has been assumed that the MST ACLS has sufficient lateral width and resultant rolling stiffness that an outrigger system will not be required. Further analysis supported by tests will be necessary to determine the validity of this assumption. In the CC-115 ACLS modification, it has been found mandatory to provide wing-mounted outriggers (floats), as the allowable rolling angle is highly restricted because of the propeller tip clearance requirement - especially in amphibious operations. Should an outrigger be required for the MST, it might be similar to one of those shown in figure 19 or 23. Figure 23 is a design that could be used for nonwater applications; figure 19 is more flexible in that it could be used either for water or nonwater operations. The nonwater design could be made to retract into an enlarged flap track housing. The wing float would most probably be a fixed concept with external bracing for structural rigidity. Initial preliminary weight estimate for the wing float installation is 1,650 pounds.

3.4.6 ENGINE STARTING

Air cushion supply engine starting could be individual or simultaneous. Where engines are started simultaneously, there should be no problem associated with both engines discharging the fan air into a common plenum (the ACLS trunk). For individual engine starts, the air supply duct on the inoperative engine would have to be closed to prevent backflow into the engine. On starting of the second engine, the shutoff valve may require sequencing during the starting cycle to avoid potential fan stall from the backflow of air from the operating engine. A test setup exploring the characteristics of fan engines discharging fan airflow into a common plenum during both starting and normal running may be desirable. Similar testing should be considered for the turboshaft/compressor engine system.

3.4.7 AUXILIARY AIRFLOW EXIT DOOR

In addition to the problems in the starting cycle as previously discussed, a further consideration is involved. This is the possible need for providing an auxiliary discharge flow area for the air supply system until the

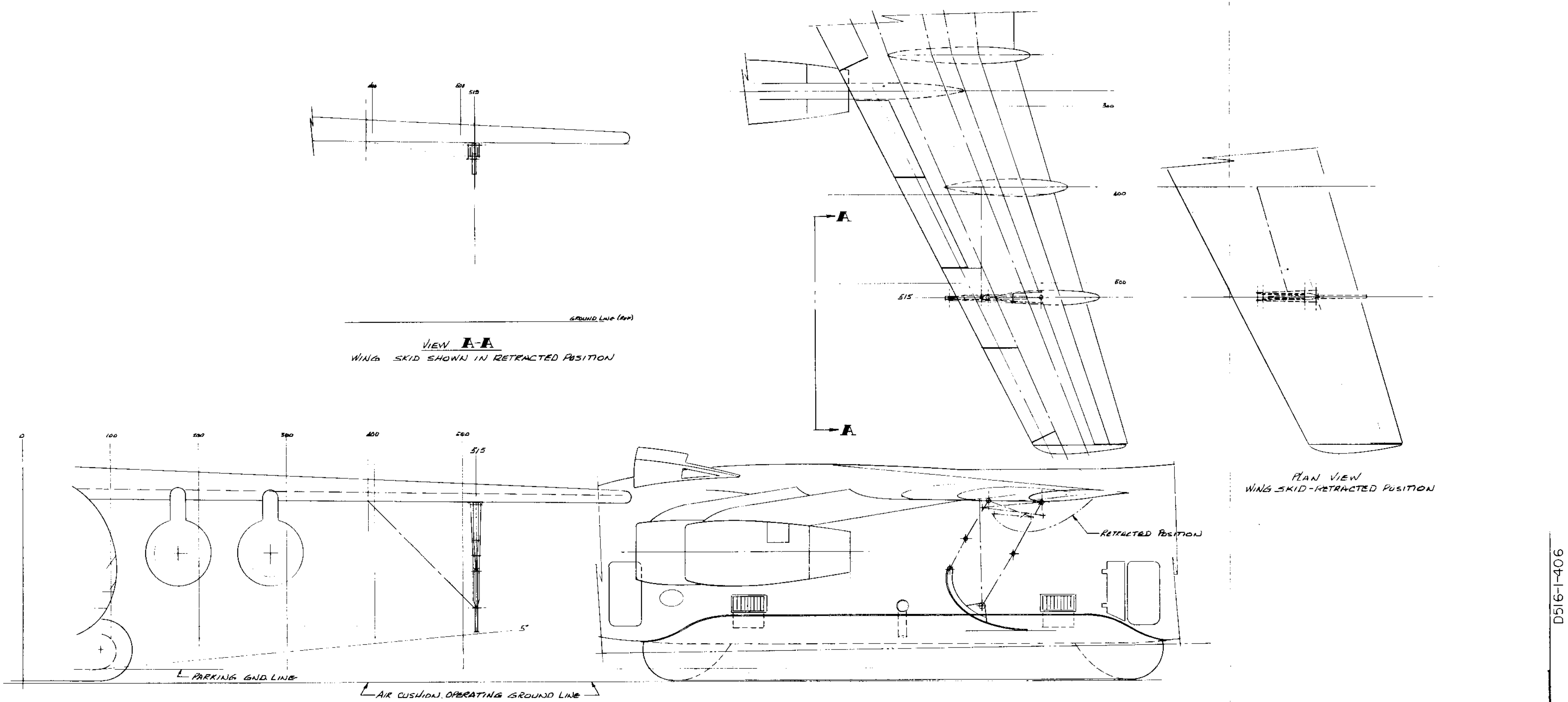


Figure 23. Wing Skid Study - MST Air Cushion Landing System

trunk is properly inflated to provide the design discharge area required to match the system flow and pressure characteristics. A spring-loaded auxiliary exit door, located in the supply duct, may be necessary to allow the fan airflow to discharge overboard until the supply pressure attains the 1.77 psi value. Fan/compressor pressure ratio data available were insufficient to evaluate this problem. Analysis and tests to verify a suitable system may be required. The CC-115 ACLS modification will require a similar installation that is called a fan flow dump.

3.4.8 FOREIGN OBJECT INGESTION

The wing-mounted main propulsion engines, particularly the inboard engines, may encounter foreign object ingestion from the debris moved by the cushion airflow. This operational problem should be considered in the detail prototype design.

3.4.9 HANGAR MANEUVERABILITY

When maintenance or rework procedures require moving the aircraft into a hangar, the exhaust of the cushion air may cause dust and debris to be blown around. If the floor is spotless prior to bringing in the ACLS-equipped aircraft, there should be no problem. Should floor cleaning or the potential fire hazard prove unsuitable, special AGE, such as a wheeled flatbed dolly, could be constructed to provide a wheeled, power-off, transport capability. The special hard points that must be provided on the aircraft to permit jacking during cushion maintenance or installation could be used for mounting special handling wheels.

3.4.10 PILOT TRAINING

The unique characteristics of an ACLS-equipped aircraft will require new pilot techniques to be learned and practiced. Some of the possible problems include:

- Taxing in a crosswind
- Taxing up-hill or down-hill
- Taxing along crown of runway
- Taxing in and out of hangar or shelter
- Crosswind landings
- Rough field operation
- Amphibious operation

None of the techniques required will be impossible to master, but sufficient pilot training must be planned and sufficient time allocated for practice so that each pilot becomes fully familiar with the ACLS characteristics and is adequately proficient.

SECTION IV

CONVENTIONAL LANDING GEAR SYSTEM

4.1 APPROACH

To provide sufficient conventional gear data to properly compare with the air cushion system, three combinations of conventional landing gears were designed and analyzed in detail. The field operational characteristics of these gears are determined and can be plotted as a function of California bearing ratio (CBR) and number of aircraft passes. For lower footprint pressures, larger and/or more wheels and tires will be required. The aerodynamic fairings or pods required to stow these wheels and tires also become larger and create more aerodynamic drag at the cruise condition. Also, the larger gear requires much larger gear doors, both for retraction and operation. A weight assessment must be made that includes all these design effects. Thus, gear and aircraft gross weight effects can be established for any desired landing operational criteria.

4.2 CBR DEFINITIONS

By definition, the CBR is the ratio of force required to penetrate one-tenth inch of soil compared to that required to penetrate one-tenth inch of crushed rock. The approximate CBR spread for various types of soil is summarized in figure 24. Also shown is the lowest CBR value in which a four-wheel drive jeep can normally operate.

