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A NEW CONCEPT FOR AIRSHIP MOORING AND GROUND HANDLING

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ABSTRACT: Calculations have been made to determine the feasibility of applying the Negative Air Cushion (NAC) principle to the mooring of airships. Pressures required for the inflation of the flexible trunks are not excessive and the maintenance of sufficient hold down force is possible in winds up to 50 knots. Fabric strength requirements for a typical NAC sized for a 10-million cubic foot airship were found to be approximately 200 lbs./in. Corresponding power requirements range between 66-HP and 5600-HP. No consideration has been given to the internal airship loads caused by the use of a NAC and further analysis in much greater detail is required before this method could be applied to an actual design, however, the basic concept appears to be sound and no problem areas of a fundamental nature are apparent.

INTRODUCTION

Recent publications have pointed out some potential advantages possessed by airships in certain mission areas and have advocated the construction of large airships employing modern technology and materials. If the airship is indeed to stage a "comeback," then in addition to the application of new materials and technology in the vehicle itself, some quantum jump in the area of mooring and ground handling must also be accomplished. It is the purpose of this paper to suggest a means by which this quantum jump might be made.

For several years, development work has been proceeding which is aimed at applying the basic principles of Air Cushion Vehicles (ACV) to aircraft takeoff and landing systems. (Ref. 1, 2, 3 and 4.) A schematic of a typical system is shown in Figure 1. A flexible

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toroidal shaped trunk of rubberized fabric is located on the bottom of the aircraft and its shape is maintained by pressurizing it to a pressure (P_t) greater than atmospheric. Air is allowed to flow through holes (A) and (B) to maintain the cushion pressure (P_c) and to provide lubrication between the trunk and the ground. The cushion pressure is greater than atmospheric (but less than trunk pressure) and supports the weight of the aircraft by acting over the bottom portion of the aircraft enclosed by the trunk.

DESCRIPTION OF CONCEPT

Figure 2 is a sketch illustrating a Negative Air Cushion (NAC) as applied to a large somewhat conventionally shaped airship. The major departure from a conventional airship shape stems from the employment of a large flat bottom rather than the usual rounded extension of the hull body of revolution. A flat airship bottom is not essential to the concept, however, a rounded hull bottom would require a slightly more complex trunk design and construction. The two NAC trunks shown may, in general, assume any planform shape, but for the analysis to follow, they are assumed to be circular. The trunk material itself may be either elastic or inelastic non-porous fabric. A pump (M_1) is used to inflate the trunk to a pressure (P_2) greater than atmospheric pressure (P_o). Another pump (M_2) evacuates the space enclosed by the trunk, the ground and the airship bottom so that a cushion pressure (P_1) is maintained less than P_o. The pressure difference (P_o-P_1) acting over the airship bottom produces a force acting to hold the airship down to the ground. Obviously, the pump (M_2) might, through the use of appropriate valves and lines, supply the air to pressurize the NAC trunk, thus obviating the need for separate pumps for trunk and cushion pressure. Operation in this manner might not be practical, however, in view of the differing pressures and air flow rates associated with the NAC cushion and a trunk which utilized bleed air lubrication. This paper will not consider design details to this depth.

In order to satisfy the condition that the airship will weathervane two alternative methods may be proposed. One involves special installations on the airship itself while the other would utilize permanently installed ground equipment. Some representative turntable schemes are illustrated in Figure 3. In the methods depicted in 3A and 3B, the entire forward NAC trunk would be mounted on rollers (R) so that it could rotate about its vertical axis of symmetry. The arrangement of 3B requires a seal in order to prevent atmospheric air from leaking into the cushion volume. It can be seen that with arrangements 3A and 3C, no seals are required, since solid structure effectively separates regions of differing pressures. In the first two designs, the NAC trunk remains stationary with respect to the ground while the airship hull is free to swivel as the wind direction changes. (It should be noted that the air station real estate required to permit 360° airship rotation is considerably less than if the conventional mooring mast is located at the airship nose.) The second method of swiveling would employ a NAC trunk fixed to the airship (Figure 3C) but a flat turntable permanently mounted flush with ground at the air station would provide the swiveling action.

The methods mentioned above represent alternative means of obtaining airship weathervaning. The first method, wherein the forward NAC is connected to the airship through a swivel, will permit operation at virtually any suitable remote site. The second method could be used only at an established site equipped with the appropriate turntable. The obvious advantage to the second method lies in the simplified airship installation. A third possibility, applicable to the fixed site, is the use of a ground based pump to supply the forward cushion suction. Since the forward NAC trunk need only be inflated initially and then sealed, no airship borne power need be expended to provide the airship hold down. The ground-based cushion pump could be mounted directly on the turntable or connected to the turntable through suitable rotary seals.

