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REPORT 1546
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NAVY DEPARTMENT
THE DAVID W. TAYLOR MODEL BASIN
AERODYNAMICS LABORATORY
WASHINGTON 7, D.C.

RESULTS OF GEM III TETHERED TESTS

by

Arthur E. Johnson and Harvey R. Chaplin

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SYMBOLS

S	base area in square feet, measured to outer edge of nozzle
h	height above surface, (in feet, unless indicated otherwise) measured at center of base to plane containing the lower edges of the nozzle
C	perimeter of the base in feet, measured at outer edge of nozzle
b	length of base in feet measured to outer edge of nozzle
a	width of base in feet measured to outer edge of nozzle
β_v	nominal nozzle control vane angle in degrees
β_e	effective tangential jet deflection in degrees
p_t	total pressure measured in plenum, pounds per square foot
Q	airflow rate, cubic feet per second
ρ	mass density of air in slugs per cubic foot
ϕ	roll angle in degrees
α	pitch angle in degrees
N_f	fan rpm, or percent (nominal) of rated fan rpm
T	propulsive thrust in pounds
L	total lift, or gross weight, in pounds
M	pitching moment in pound-feet
$\mathcal{L}$	rolling moment in pound-feet
N	yawing moment in pound-feet
$\bar{M}$	figure of merit $\left(\bar{M} \equiv \frac{1}{2\sqrt{\rho S}}\,\frac{L^{\frac{3}{2}}}{550\ \mathrm{HP}} \doteq \frac{1}{53.7}\,\frac{L}{\mathrm{HP}}\sqrt{\frac{L}{S}}\right)$

SYMBOLS (Concluded)

HP	total shaft power delivered by engines (horsepower)
η_{aoh}	apparent over-all hovering efficiency
S_{jo}	total effective nozzle area with control vanes neutral, in square feet
A_o	augmentation factor with control vanes neutral
q_j	jet dynamic pressure at nozzle exit in pounds per square foot
η_{int}	internal efficiency

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SUMMARY

Static test results on hovering performance, pitch and roll stability, and control effectiveness are presented. The vehicle hovered at a height of 14 inches with a gross weight of 1850 pounds. Both pitch and roll stability were practically neutral at this height. (Weak stability was measured at lower heights.) Propulsion, braking, and steering controls, accomplished by means of variable-camber vanes in the main nozzles, were partially effective. Pitch and roll controls, accomplished by a system of four dump valves bleeding air from the cushion, were completely ineffective. Some data were obtained which indicated that a simple jet spoiler installation could provide satisfactory pitch and roll control.

INTRODUCTION

GEM III is a one-ton experimental manned ground effect machine constructed for the Marine Corps by National Research Associates, Incorporated. The subject tests were undertaken at the request of the Marine Corps (Reference 1) to provide static data on the hovering performance, stability and control of GEM III, preparatory to flight evaluation of the machine by USMC. Reference 2 provided Bureau of Weapons endorsement of this request.

TEST RIG AND APPARATUS

Principal dimensions of GEM III are given in Figure 1. GEM III is an integrated-air-curtain type machine. It is powered by two nacelle units, each with a Solar YT62-S-2 engine driving a Joy 38-17 1/2 fan through a centrifugal clutch, belt and pulleys, and a shaft. A system of cascade vanes guides the air through a 90° bend within the nacelle, after which it is dumped into the hull at a mean velocity of slightly less than half the final jet-exhaust velocity. Controls are engine throttles, aircraft-type control wheel which turns for steering (differential deflection of variable-camber nozzle control vanes) and push/pulls for propulsion/braking (collective deflection of vanes), four aircraft-type trim crank devices which actuate the four dump valves for attitude trim, and brake pedal which actuates hydraulic brakes on the main wheels. The machine was tested as delivered from the manufacturer, except for the addition of the half-round fairings noted in section A-A of Figure 1.

Photographs of the vehicle in its static test rig are presented in Figure 2. There was a system of six nominally horizontal cables, two running to each side, one forward and one aft, which prevented the vehicle from moving in a horizontal plane. The aft and starboard cables ran over pulleys to weights which held them taut; the forward and port cables ran over pulleys to strain-gage dynamometers. Also, there was a system of four vertical cables, running over pulleys to loading pans, by means of which known pitching and rolling moments could be imposed on the vehicle. The vehicle's height and attitude were measured by means of graduated rods and pointers attached to the vertical cable system. From the strain-gage readings, and the known weights and vehicle attitude, it was possible to calculate total thrust, side force, and yawing moment, as well as the secondary interaction of the horizontal cable system on lift, pitching moment, and rolling moment.

Static pressure orifices were installed in the nacelle and plenum on each side of the vehicle, with tubes running to an alcohol manometer. From the manometer readings, the air quantity flow and plenum pressure were calculated with the aid of calibration data from test-stand operation of an identical nacelle (Reference 3).

A temporary pilot's seat is visible in Figure 2 at the center of the top deck between the nacelles. Provisions were made to permit all controls to be operated from this position. The vehicle was operated from this temporary seat during all tests, to minimize the danger of injury to the pilot in the event of fan failure.