4.3 GEAR SELECTION AND PERFORMANCE CAPABILITY

The initial basepoint design by this contractor for the MST consisted of tri-tandem main gear and a twin-wheel nose gear. All wheels and tires were to be identical for simplified maintenance and were to be 17.00 - 20 type III, size. This tire has a maximum width of 17.25 inches and diameter of 48.75 inches. The in-line arrangement of tires and wheels appeared to provide the minimum low-drag pod for stowage. A review of the CBR calculations reveals that this tire is slightly below the MST requirement of 200 landings at CBR 6. For the study, the basepoint tire is increased to 50 x 20.0 -20 "new design" type, which has a maximum outside diameter of 50 inches and a maximum width of 20 inches. For 200 passes with the tri-tandem arrangement,

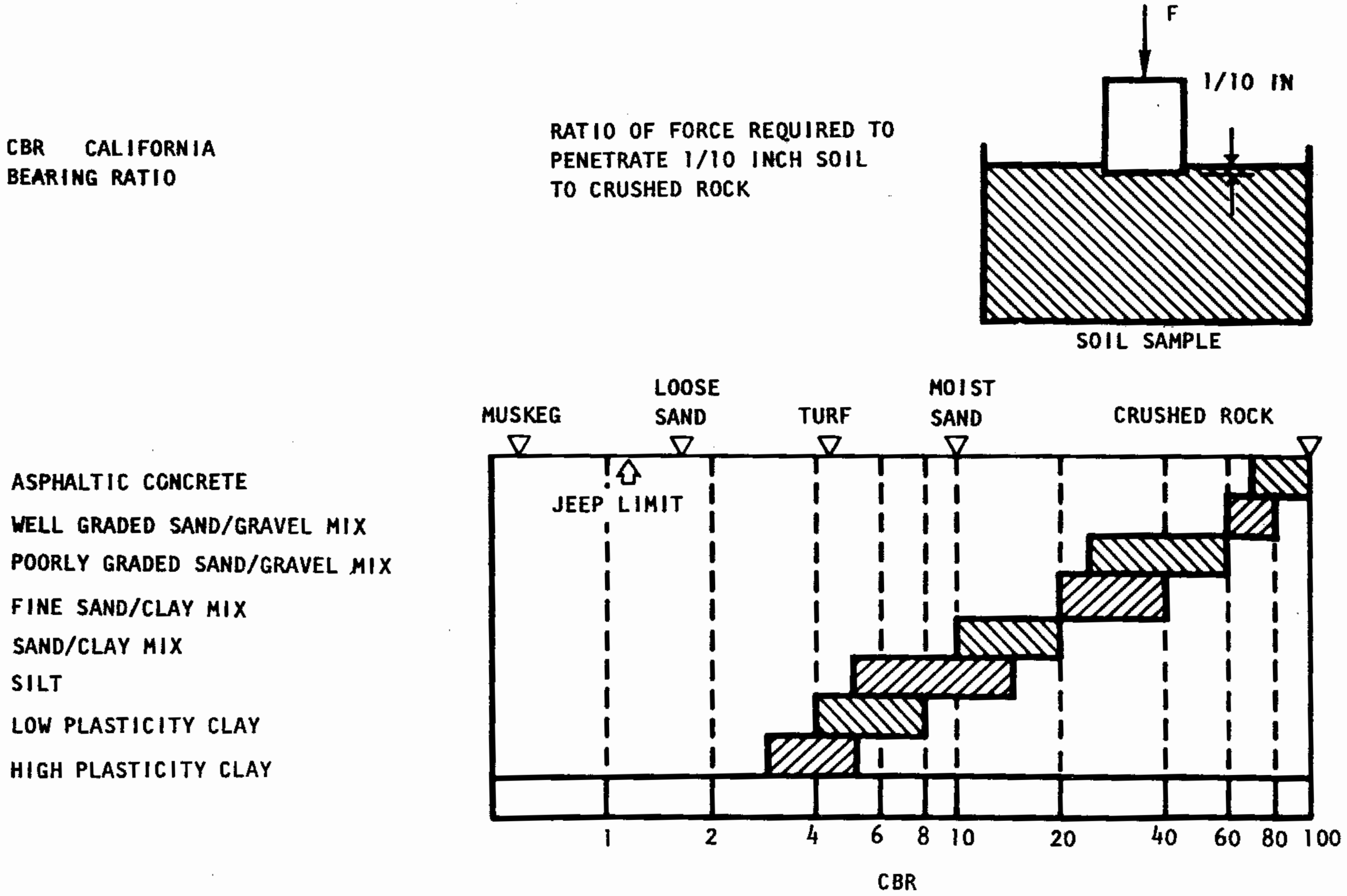


Figure 24. CBR Definition

the allowable CBR is about 6.4 - close to the required 6.0. In order to reduce the footprint pressure, two other tire/wheel combinations can be considered, both of the tri-twin-tandem type. At the high-pressure end of the spectrum, three tire/wheel combinations are considered, all with a tri-tandem arrangement. To continue the concept of using nose wheels and tires of the same size as the main gear, the nose gear has to be a triple-wheel arrangement for the mains with tri-twin-tandems. Conventional twin-wheel nose gears are satisfactory with main gears of the tri-tandem type. Ply rating and pressures are estimated for each candidate tire. These candidate gears are summarized in table VI.

TABLE VI. CANDIDATE MAIN GEAR TIRES

Wheel Arrangement	Tire Size	Type	Ply Rating	Tire Pressure (psi)	CBR for 10 Passes
Tri-twin-tandem	50 x 20.0 -20	"New design"	10	27	2
Tri-twin-tandem	15.00 - 10	III	10	46	3
Tri-tandem (basepoint)	50 x 20.0 -20	"New design"	16	55	4
Tri-tandem	15.00 - 16	III	16	90	5
Tri-tandem	40 x 14	VII	20	120	8.5
Tri-tandem	34 x 11	VII	22	185	14

The field performance characteristics of these main gears can be plotted in terms of CBR as a function of number of landings. (See figure 25.) The primary significance of this figure is that each set of gears will provide the field performance shown for a 150,000-pound MST, and that a broad spectrum of gear capability or choice exists. In order to provide the greatest spread in the trade data, three gear combinations were selected for detailed study - the two extremes as shown in the figure and the basepoint.