Regardless of the method used to allow weathervaning, the horizontal shear force between the airship and the ground, which resists the wind force, is a function of the friction coefficient between the trunk and the ground and the force pressing the trunk to the ground. This force must be supplied entirely by the forward trunk, since the aft trunk can furnish none while the airship is turning.

The aft trunk might be operated in two different ways. In the first mode, air would be supplied continuously to the trunk and be allowed to bleed out through lubrication holes located where the trunk is tangent to the ground. This method of operation would require a continuous power output to drive the pumps. However, the ability to reduce the horizontal friction between the trunk and the ground by this method is not certain. The second method of operating the aft trunk would entail the use of sensors on the airship which would detect the presence of crosswinds requiring airship weathervaning. The aft trunk would be identical to the forward trunk, that is, it would have no bleed holes and could be sealed after inflation. When the sensors determine that the crosswind has reached some predetermined valve, the cushion pressure would be released, reducing the ground contact force and permitting the hull to rotate around the forward trunk. While this rotation is taking place, all external horizontal and vertical forces and moments applied to the airship would be resisted by the forward trunk alone.

All of the previous comments have considered only airship mooring on a solid surface. Figure 4 illustrates the NAC in use on a water surface. Since it is not possible to develop horizontal shear forces with the water, the airship could tie up to an anchored buoy or, alternatively, could carry its own anchor. In either case, the weathervaning problem is solved automatically if a single anchor near the nose is used. A variation to the water based mooring concept is the use of a raft anchored at a single point so as to be free to swivel. If the raft were large enough to receive both trunks, the airship would have complete freedom to weathervane with essentially a dry land interface.

ANALYSIS OF CONCEPT

In the following analysis, it will be assumed that the airship is ballasted to produce a condition of neutral buoyancy. Additionally, the airship is assumed to be a rigid body and internal loads caused by the externally applied loads are not considered.

Axial Horizontal Forces

The drag force on the airship along its axis is given by

$$D_x = C_{D_x} q S_o \qquad (1)$$

The magnitude of the force holding the airship down to the ground is given by

$$H = (P_o - P_1) A_o \qquad (2)$$

In order to restrain the airship while facing into the wind, equation (3) must be satisfied.

$$D_x = \mu H \qquad (3)$$

Combining equations (1), (2) and (3), and assuming that $A_o = a^2 S_o$

$$C_{P_{1x}} = \frac{C_{Dx}}{\mu a^2} \qquad (4)$$

where $C_{P_1} = (P_o - P_1)/q$.

Lateral Horizontal Forces

Similarly, an equivalent pressure coefficient related to a crosswind is given by

$$C_{P_{1y}} = \frac{C_{Dy}}{\mu a^2} \qquad (5)$$

Vertical Forces

In addition to increased drag (in the lateral direction) and rolling moment, a crosswind can also result in an aerodynamic lift on the airship hull. In order to relate the lift and lateral drag force to the same reference area, it is assumed that the airship is a cylinder with an arbitrary length/diameter ratio. Thus,

$$S/S_o = 1.274\ l/d \qquad (6)$$

The magnitude of the lift force is given by

$$L = C_L q S_o \qquad (7)$$

and the pressure coefficient required to counteract this aerodynamic lift is shown in equation (8).

$$C_{P_{1L}} = \frac{C_L}{a^2} \qquad (8)$$

Vertical Ground Reaction

In order to belance the down load produced by the NAC, a ground reaction force is transmitted through the trunk over the shaded areas shown in the trunk plan views of Figure 5. Two conditions are indicated, one with no wind and the other with enough wind to raise the upwind trunk contact area to a line.

First considering the no wind case,

(ground reaction force) = (hold down force)

$$\pi/4 (P_2 - P_o)[(a+2f)^2 d^2 - a^2 d^2] = \pi/4 (P_o - P_1) a^2 d^2$$

$$(P_2 - P_0) = \frac{a^2(P_0 - P_1)}{4f(a+f)} \qquad (9)$$

For the case with maximum crosswind,

(ground reaction force) = (hold down force) - (lift force)

$$C_{P_2} = \frac{a^2 C_{P_1} - C_L}{4f(a+f)} \qquad (10)$$

where $C_{P_2} = (P_2 - P_0)/q$.