TESTS

All tests were made with the effective weight of the machine near its normal gross weight of 1850 pounds. The engine throttles were set in either the 100 percent rpm detent or the 87 percent rpm detent during all tests. The fan blades were set at the manufacturer's blade-angle index of -2 at all times, to be compatible with power available from the engine. Normally, all variables (dynamometer readings, manometer readings, loading-pan weights, vertical cable movements, and control settings) were recorded for each data point. During stability runs moments were applied to the vehicle through the vertical cables, and the resulting change in attitude was observed. During control runs, the control settings were varied with the vehicle attitude maintained constant, and the resulting changes in forces and moments were observed. No performance runs, as such, were made; performance data were obtained during stability and control runs.

RESULTS AND DISCUSSION

The following results were obtained:

1. Performance - The operating height attained by the vehicle at 100 percent and at 87 percent rpm at various pitch and roll angles is presented in Figure 3. (Note that height is measured to the center of the base, the base plane being the plane containing the lower edges of the nozzles. Thus, the vehicle is at a height of three inches when it rests, power-off, on its wheels.) An indication of the shaft horsepower is provided by Figure 4, based on data from Reference 3. The effective exhaust area of the vehicle in normal hovering operation is approximately seven square feet per nacelle, indicating, from Figure 4, a shaft power of 70 horsepower per nacelle at the -2 blade-setting index. The corresponding figure of merit is approximately

$$\bar{M} \doteq \frac{1}{53.7} \frac{L}{HP} \sqrt{\frac{L}{S}}$$

$$\bar{M} \doteq \frac{1}{53.7} \frac{1850}{140} \sqrt{\frac{1850}{150}}$$

$$\bar{M} \doteq 0.86$$

The size/height ratio is

$$\frac{S}{hC} \doteq \frac{150}{\frac{14}{12}(48.3)} = 2.66$$

which gives an apparent over-all hovering efficiency of

$$\eta_{aoh} = \frac{\bar{M}}{\frac{S}{hC}} = 0.32$$

This is comparable to the performance of other early-generation GEM's. In Figure 5, on a graph of plenum pressure versus air-flow quantity, is presented a network of nacelle characteristic lines (from Reference 3) and vehicle air-requirement lines.

The vehicle air requirements were estimated from semi-empirical theory (Reference 4) as follows:

$$q_j \doteq \frac{L}{2S_{jo}\cos^2\beta_e\, A_o}$$

$$p_t \doteq q_j + \frac{L}{2S}\left(1 - \frac{0.7}{A_o}\right)$$

$$Q \doteq 29\sqrt{q_j}\, S_{jo}\cos\beta_e$$

An appropriate value for S_{jo} was estimated to be 16.0 square feet. The following estimates were used for A_o:

h inches	A_o
6	7.37
8	6.17
10	5.32
12	4.63
14	4.10

For heights below 6 inches, the curves were arbitrarily faired to the point $p_t = \frac{L}{S}$, Q = 0, at h = 0. Superimposed on this network are measured data points for (a) 100 percent rpm, control vanes neutral (b) 100 percent rpm, control vanes fully deflected, and (c) 87 percent rpm, control vanes neutral. The agreement indicates that the combination of semi-empirical theory and nacelle test data can be used for analyses of GEM III with confidence. The 19.3 psf, 880 cfs data point in Figure 5 for 100 percent rpm, control vanes neutral, is equivalent to

$$\frac{19.3\ (880)}{550} = 30.9 \text{ air horsepower}$$

per nacelle, giving an internal efficiency of

$$\eta_{int} = \frac{30.9}{70} = 0.44$$

These efficiency values correspond very closely to measured values for DTMB Model 472 (Reference 5), which has a similar nacelle design and approximately the same ratio of nozzle area to fan area.

2. Stability - The results of pitch and roll stability measurements are presented in Figures 6 and 7. (All moments are referred to the center-of-gravity location indicated in Figure 1, which would be the actual center of gravity for the

vehicle operating with the pilot in the cockpit and with half-filled fuel tanks.) To experimental accuracy (approximately ±50 pound-feet), the vehicle had neutral pitch and roll stability at 100 percent rpm (h = 14 inches) and had positive roll stability at 87 percent rpm (h = 10 inches). Pitch stability was not measured at 87 percent rpm, but it may be safely assumed that the vehicle also had positive pitch stability at this condition. The rather weak stability characteristics of GEM III may be attributed, at least in part, to the fact that the stabilizing nozzles are fed from the main plenum, and exhaust to the air cushion, which, because of the rather thick primary nozzles, is at a gage static pressure of more than half the plenum pressure.