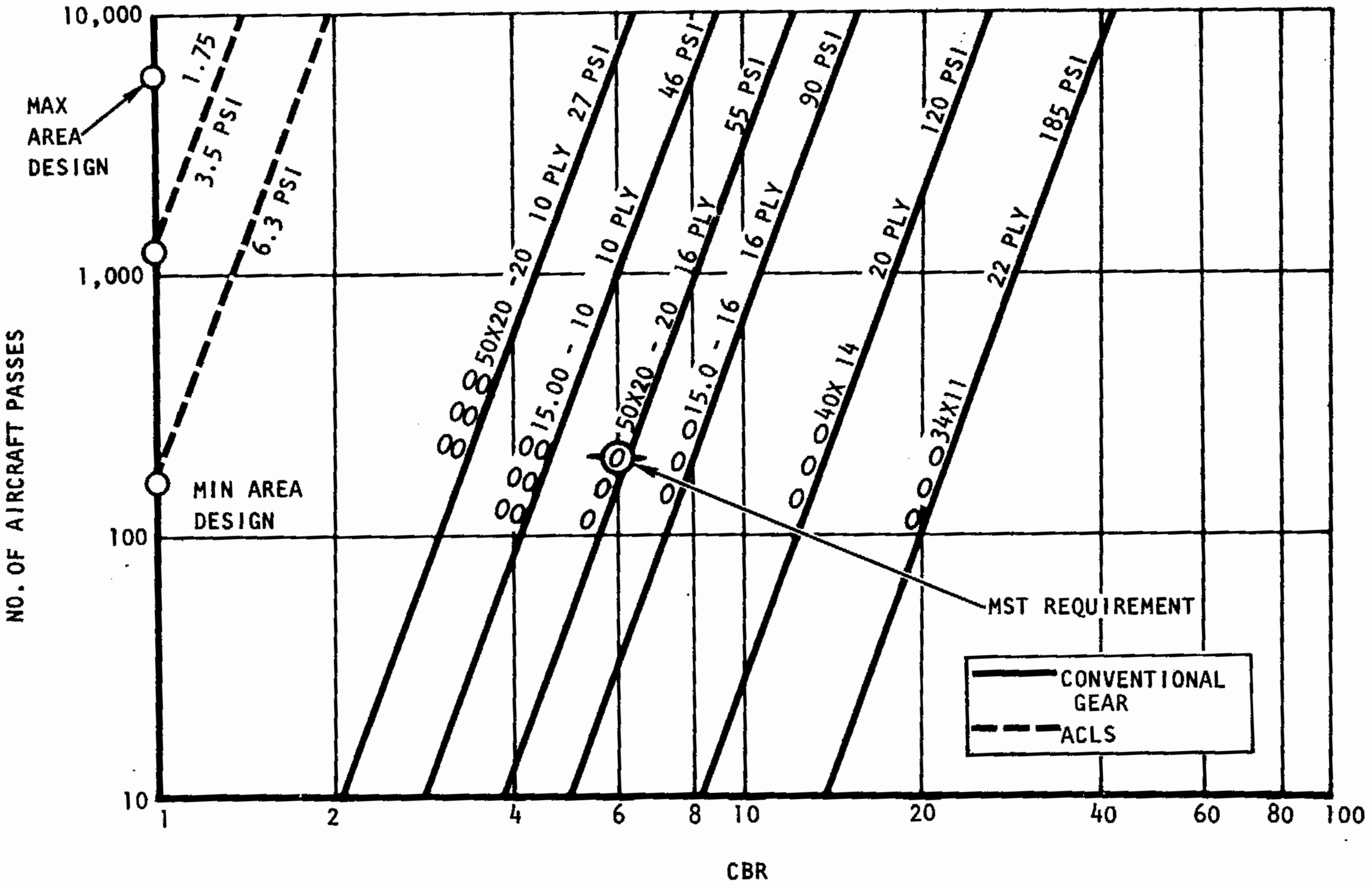


Figure 25. Field Performance

4.4 GEAR DESIGN DETAILS

In this section, are presented the gear design details that have been generated to support the weight and drag estimations for the conventionally geared MST. In each case, the actuators and structural gear members are sized by conventional advanced design practice. Three identical struts, downlocks, and retraction mechanisms will be used for each main gear design. In actual practice, metering pins may prove to be different according to strut location. Also, if the aft strut is allowed to swivel to reduce wheel scrubbing in tight turns, it would require additional door clearance and components. For each design, the main gear is the articulated type. The nose gears for the basepoint and the low CBR designs also incorporate the articulated shock strut arrangement. The nose gear for the high CBR design will use a conventional nose strut arrangement.

4.4.1 BASEPOINT CONVENTIONAL LANDING GEAR

Figure 26 summarizes the details of the conventional gear for the basepoint configuration. Each strut of the tri-tandem main gear is essentially identical in design and mounted on 69-inch centers. The articulated concept provides a good stroke capability with a low profile configuration when retracted. Ample space within the wheels is available to mount conventional disk brakes. As the fuselage attach point for the downlock brace is located in line with the articulation and retraction pivot points, this axis could be used to swivel the aft wheel and reduce tire scrubbing in tight turns. Since the wheels protrude into the wheel well for normal operation, the well would have to be much larger to provide clearance for a swiveling main gear. Structural and drag penalties would increase to attain this capability. The twin-wheel nose gear rotates about the shock strut for steering. As with the main gear, the nose gear must operate within a well to avoid contacting the structure. The nose gear retracts forward to a position below the crew compartment.

4.4.2 LOW CBR CONVENTIONAL LANDING GEAR

Figure 27 summarizes the details of the conventional gear for the low CBR configuration. Essentially, a second wheel and tire of the same size as the basepoint (50 x 20.0 -20) is mounted inboard on each of the main gear axles. The tires are of lower ply rating and operating pressure than the basepoint. The spacing must be opened to 75 inches to allow for inner tire clearance. Operating and retracting geometry and mechanism can be essentially