Rolling Moments

The ability of the NAC to resist the overturning moment caused by a crosswind condition is analyzed in the following manner. If it is assumed that the trunk bleed holes are completely effective in reducing the horizontal friction force between the trunk and ground to zero, then all of the horizontal wind force must be resisted by the forward trunk alone but both trunks are capable of furnishing a counter rolling moment to resist overturning. Figure 5 indicates the forces being considered along with their geometric relationships. Taking moments about point X, we consider first that moment produced by the difference between the hold down force and the aerodynamic lift which is assumed to act through the vertical centerline. Next is the moment produced by the drag force which is assumed to act a distance d/2 above the ground. Finally, there is the moment produced by the ground reaction force which acts on the shaded area of Figure 5. All of these moments are combined as follows.

(hold down - lift) + (drag) - (ground reaction) = 0

$$2(P_0 - P_1)A_0\left(\frac{ad}{2}\right) - L\left(\frac{ad}{2}\right) + D_y\left(\frac{d}{2}\right) - 2\left[(P_2 - P_0)A_1\frac{(a+2f)d}{2} - (P_2 - P_0)A_0\left(\frac{ad}{2}\right)\right] = 0$$

Substituting appropriate terms and dividing by q we have

$$C_{D_y} = a C_L + 2 C_{P_2}\left[(a+2f)^3 - a^3\right] - 2a^3 C_{P_1} \qquad (11)$$

Equation (11) indicates the maximum value of the lateral drag coefficient (based on airship cross sectional area) at which an overturning moment can be resisted.

Trunk Fabric Loads

The tension in the trunk fabric can be computed by considering the trunk pressures which are required to hold the airship in a given wind condition. If the trunk is attached to the airship bottom as sketched in Figure 6, then the fabric tension is given by,

$$T = \frac{(P_2 - P_0)\left[\frac{\pi}{4}(w+2u)^2 d^2 - \frac{\pi}{4} w^2 d^2\right]}{\pi(w+2u)d + \pi w d}$$

$$T = \tfrac{1}{2} C_{P_2}\, q\, d\, u \qquad (12)$$

Power Requirements

The horsepower required to maintain a given air flow over a specified pressure drop is given by

$$HP = \frac{Q(\Delta P)}{550\eta} \qquad (13)$$

Assuming that the cushion air flow is equal to the leakage area times the square root of twice the pressure differential divided by the air density, we have

$$Q_c = \pi had\sqrt{\frac{2(P_o - P_1)}{\rho}} \qquad (14)$$

The power required to maintain the aft NAC would be considerably greater than the above value. At a minimum, this same power would be required to maintain the same air leakage from the atmosphere to the cushion area. In addition, power is required to maintain the trunk pressure while supplying the lubrication air through the trunk bleed holes. The aft NAC power requirement becomes,

$$HP = \frac{1}{550\eta}\left[Q_c(P_o - P_1) + Q_T(P_2 - P_o)\right] \qquad (15)$$

The airflow Q_t is based upon a pressure drop equivalent to the difference between trunk pressure and a pressure half way between atmospheric and cushion.

$$Q_T = \pi had\sqrt{\frac{2\left[(P_2 - P_o) + \frac{1}{2}(P_o - P_1)\right]}{\rho}} \qquad (16)$$

Operation Over Water

The essential features of a NAC operating over a water surface are shown in Figure 4. In order to maintain vertical equilibrium (airship ballasted to neutral buoyancy), the weight of water displaced by the trunks plus the aerodynamic lift generated on the hull is equal to the weight of water drawn up into the cushion chamber above the free water surface. Figure 4(A) illustrates the static situation with no wind. The shaded volumes above and below the free surface are equal. The weight of water above the free surface is numerically equal to the hold down force. Figure 4(B) shows the effect of wind. In this case, the weight of water in the similarly shaded volumes above and below the free surface level are equal to the hold down force minus the lift force. The weight of the oppositely shaded volume is equal to the lift force. It can be seen, qualitatively, that roll stability is maintained by the trunk sinking to a greater depth on the down wind side which produces a greater vertical reaction force on that side and thus, is a function of the trunk geometry. No quantitative analysis of roll stability on water has been made at this time.