3. Propulsion, Braking, and Steering Control - The variable-camber vanes in the main nozzle (Figures 1 and 2) were intended to be deflected collectively (i.e., in the same direction on the port and starboard sides) for propulsion and braking control and to be deflected differentially (i.e., in one direction on the port side, in the opposite direction on the starboard side) for yawing-moment control (steering). The effectiveness of these vanes is shown in Figures 8 and 9. The propulsive thrust includes an estimated 24 pounds of engine exhaust thrust. The response to either collective or differential deflection is linear up to about one-third of the maximum deflection, and then bends over sharply at higher deflections as the jet flow separates from the convex side of the vanes. This behavior is due to insufficient vane solidity and to leakage past the edges of the vanes. The effective solidity of the vanes is substantially lower than the geometric solidity, due to the fact that only a portion of the vane is capable of being deflected (Figure 1). The control effectiveness shown in Figures 8 and 9 corresponds

roughly to a maximum jet deflection angle of ±20°. The vane system should be capable of jet deflections of perhaps ±45°, if the solidity were increased sufficiently to retard flow separation, and if leakage past the edges of the vanes were prevented.

4. Pitch and Roll Control - The four dump valves indicated in Figure 1 were supposed to provide pitch and roll control. For example, upon opening the front dump valve, allowing air to escape from the front part of the cushion, a reduction of base pressure was supposed to occur at the front of the vehicle, resulting in a nose-down pitching moment. This system was not effective. Within the accuracy to which moments could be measured (approximately ±50 pound-feet), no change in pitching or rolling moment was produced by opening or closing the valves, singly or in combination. (Tests were made at 100 percent rpm, control vanes neutral.) Rough airflow measurements indicated an air escape rate of approximately 70 cubic feet per second through a single fully-opened valve, or approximately four percent of the total airflow through the nozzles. This produced a slight decrease of height; the operating height was reduced from 14 inches to about 12 inches when all four valves were fully opened.

5. Simulated Jet Spoiler for Attitude Control - In view of the inadequacy of the dump valve system for pitch and roll control, an effort was made to obtain an indication of the effectiveness of a simple jet-spoiler control system which could be installed on the vehicle without major modifications. This was done by sealing off sections of the main nozzle with masking tape, to simulate the effect of a fully-deflected jet spoiler, and measuring the resulting change in rolling moment and operating height. The results are presented in Figure 10, where maximum effectiveness of a roll-control spoiler is given

as a function of spoiler length. The results indicate that this form of attitude control could be highly effective, and that a control deflection would not produce a serious loss of operating height.

GENERAL COMMENTS

The following observations may be made concerning the behavior of the vehicle during the tests:

1. Reliability - The accumulated total time of actual operation of the vehicle was less than ten hours. Accordingly, no definite conclusions on reliability can be drawn. The test experience was encouraging to the extent that no major structural or mechanical failures of any kind occurred. One malfunction did occur on each engine. These were rather costly in terms of time lost, due to delays in obtaining technical service and spare parts, but were quite minor in nature.

2. Steadiness - The vehicle experienced a continual small random disturbance of its roll and heave modes, apparently stemming from minute fluctuations in engine rpm. This might have no serious significance in terms of normal operation of the vehicle, but could be annoying to the pilot. During the tests, these disturbances constituted an obstacle to obtaining accurate force and moment readings, and were responsible in large part for the scatter apparent in the data. The roll disturbance could probably be alleviated by providing openings through the center bulkhead, which would tend to equalize the pressure in the port and starboard plenums.

RECOMMENDATIONS

The following recommendations are based on the test results:

1. The following modifications to the vehicle are considered essential:

a. Modify the variable-camber control vane installation to increase the range of tangential jet deflections.

b. Install a jet-spoiler pitch-control and roll-control system on the vehicle.

c. Install cockpit controls which give the pilot continuous control of pitch, roll and steering, and selective control of thrust and braking.

2. Additional tests should be performed on the static test rig, following these modifications, to evaluate the changes in vehicle characteristics.

3. No effort should be made to operate GEM III in free flight in its present condition.

Aerodynamics Laboratory
David Taylor Model Basin
Washington, D. C.
August 1961

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1. USMC P. O. No. 1-0018 of 7 Dec 1960.
2. BUWEPS ltr RAAD-342:EE of 27 Dec 1960.
3. Murphy, Richard D. Subject: Test Stand Investigation of a GEM III Nacelle Unit. (Data to be reported later)
4. Chaplin, Harvey R. Design Study of a 29-Foot GEM. Wash., Apr 1961. 54 l. incl. illus. (David Taylor Model Basin. Rpt. 1521. Aero Rpt. 999)
5. Burgan, Elmer T. Subject: Wind Tunnel Tests of GEM Model 472. (Data to be reported later)