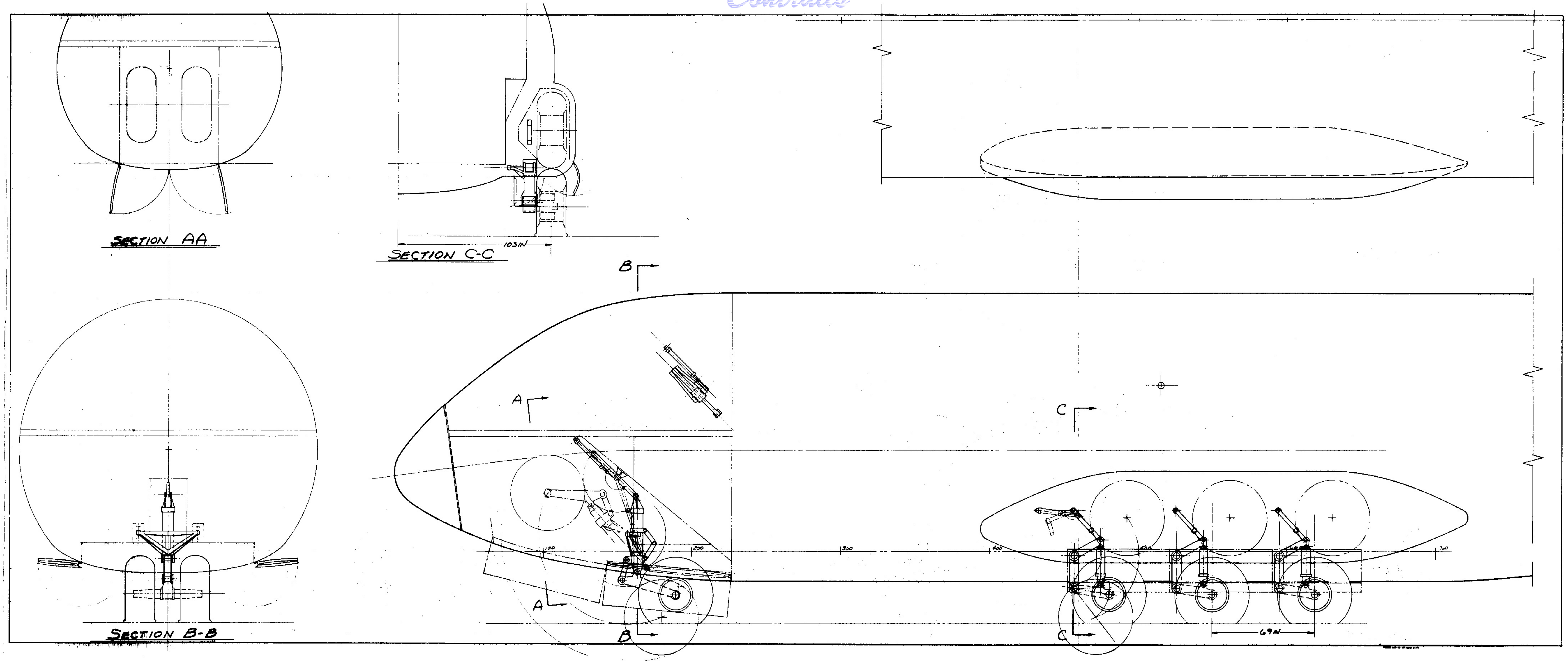


Figure 26. MST Basepoint Gear Details Tri-Tandem 50 x 20.0-20 "New Design" Tires

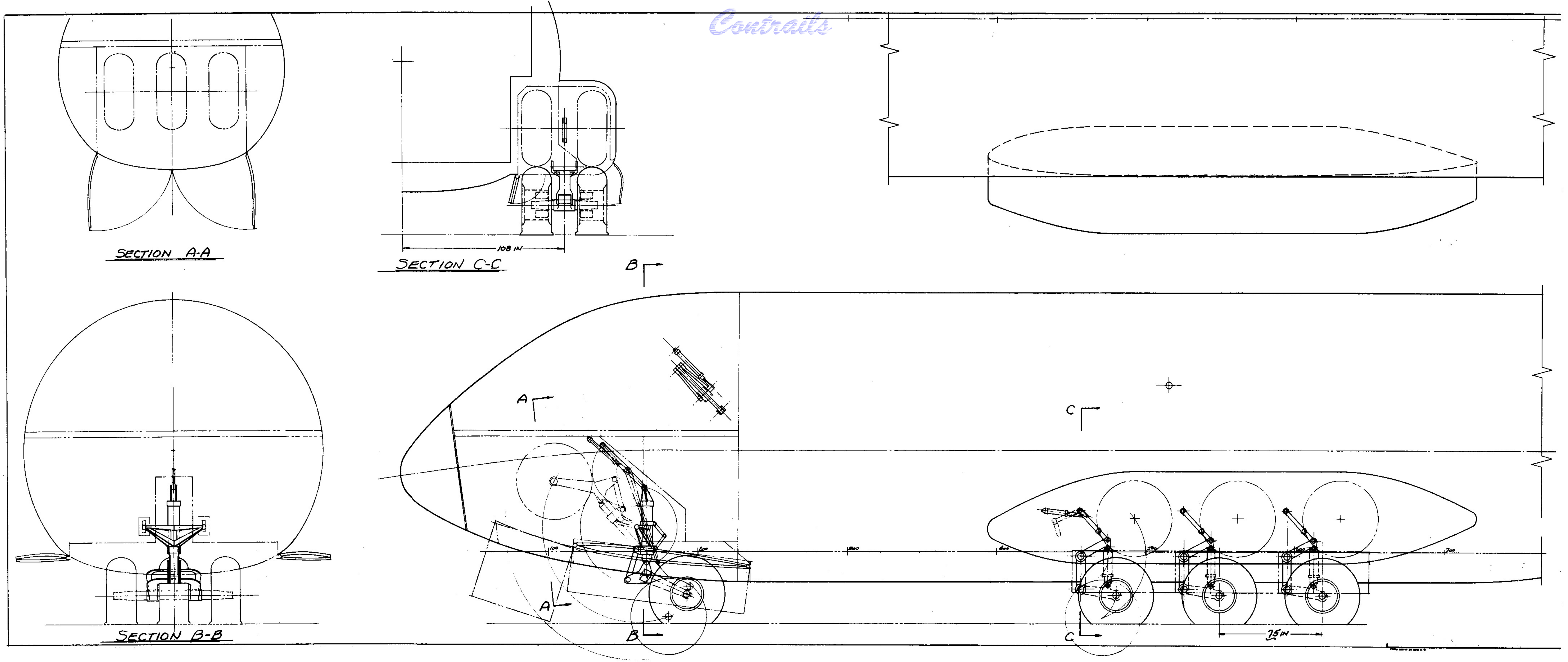


Figure 27. MST Low CBR Gear Details - Tri-twin Tandem 50 x 20.0-20 "New Design" Tires

the same as for the basepoint. The additional width due to the dual-wheel arrangement requires a much larger pod to stow the gear in the retracted position. Even greater width would be required should it prove desirable to swivel the aft set of wheels to reduce tire scrubbing. To match the capability of the main gear, the nose gear must use a triple-wheel concept. The yoke-mounted shock strut can also use the lever or articulated operation concept. Steering is accomplished by rotating the gear about the shock strut. Nose gear doors are sized to allow full swiveling of the wide gear. Door size could be slightly reduced if a conventional strut were used. The nose gear retracts forward to a stowed position just below the crew compartment floor.

4.4.3 HIGH CBR CONVENTIONAL LANDING GEAR

Figure 28 presents the design details of a conventional landing gear with high-pressure tires that is restricted to operating at high CBR values. A tritandem arrangement can be used for the main gear, as with the basepoint. Identical struts and structural elements would be mounted on 58.5-inch centers. The reduced gear size permits a smaller pod to be used for stowing the gear. Should the aft strut be required to swivel for reducing tire scrubbing, the additional space required would be much less than for any of the larger wheel designs. The twin-wheel nose gear is mounted on a conventional strut, rather than the articulated arrangement of the lower CBR designs. Also, less steering force will be required and a much smaller door is needed to accommodate a full 90-degree swivel. The longer strut is mounted similar to the other nose gear designs and also retracts forward for stowage.

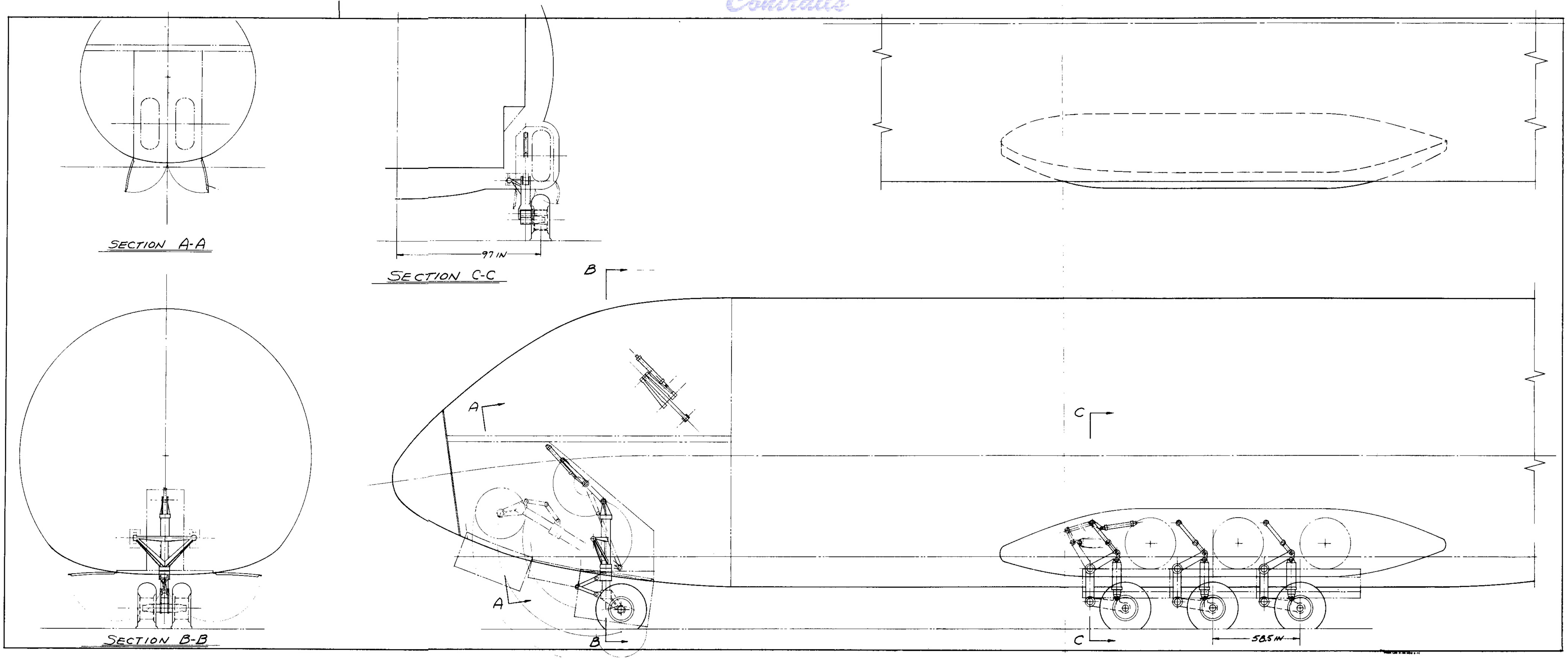


Figure 28. MST High CBR Gear Details - Tri-Tandem 34 x 11, Type VII, Tires

SECTION V

AIRCRAFT PERFORMANCE ANALYSIS AND COMPARISON

5.1 METHODOLOGY

The ground operational characteristics for both ACLS-equipped and conventionally geared MST aircraft are summarized in previous sections of this report. The primary method of comparison is the number of aircraft passes as a function of CBR or field hardness. These characteristics are based on a takeoff gross weight of 150,000 pounds. This makes a valid comparison, as fuel can be varied to account for the varing structural and system weight for each configuration. A true comparison must take into account both the weight change and the aerodynamic drag change. The best common factor for comparison is airplane gross weight for a constant performance. Gross weight sensitivities to incremental drag and weight effects have been determined for other trade studies and are readily adaptable to this trade study. Another possible comparison is takeoff performance. Normally, the takeoff performance requirement will size the engine. However, 90 percent is the lowest scale engine that can be used for the subject study. The basepoint configuration already uses the 90-percent engine, so normal takeoff is better than the MST required 2,000 feet. For the subject study, the increased drag of the air cushion installation is used to compare takeoff distance, which is still within the design requirement and no change of engine size is required.