Cushion Pump-Down Time

The cushion pump-down time is calculated on the basis of Equation (13). The airflow out of the cushion volume is calculated as a function of the pressure drop across the pump. Since, by this equation, the airflow approaches infinity as the pressure drop approaches zero, an arbitrary maximum airflow is assumed for cushion pressures less than 16 psf. Air is assumed to leak into the cushion volume in accordance with Equations (14) and (16). Thus, combining the results of these two equations and Equation (13) permit a determination of the net flow out of the cushion. Integration of this net flow provides an expression of cushion pressure as a function of time, that is,

$$P_1 = P_0 - \frac{gRT}{V}\int_0^t (\dot{M}_{OUT} - \dot{M}_{IN})\,dt \qquad (17)$$

NUMERICAL EXAMPLE

To illustrate the application of the NAC concept to an airship design, a sample calculation will be made to indicate the characteristics of a NAC as applied to an airship of ten-million cubic feet displacement. The basic airship layout is as shown in Figure 2 with other pertinent details listed in Table I. Equations (4) and (5) determine the NAC pressure coefficient required to withstand axial and lateral wind, respectively. It can be seen that the lateral force

$$C_{P_{1x}} = 0.81 \qquad (A)$$

$$C_{P_{1y}} = 17.06 \qquad (B)$$

is about twenty times the axial force for any given wind velocity. If weather conditions and local topography are such that wind directions can be accurately predicted, then operation of the NAC can be based upon axial winds. For the purpose of this example, the worst case will be assumed, that is, lateral winds at the maximum expected velocity will be considered.

Equation (8) can be used to determine the NAC pressure coefficient which will counteract the lift produced on the airship hull by a crosswind. The total pressure coefficient required is the sum

$$C_{P_{1L}} = 2.13 \qquad (C)$$

of Equations (B) and (C). Thus

$$C_{P_1} = 17.06 + 2.13 = 19.19 \qquad (D)$$

Equations (9) and (10) show the relationship between cushion pressure, trunk pressure, lift coefficient in crosswind, trunk diameter and trunk ground contact area. From Equation (10),

$$C_{P_2} = \frac{(.50)^2(19.19) - (.533)}{4f(.5+f)} \qquad (E)$$

Values of C_{P_2} as a function of f are plotted in Figure 7.

If the flattened portion of the trunk (f) is taken as 0.05 of the nominal inside trunk diameter (a), the allowable C_{D_y} which can be tolerated before the airship will begin to roll over is given by Equation (11). Substituting appropriate values yields

$$C_{D_y} = (.533)(.5) - 2(40)[(.5+2(.05))^3 - (.5)^3] - 2(19.19)(.5)^3$$

$$C_{D_y} = 2.75 \qquad (F)$$

This allowable value of C_{D_y} is less than the estimated value.

The fabric loads in the trunk are computed from Equation (12) using a design crosswind of 50 knots.

$$T = (.5)(40)(8.47)145(.10) \approx 2450 \text{ lbs/ft}$$

$$T = 205 \text{ lbs/in} \qquad \text{(G)}$$

The NAC power requirements will now be calculated using Equations (13) through (16). From Equation (14),

$$Q_c = \pi(.001)(.5)(145)(.10)\sqrt{\frac{2(162.3)}{.002376}} = 84 \text{ ft}^3/\text{SEC} \qquad \text{(H)}$$

where; $(P_o - P_1) = C_{p_1} = 19.19(8.47) = 162.3 \text{ lbs/ft}^2$

From Equation (13), the horsepower requirement of the forward NAC trunk is

$$HP = \frac{84(162)}{550(.75)} = 33.1 \qquad \text{(I)}$$

If the aft NAC trunk utilizes bleed holes for lubrication, Equation (16) is used to compute the airflow requirement based upon bleed hole area fifty times the forward trunk leakage area. This area would allow 10 rows of 0.25 in. diameter bleed holes spaced approximately 0.8 inches apart.

The horsepower requirement of the aft trunk utilizing bleed air is given by Equation (15).

$$HP = \frac{[84(162.3) + 6771(339)]}{550(.75)} = 5598 \qquad \text{(K)}$$

This high power requirement for the aft trunk, when bleed hole lubrication is employed, indicates that the alternative scheme, which would utilize interrupted suction when crosswinds of a certain magnitude are exceeded, might be a more attractive means to provide for airship weathervaning.

If operation from a water surface is anticipated, the cushion pressure of 162.3 lbs/ft^2 would result in water rising in the cushion volume to a height of 2.6 feet above the free surface.

The cushion pumpdown time of the forward NAC trunk is computed by performing a numerical integration of Equation (17). A maximum value of $\dot{M}_{out}$ of 10 times the steady state value of the design cushion pressure is assumed.