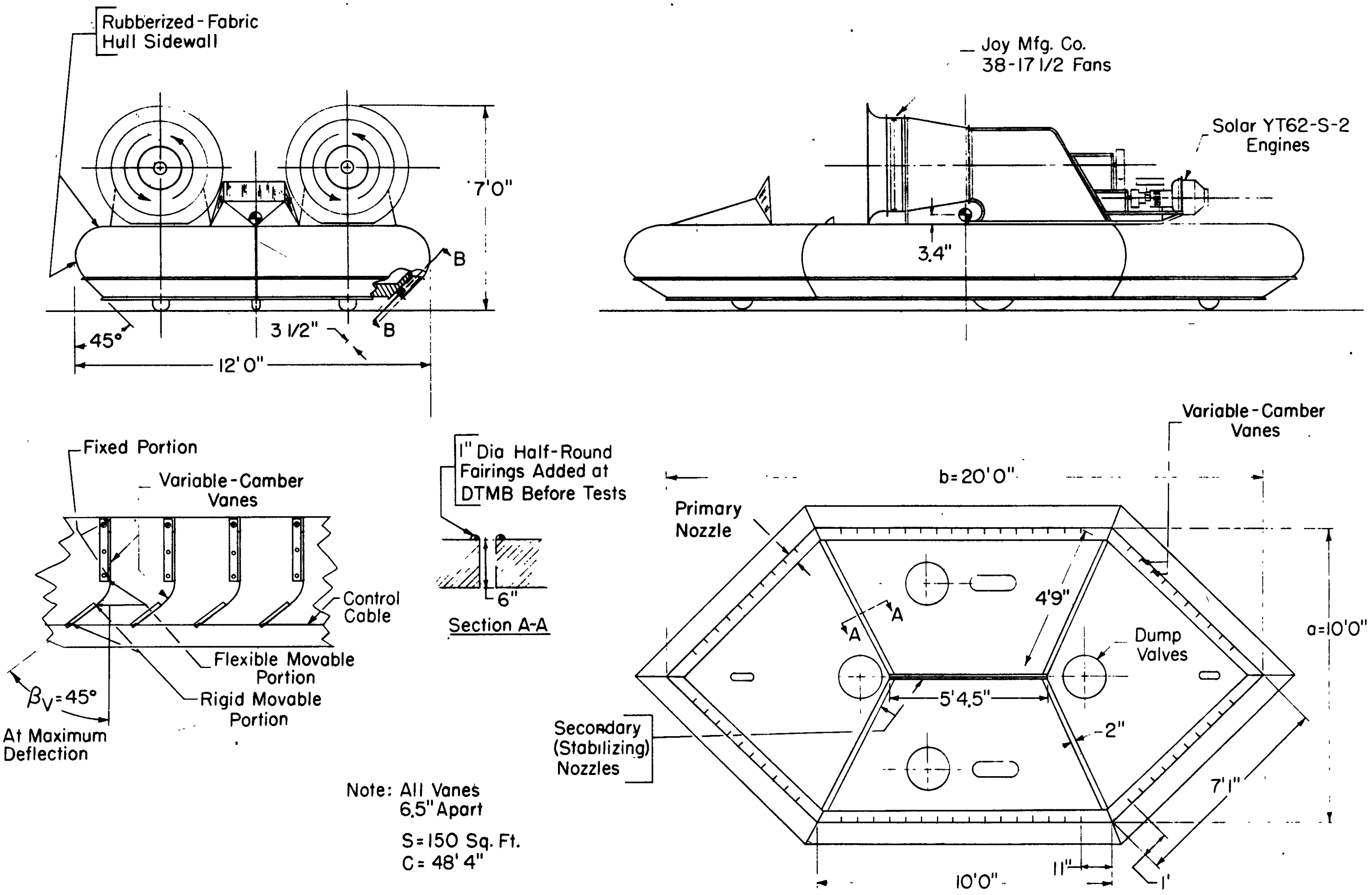
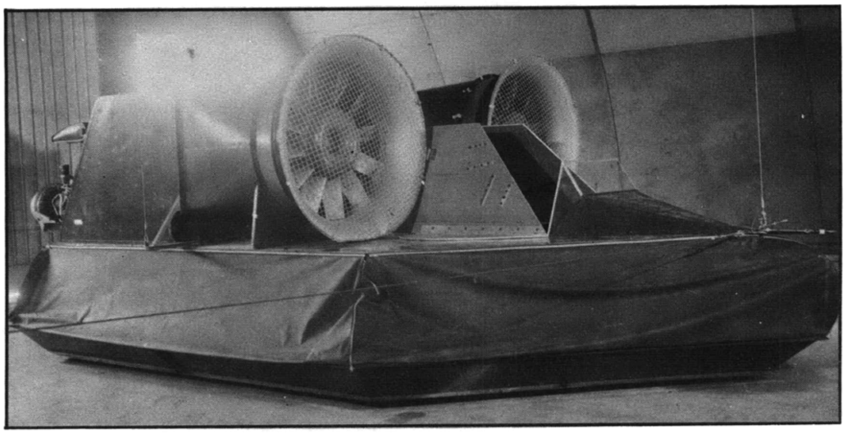