5.2 WEIGHT ESTIMATION

Conventional contractor weight estimating procedures have been used to evaluate the various gear and cushion concepts. All estimates are in terms of incremental weight from the D516-1 basepoint. When possible, direct application or appropriate scaling of previous ACLS designs have been made. Basic references have been the AFFDL ACLS reports and some advanced Buffalo CC-115 ACLS modification data.

5.2.1 AIR CUSHION LANDING SYSTEM WEIGHTS

Weights for both the low- and high-pressure ACLS designs have been estimated and are summarized in table VII.

TABLE VII. AIR CUSHION LANDING SYSTEM WEIGHTS

Item	Weight (lb)	
	Low-Press.	High-Press.
Landing system		
Attachment	410	407
Trunk	769	1,548
Treads	868	133
Brake	150	150
Inflatable tube	253	212
Subtotal	2,450	2,450
Fuselage changes (landing provisions)		
Fuselage shell	-	70
Engine blast shield	125	125
Fwd bulkhead	350	350
Aft bulkhead	165	165
Plenum sidewall	135	135
Control louver ports	45	45
Subtotal	820	890
ACLS power system		
Exhaust ducts	380	380
Valves	256	356
Inlet system	196	196
Engine mounts	23	33
Engines (2)	2,290	3,300
Fuel system, starting & misc	100	100
Subtotal	3,245	4,265
Miscellaneous		
Noise suppression (ACLS power system)	195	195
Total	6,710	7,800

The items listed in table VII are the weights for the air cushion components and all related equipment. In order to obtain the net weight change from the basepoint configuration, the weight of the landing gear, ground mobility system, and backup fuselage structure, due to concentrated gear loads, must be subtracted. A summary of these items is as follows:

Item	Weight (lb)
Alighting gear group	-6,160
Ground mobility	- 320
Body group landing provisions	-2,840
Total	-9,320

Total weight change

Low-pressure system = 6,710 - 9,320 = -2,610
High-pressure system = 7,800 - 9,320 = -1,520

The net change from the basepoint is then the sum of these changes - a weight saving of 2,610 pounds for the low-pressure ACLS and a saving of 1,520 pounds for the high-pressure ACLS. These totals are further summarized in tables IX and X, that include comparisons with changes of the conventional gear system.

5.2.2 ALTERNATE CONVENTIONAL GEAR WEIGHTS

The conventional landing gear design details, as shown in section IV of this report, have been used to estimate the weight changes from the basepoint for a low CBR landing gear and a high CBR gear. These weights are summarized in table VIII.

The net change for the low CBR system is +3,022 pounds; for the high CBR system, -2,798 pounds. These weights are also summarized in tables IX and X, that include changes due to the ACLS configurations. Knowing the CBR/landing characteristics of these gears, the incremental landing system weights can be plotted against CBR as a function of the number of aircraft passes. (See figure 29.) Also plotted are the ACLS incremental weights for both the high- and low-pressure system.

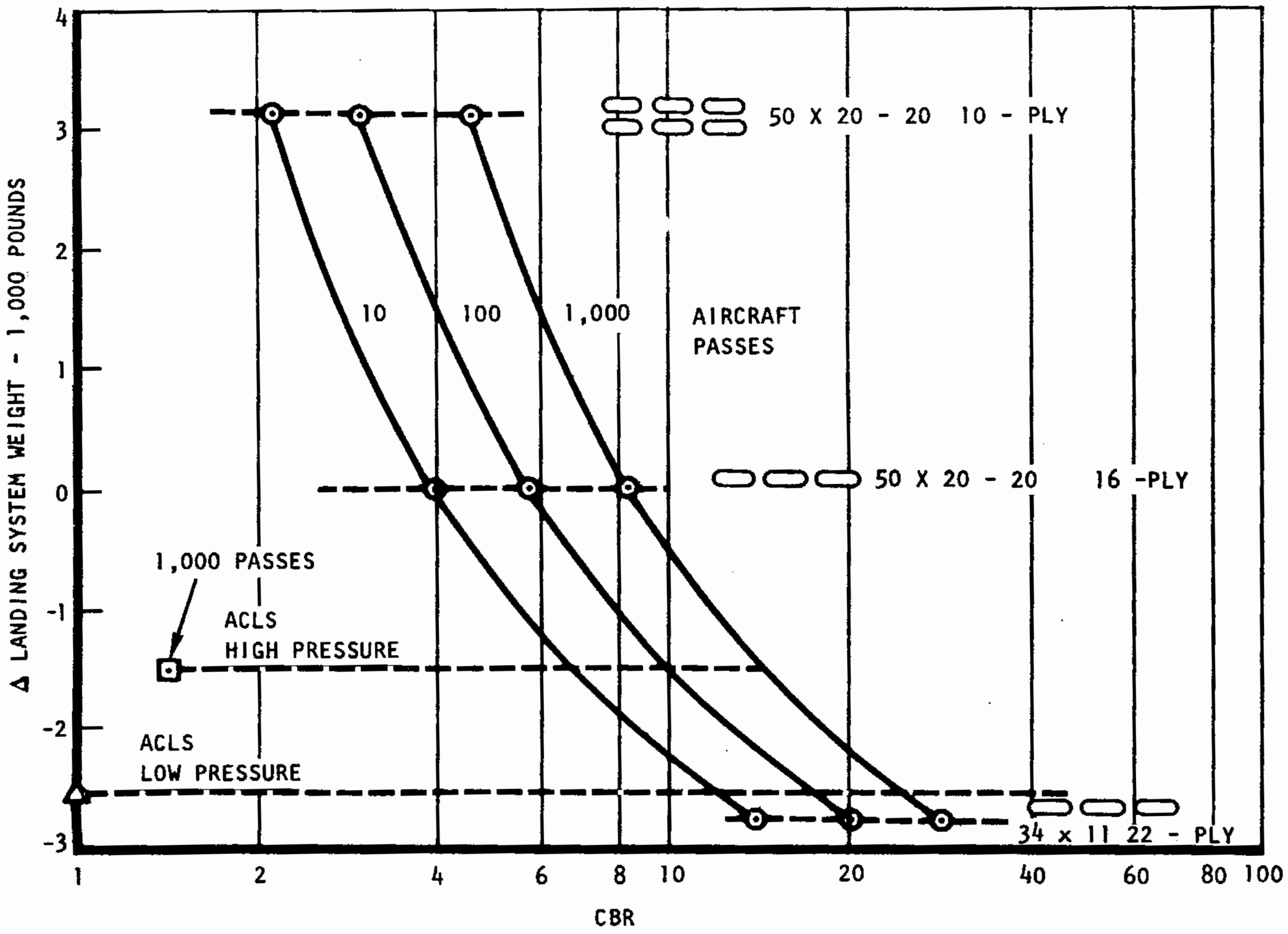


Figure 29. Incremental Landing System Weights Versus CBR

TABLE VIII. INCREMENTAL WEIGHTS - CONVENTIONAL LANDING GEAR

Item	Weight (lb)	
	Low CBR	High CBR
Landing Gear		
Wheels, tires & brakes	+200	-1,536
Structures & controls	+1,822	-492
Fuselage		
Nose gear doors	+231	-363
Main gear doors	+417	-289
Main gear pods	+368	-187
Main gear supports	-17	+69
Nose gear supports	-	-
Total	+3,022	-2,798

5.2.3 WING-MOUNTED FLOAT WEIGHTS

Should lateral stability in amphibious operations prove marginal, wing floats may prove to be required. The weight for the preliminary design, as sketched in figure 19, is estimated to total 1,650 pounds. This estimate is based on data from the R3Y vehicle, which has nearly the same gross weight, but has wing pod floatation capability some three times that shown for the subject design.