The approximate volume of the NAC cushion chamber is,

$$V = \frac{\pi}{4}(.5)^2(145)^3 \cdot \frac{.10}{2} = 29{,}930 \text{ ft}^3 \qquad \text{(L)}$$

The initial mass of air in the cushion (at sea level standard conditions) is,

$$M = \rho V = .0023769(29930) = 71.14 \text{ slugs} \qquad \text{(M)}$$

The flow out of the cushion is given by Equation (13).

$$\dot{M}_{OUT} = 34.45/\Delta P \text{ slugs/sec} \qquad \text{(N)}$$

The flow into the cushion is given by

$$\dot{M}_{IN} = 0.0157\sqrt{\Delta P} \text{ slugs/sec} \qquad \text{(O)}$$

These flows are plotted in Figure 8.

A numberical integration of Equation (17) was performed using the flow rates of Figure 8. Two curves are shown, the first which assumes a single pump with 33.1-HP input, the second which assumes the addition of another identical pump. When two pumps are used, it is assumed that one pump is shut down when the steady state pressure is reached.

REFERENCES:

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2. Bell Aerospace Company, Preliminary Design, Analysis and Development Data for an Air Cushion Landing System Applied to a High-Performance Aircraft, Report 7414-950001, Buffalo, New York (October, 1971).

3. The Boeing Company, Navy A-4 Air Cushion Landing System Preliminary Design Study, Report D162-71046-1, Seattle, Washington (November, 1971).

4. San Diego Aircraft Engineering, Inc., Preliminary Design Study of an Air Cushion Landing System on a High-Performance Aircraft, Report No. SAE 71-044, San Diego, California (December, 1971).

GLOSSARY OF TERMS:

Symbols

A_O	Area within trunk-to-ground inner tangent line. (ft^2)
a	Diameter of NAC inner ground tangent line as fraction of airship diameter (See Figure 5).
C_D	Drag coefficient in ground proximity.
C_L	Lift coefficient in ground proximity.
C_p	Pressure coefficient.
D	Aerodynamic drag in ground proximity. (lbs)
d	Nominal diameter of airship (See Figure 2). (ft)
f	Radial dimension of trunk in ground contact as fraction of airship diameter (See Figure 5).
g	Acceleration due to gravity. (ft/sec^2)
H	NAC hold down force. (lbs)
h	Equivalent gap between NAC trunk and ground. (ft)
L	Aerodynamic lift in ground proximity. (lbs)
l	Length of airship. (ft)
$\dot{m}$	Mass flow. (slugs/sec)
P	Pressure. (lbs/ft^2)
Q	Airflow. (ft^3/sec)
q	Dynamic pressure. (lbs/ft^2)
R	Universal gas constant. (ft-lb/lb/°F)
S	Area. (ft^2)
T	Temperature. (°R); tension in trunk fabric. (lbs/ft)
u	Radial dimension between inner and outer trunk attachment as fraction of airship diameter (See Figure 6).
V	Volume of NAC chamber. (ft^3)
μ	Coefficient of friction between trunk and ground.
η	Overall pump efficiency.
ρ	Density of air. ($slugs/ft^3$)

Subscripts

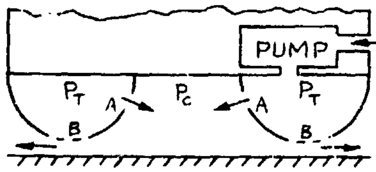
0	With pressure, ambient.
	With area, airship cross section normal to x axis.
1	With pressure, air cushion chamber.
	With area, airship cross section in x-y plane.
2	With pressure, air cushion trunk pressure.
C	Air cushion.
T	Trunk.