Figure 1 - Principal Dimensions and General Arrangement of GEM III



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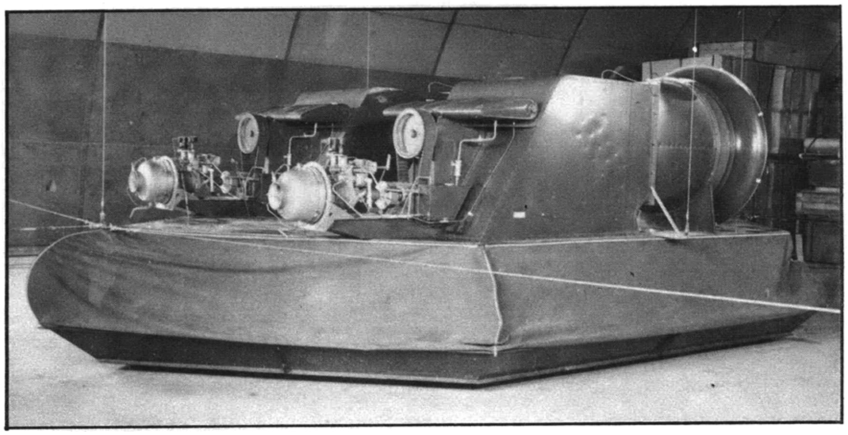
(a) Three-Quarter Front View

(Note: Inlet screens and cockpit armor were not present during tests)



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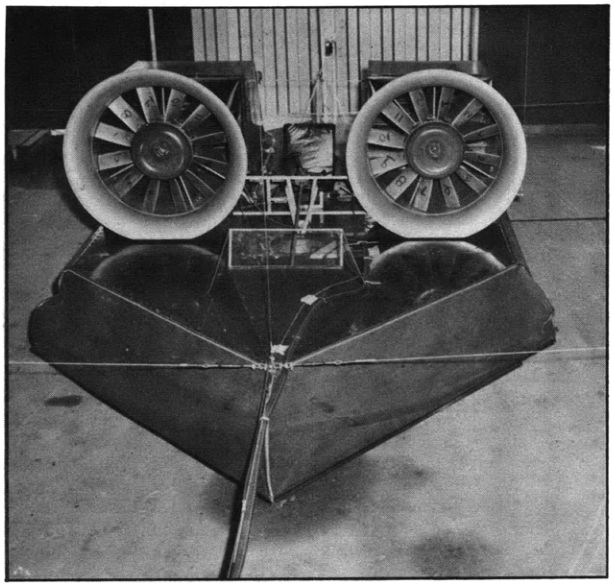
(b) Three-Quarter Rear View

Figure 2 - Model and Test Set-Up Photographs



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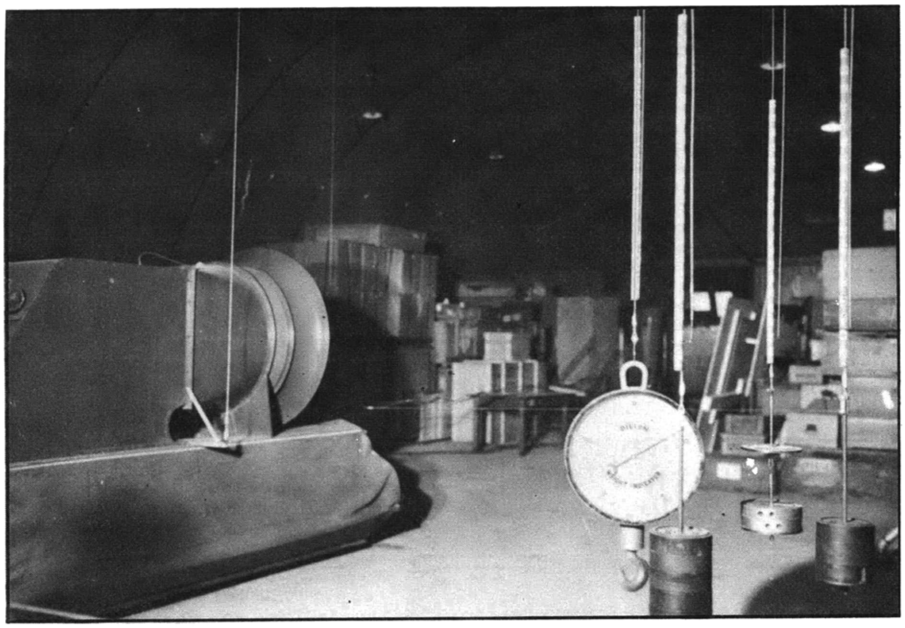
(c) View Showing Temporary Pilot's Seat and Restraining Cables



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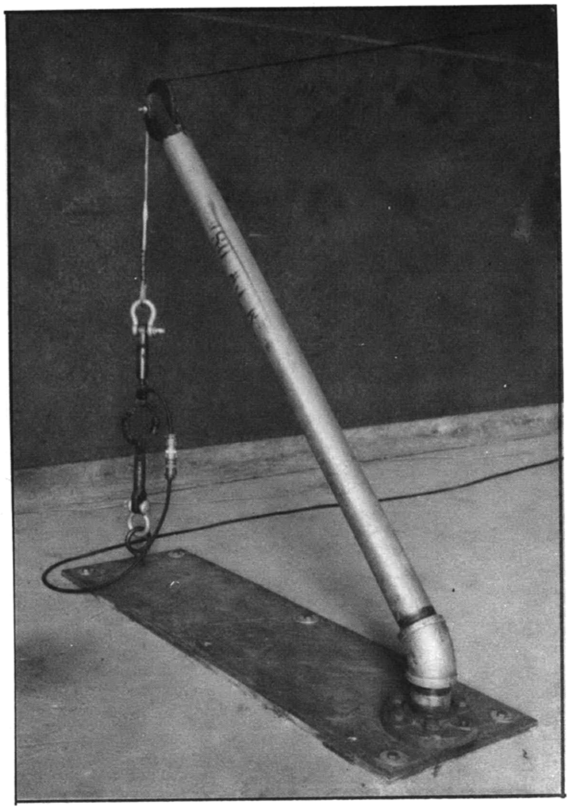
(d) Pitch and Roll Instrumentation