5.3 AERODYNAMIC DRAG ESTIMATION

To fully compare the air cushion system with a conventionally geared airplane, the effects of changes in aerodynamic drag must be included. The incremental drag for the ACLS has been estimated with the cushion fully extended for the takeoff condition and fully retracted for the cruise condition. For the conventional gear, drag effects for both a larger pod and a smaller pod have been estimated. In all cases, the increment drag is considered constant with lift and constant to the mach 0.75 and 40,000-foot cruise condition. Above this mach number, drag difference could increase significantly.

TABLE IX. SUMMARY - WEIGHT CHANGES FROM BASEPOINT

Description	Weight Changes from Basepoint (lb)			
	Conventional Landing Gear System		Air Cushion Landing System	
	-403 Low CBR	-404 High CBR	-400 Low Pressure	-401 High Pressure
Body Group	(+1,000)	(-770)	(-2,020)	(-1,950)
Landing provisions	+1,000	-770	-2,020	-1,950
Alighting Gear	(+2,022)	(-2,028)	(-3,710)	(-3,710)
Wheel, tires & brakes	+200	-1,536		
Structure	+1,822			
Trunk, tread & brake			-3,710	-3,710
Inflatable tube				
Attachments				
Landing gear ducting and control units			(+3,245)	(+4,265)
Ducts (bypass, innertube fill, innertube bleed & control			+380	+380
Valves (innertube fill, bypass, louvers & deflation)			+256	+256
Engines			+2,290	+3,300
Fuel starting system & misc			+123	+133
Retractable air inlet			+196	+196
Furnishings			(+195)	(+195
Noise suppression			+195	+195
Ground Mobility			(-320)	(-320)
Total Δ	[+3,022]	[-2,798]	[-2,610]	[-1,520]
Fuel available TOGW:150,000 lb	24,103	29,923	29,735	28,645

TABLE X. SUMMARY - TOTAL SYSTEM WEIGHTS ACLS/GEAR TRADE STUDY

	B. Point 402	Low CBR 403	Hi CBR 404		Low Pres ACLS	Hi Pres. ACLS
TOTAL STRUCTURE	(65670)	(68692)	(62872)		(63185)	(64275)
WING GROUP	23305	23305	23305		23305	23305
TAIL GROUP	6865	6865	6865		6865	6865
BODY GROUP	21905	22905	21135		19885	19955
SURFACE CONTROLS	2595	2595	2595		2595	2595
ENGINE SECTION	4840	4840	4840		4840	4840
ALIGHTING GEAR GROUP	6160	8182	4132		2450	2450
LDG GEAR DUCT & CNTL UNITS	-	-	-		3245	4265
PROPULSION GROUP	(17815)	(17815)	(17815)		(17815)	(17815)
ENGINE	14600	14600	14600		14600	14600
BLC	1175	1175	1175		1175	1175
AIR INDUCTION SYSTEM						
COOLING & DRAIN PROVISIONS						
FUEL SYSTEM	1140	1140	1140		1140	1140
ENGINE CONTROLS	125	125	125		125	125
STARTING SYSTEM	325	325	325		325	325
APU	450	450	450		450	450
FIXED EQUIPMENT	(10090)	(10090)	(10090)		(9965)	(9965)
INSTRUMENTS	900	900	900		900	900
HYDRAULIC & PNEUMATIC GROUP	945	945	945		945	945
ELECTRICAL GROUP	1310	1310	1310		1310	1310
ELECTRONICS GROUP	1060	1060	1060		1060	1060
ARMAMENT PROVISIONS						
FURNISHINGS	4045	4045	4045		4240	4240
AIR CONDITIONING EQUIPMENT	1410	1410	1410		1410	1410
PHOTOGRAPHIC						
AUXILIARY GEAR	100	100	100		100	100
GROUND MOBILITY	320	320	320		-	-
TOTAL WEIGHT EMPTY	(93575)	(96597)	(90777)		(90965)	(92055)
CREW	(860)	(860)	(860)		(860)	(860)
FUEL	(27475)	(24453)	(30273)		(30085)	(28995)
INTERNAL	27125	24103	29923		29735	28645
UNUSABLE	350	350	350		350	350
OIL						
ENGINE						
UNUSABLE						
ARMAMENT						
LN_2	(90)	(90)	(90)		(90)	(90)
PAYLOAD	(28000)	(28000)	(28000)		(28000)	(28000)
TOTAL USEFUL LOAD						
TAKEOFF GROSS WEIGHT	150000	150000	150000		150000	150000

5.3.1 ACLS AERODYNAMIC DRAG

For the ACLS fully extended condition, the incremental drag when operating is 0.0276 for the cushion, plus 0.0250 to 0.0300 for the air-supply momentum drag. The 0.0276 is based on unpublished data from the Buffalo CC-115 ACLS wind tunnel tests. For the cruise condition, the main portion of the trunk retracts cleanly against the fuselage, with only the six pillow brake treads protruding into the airstream and increasing drag by 15 counts ($\Delta C_D = 0.0015$). All drags are based on the MST basepoint wing area of 1,875 square feet.

5.3.2 CONVENTIONAL GEAR AERODYNAMIC DRAG

As larger or smaller gears are considered for the MST, the fairing or pod to stow the gear in the retracted position becomes larger or smaller. For the case with the low CBR gear (larger wheels and tires), the increase in drag is estimated to be four drag counts ($\Delta C_D = 0.0004$). With this size, pod flow separation could have a more adverse effect than on the basepoint. For the case with the high CBR gear (smaller wheels and tires), the reduced size pod is estimated to provide no significant change in drag from the basepoint.

5.4 ACLS VERSUS CONVENTIONAL GEAR COMPARISON

5.4.1 CRUISE CONDITION

To fully compare the ACLS with a conventional gear system, both the aerodynamic and weight effects must be taken into account. The common factor for the comparison is airplane gross weight for a constant performance mission; namely, the employment radius mission. Optimum cruise for the MST proves to be mach 0.75 at 40,000 feet. Mission sensitivities to both drag and weight have been determined for other trade studies and are applicable to this study. The gross weight effects for both ACLS and conventional gear modifications are shown in table XI. The total gross weight effect is the sum due to the landing system weight and the aerodynamic drag. Knowing the CBR/landing characteristics of both the ACLS and conventional gears, the incremental gross weight effects can be plotted against CBR as a function of number of aircraft passes. (See figure 30.) The low-pressure ACLS is suitable for landing on fields of less than 1 CBR. It can also operate off fields of any higher CBR rating; thus, the ACLS provides the most efficient landing system for all CBR values below its intersection with the conventional gear at around CBR 22. For CBR's above this value, the conventional gear is more efficient. This