TABLE I

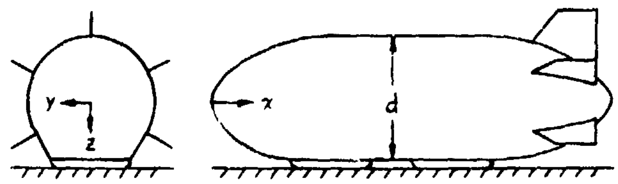
NUMERICAL EXAMPLE AIRSHIP CHARACTERISTICS

Volume = 10,000,000 ft^3

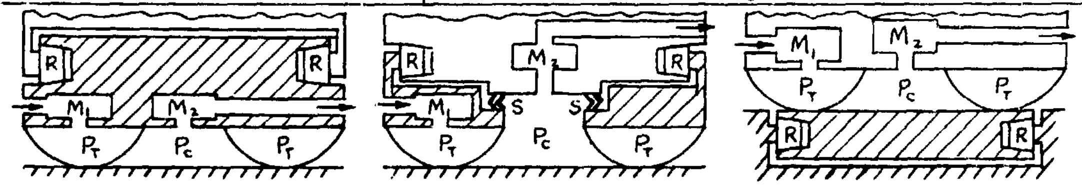
$C_L = 0.10(S_1/S_o) = 0.5333$	$a = 0.50$
$C_{D_y} = 0.20\ (S_1/S_o) = 1.066$	$\mu = 0.25$
$C_{D_x} = 0.05$	$u = 0.10$
$l = 606$ ft	$\eta = 75\%$
$d = 145$ ft	$h = 0.001$ ft



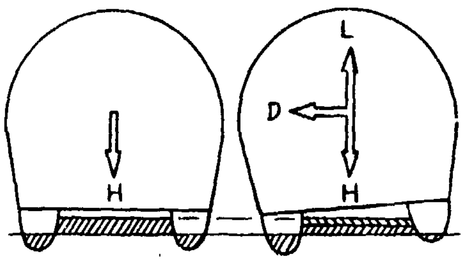
TYPICAL ACLS
Figure 1



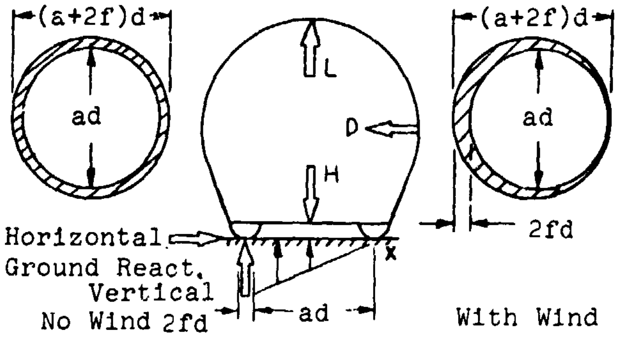
TYPICAL AIRSHIP NAC INSTALLATION
Figure 2



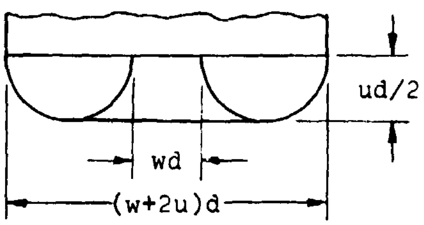
ALTERNATIVE NAC TURNTABLE ARRANGEMENTS
Figure 3A Figure 3B Figure 3C



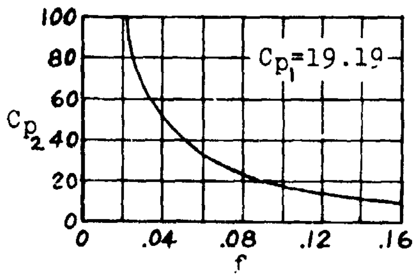
No Wind With Wind
NAC ON WATER
Figure 4A Figure 4B



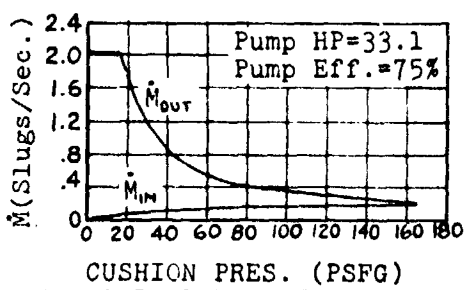
NAC GROUND REACTIONS AND FOOTPRINT
FIGURE 5



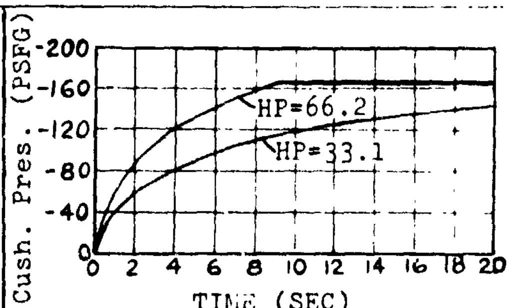
FREE AIR TRUNK CONFIGURATION
Figure 6



TRUNK FLATTENING VS TRUNK PRES.
Figure 7



CUSHION PRES. (PSFG)
LEAKAGE & PUMP FLOW VS CUSH. PRES.
Figure 8



TIME (SEC)
CUSHION PUMP-DOWN VS TIME
Figure 9