Figure 2 (Continued)



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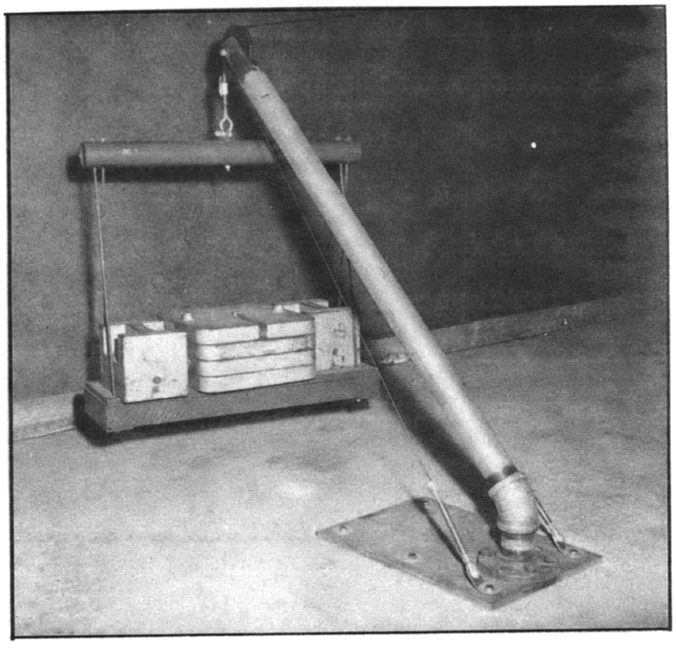
(e) Dynamometer



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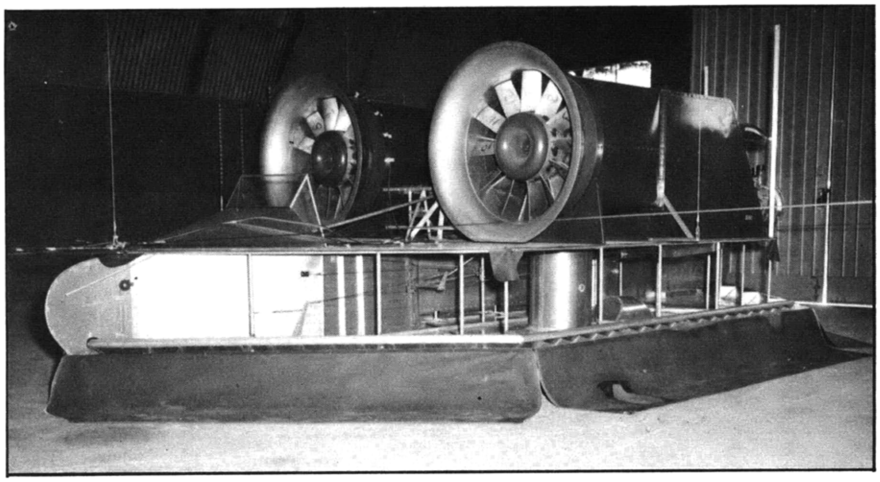
(f) Loading Pan for Horizontal Cable

Figure 2 (Continued)



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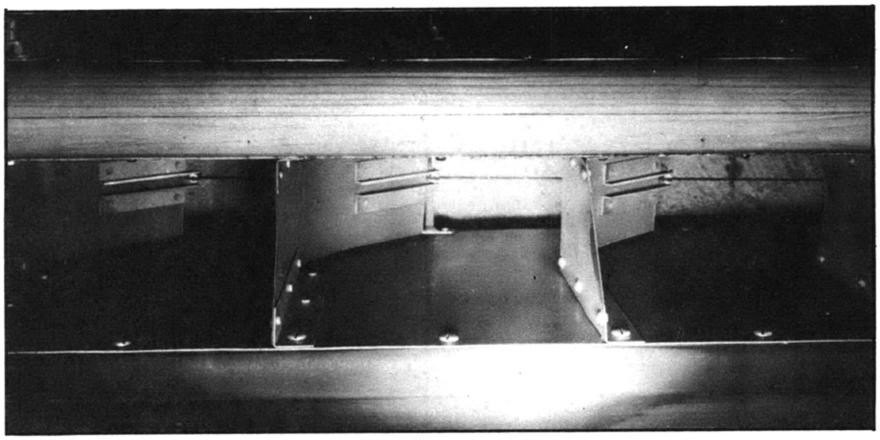
(g) View Showing Interior of Hull