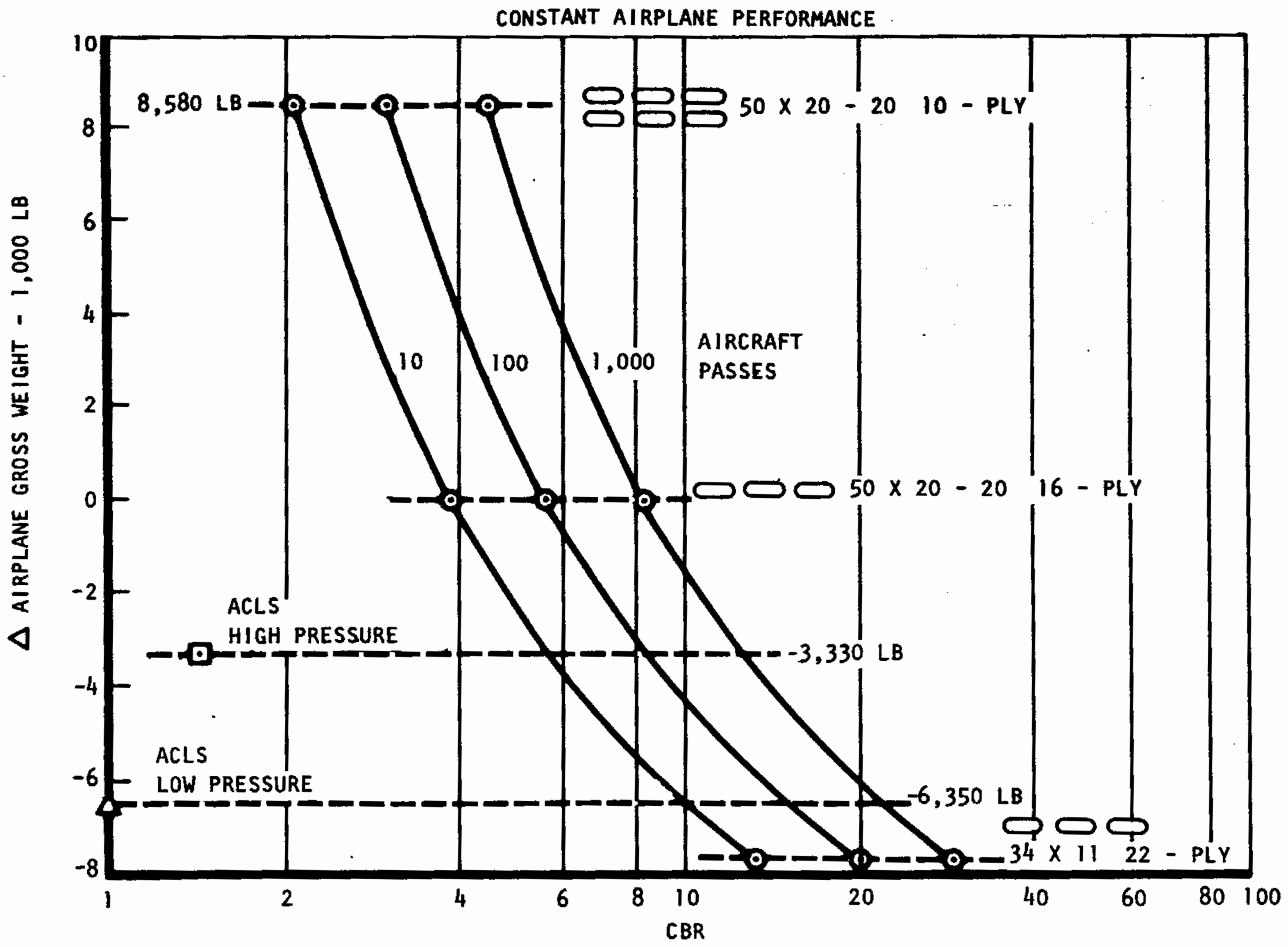


Figure 30. Incremental Airplane Gross Weight Versus CBR Trade

break-even point is more graphically presented in figure 31. As shown, the MST requirement falls within the region where the ACLS is the optimum design. Figure 30 can be replotted in terms of incremental airplane gross weight above that for an air cushion system. Thus, the airplane gross weight penalty for using a conventional landing system can be read directly as a function of CBR and number of aircraft passes desired. (See figure 32.) For example, at a CBR of three and 100 passes, a conventional gear aircraft will weigh nearly 15,000 pounds more than an airplane with an air cushion landing system.

TABLE XI. AIRPLANE GROSS WEIGHT TRADE SUMMARY

Configuration	Δ Gross Weight		
	Weight*	Drag	Total
Low CBR tires (50 x 20 - 20)	+8,400	+180	+8,580
High CBR tires (34 x 11)	-7,800	0	-7,800
Low-pressure ACLS	-7,000	+650	-6,350
High-pressure ACLS	-4,000	+670	-3,330
Constant airplane performance	*Δ System weight x growth factor		

5.4.2 TAKEOFF CONDITION

The MST takeoff requirement is to clear a 50-foot obstacle in 2,000 feet. Normally, this requirement will size the engine. The MST basepoint design already has a 90-percent size engine, which is the smallest-scale engine permissible with the study engine. The basic MST thus has a slightly oversize engine and more than meets the 2,000-foot takeoff requirement. With a different engine, it might be possible to have the takeoff condition be critical; therefore, it is worth considering the effects of the ACLS installation on takeoff performance. With the engine limited to a 90-percent size, the simplest method of comparison between an ACLS system and a conventional landing gear is to directly compare takeoff distance for several rolling resistance factors. The conventionally geared airplane is computed with the $\mu_R = 0.10$, as defined by the MST project office, and a $\mu_R = 0.025$, which corresponds to a concrete runway. This rolling resistance factor is assumed to be reduced for the ACLS by the ratio of cushion to tire pressure ratio; namely, 1.75/55. Both sets of data have been computed and are compared in table XII.

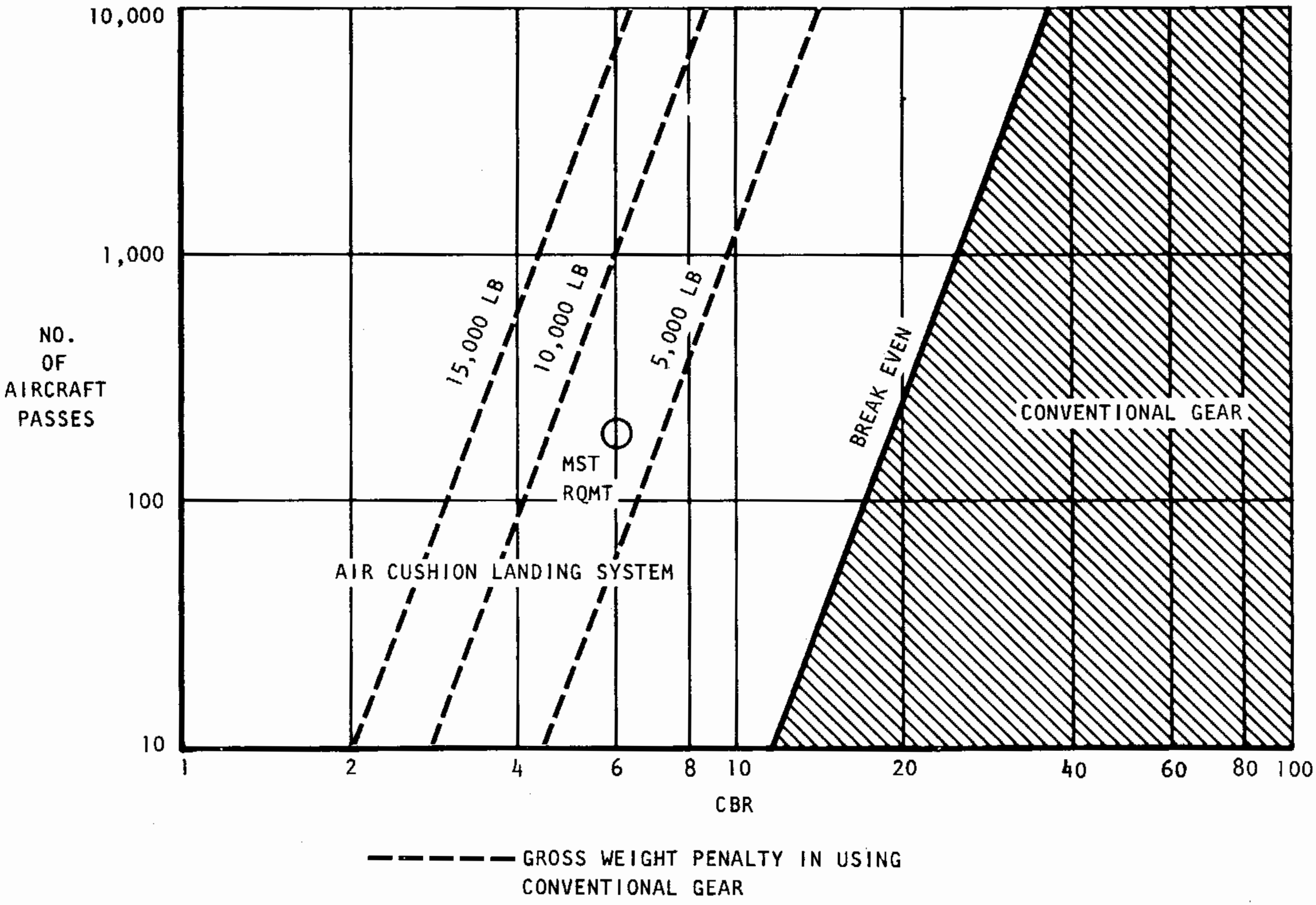


Figure 31. ACLS/Gear Selection Map

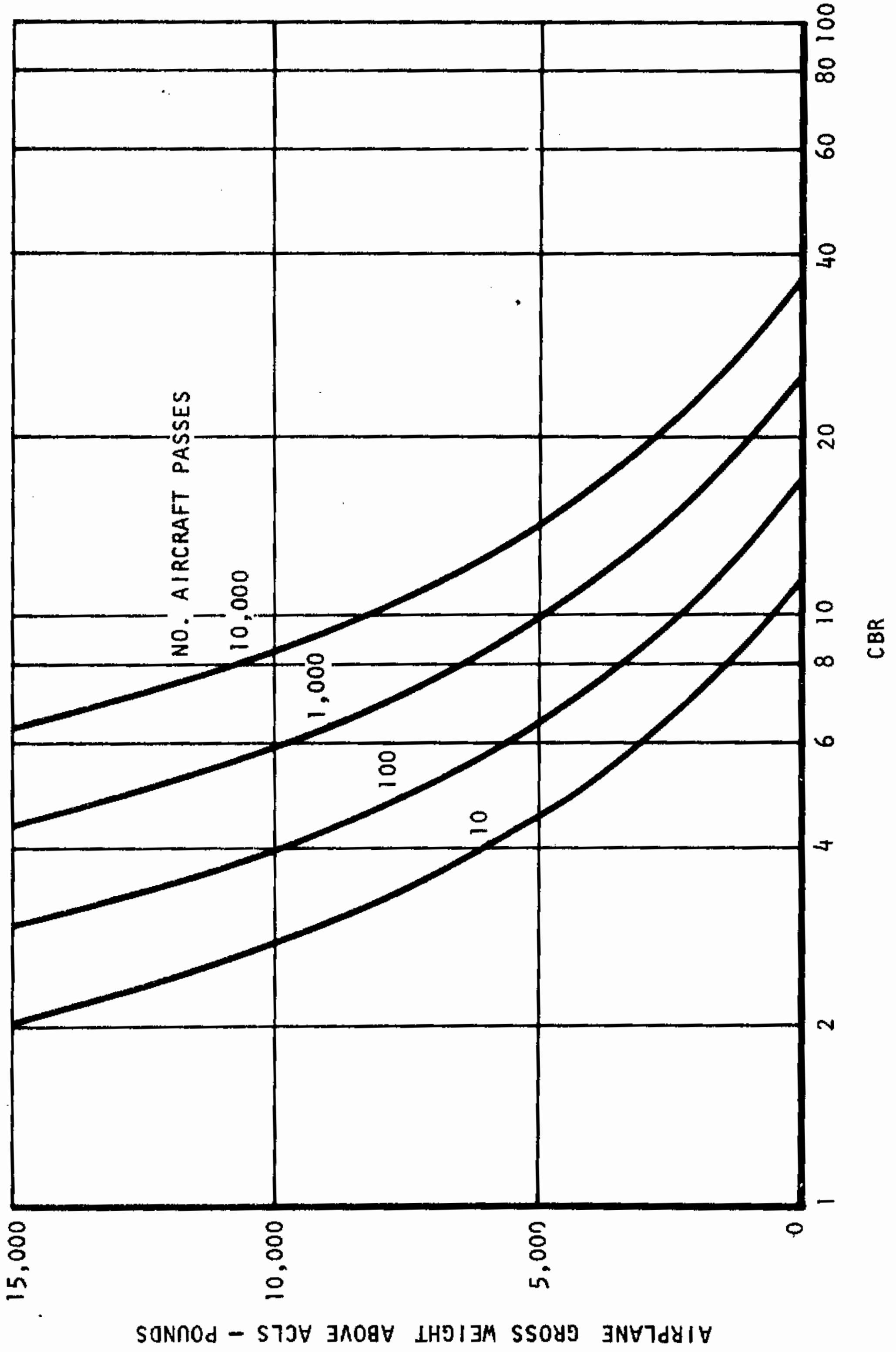


Figure 32. Airplane Gross Weight Penalty for Conventional Gear

TABLE XII. ACLS/CONVENTIONAL GEAR TAKEOFF DISTANCE COMPARISON

Rolling Resistance	ΔTakeoff Distance (ft)	
	Conventional Gear	ACLS
μ_R = 0.10 (soft field)	0	+30
μ_R = 0.025 (concrete)	-185	-15

As indicated for the soft field, the ACLS requires an additional 30 feet to clear a 50-foot obstacle. The increased drag of the ACLS in the extended position requires a 12.5-foot-per-second increase in velocity to meet the 3-degree climb-out requirement. The reduced ground run resistance of the ACLS cannot quite overcome the increased velocity requirement, so a small total increase in takeoff distance is necessary. A second run was made for each system, assuming a much lower rolling resistance to represent takeoff from a concrete surface. The takeoff distance for the conventional gear improved by 185 feet, while improving only 45 feet for the ACLS. The ACLS operates at such low-footprint pressures that the type of surface makes only a small difference in actual drag due to motion. The takeoff performance for the ACLS from hard surfaces is only slightly greater than a conventionally geared MST; the difference from soft fields is insignificant - well within the accuracy of the data being used.

5.5 TRADE STUDY CONCLUSIONS

As a result of this ACLS/conventional gear trade study, the following conclusions can be made:

1. The ACLS appears promising for this application.
2. The cushion area should be made as large as possible to minimize cushion air supply requirements.
3. The ACLS is more efficient than a conventional gear for a wide range of CBR values. For 200 passes at CBR 6, the ACLS can save up to 6,000 pounds gross weight, compared to a conventional gear. Savings are even greater at lower CBR values.

4. The ACLS takeoff performance over a 50-foot obstacle from soft ground is about equal to a conventionally geared airplane. From hard surfaces, the conventional gear is about 8 percent better than the ACLS.

5. Because of a higher braking friction factor, the ACLS landings can be as good as or shorter than landings with conventional gear.

6. For level landings, the ACLS has excellent load attenuation characteristics at all sinking speeds. Sharply reduced attenuation capability of the cushion at large noseup angles may limit the permissible sinking speed for these attitudes.

7. Having dual-cushion air supply engines, considerable capability exists to withstand extensive damage to the trunk without affecting cushion operating characteristics.

8. Similar to a ground effect machine, low-speed maneuverability of an ACLS aircraft is highly sensitive to crosswinds and slope of the ground surface.

9. The Buffalo ACLS modification should be carefully monitored to verify operational suitability and validity of trade data inputs.

SECTION VI

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13. ABSTRACT

The basic objective of the work reported herein was to provide a broader technology base to support the development of a medium STOL Transport (MST) airplane. This work was limited to the application of the externally blown flap (EBF) powered lift concept.

The technology of EBF STOL aircraft has been investigated through analytical studies, wind tunnel testing, flight simulator testing, and design trade studies. The results obtained include development of methods, for the estimation of the aerodynamic characteristics of an EBF configuration, STOL performance estimation methods, safety margins for takeoff and landing, wind tunnel investigation of the effects of varying EBF system geometry parameters, configuration definition to meet MST requirements, trade data on performance and configuration requirement variations, flight control system mechanization trade data, handling qualities characteristics; piloting procedures, and effects of applying an air cushion landing system to the MST.

From an overall assessment of study results, it is concluded that the EBF concept provides a practical means of obtaining STOL performance for an MST with relatively low risk.

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Air Cushion Landing System						
Landing Gear						

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