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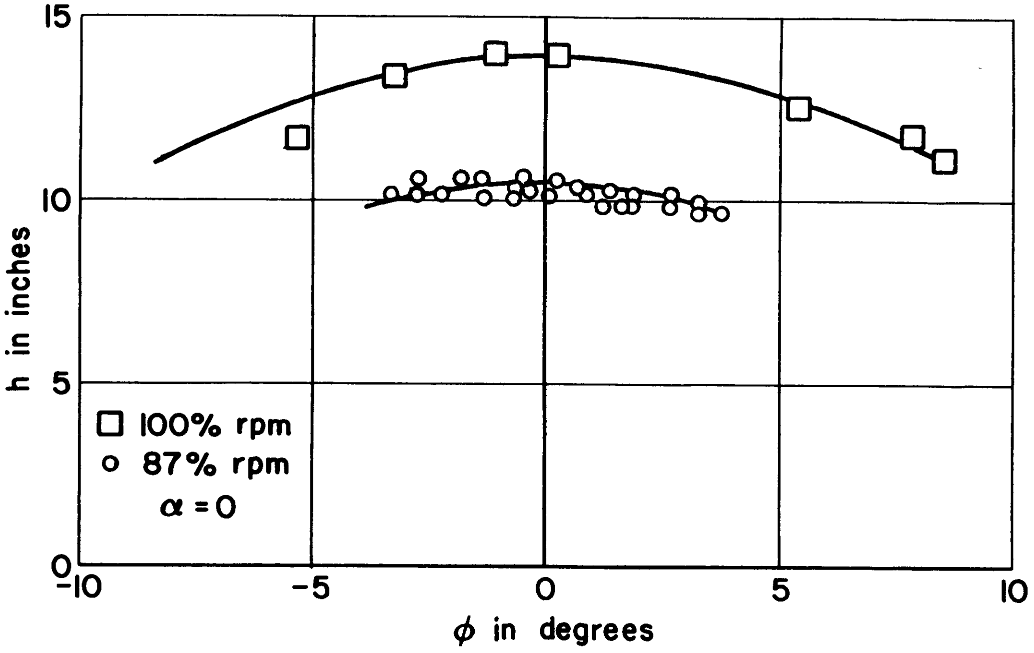
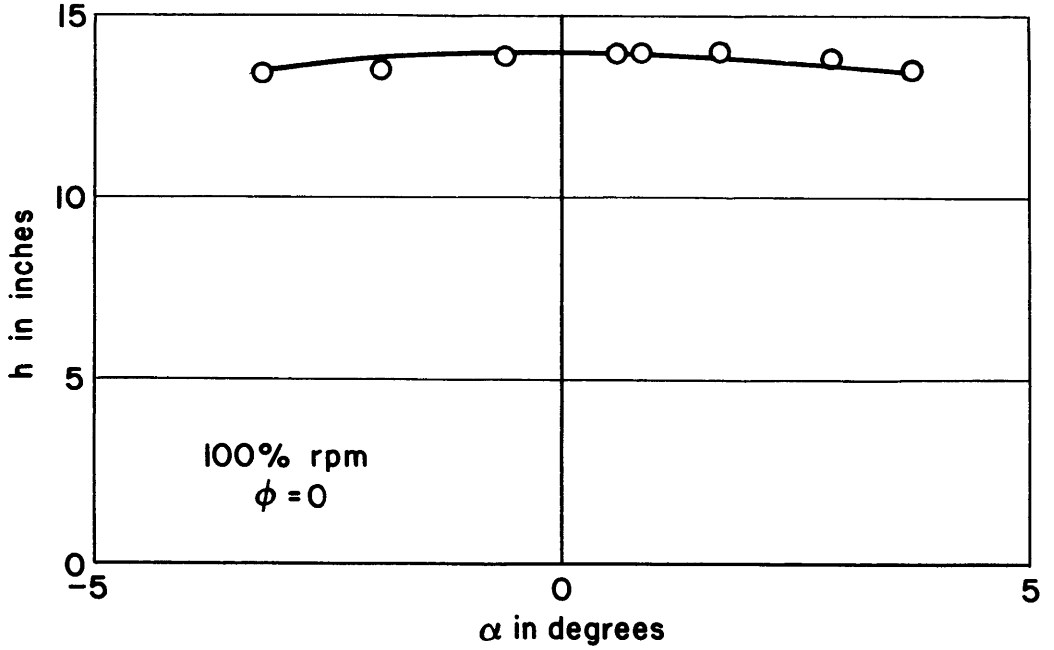
(h) View of Vanes Looking Down Through Nozzle From Plenum Chamber

Figure 2 (Concluded)



(a) Effect of Roll Angle



(b) Effect of Pitch Angle

Figure 3 - Hover Height

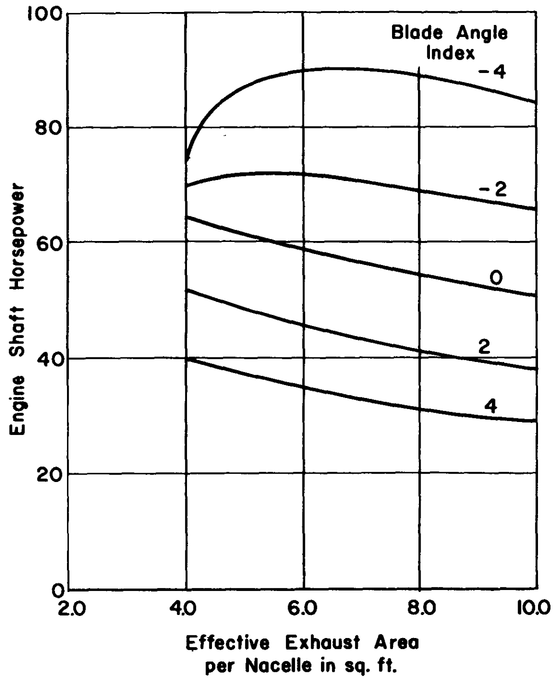


Figure 4 - Shaft Horsepower Required by One Nacelle for Several Blade Angle Index Settings. (From Reference 3)

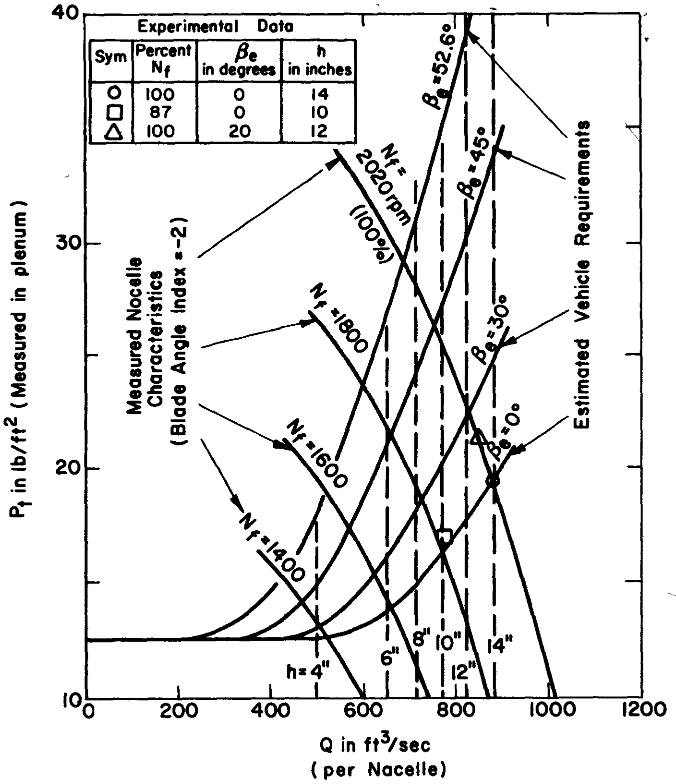


Figure 5 - Matching of Vehicle Airflow Requirements to Nacelle Characteristics

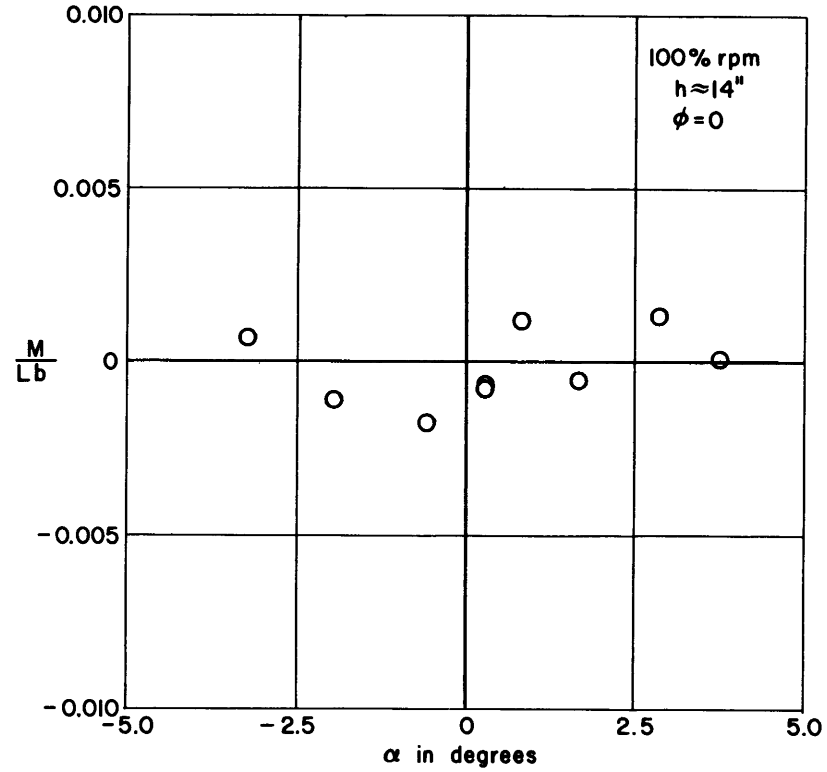


Figure 6 - Pitch Stability

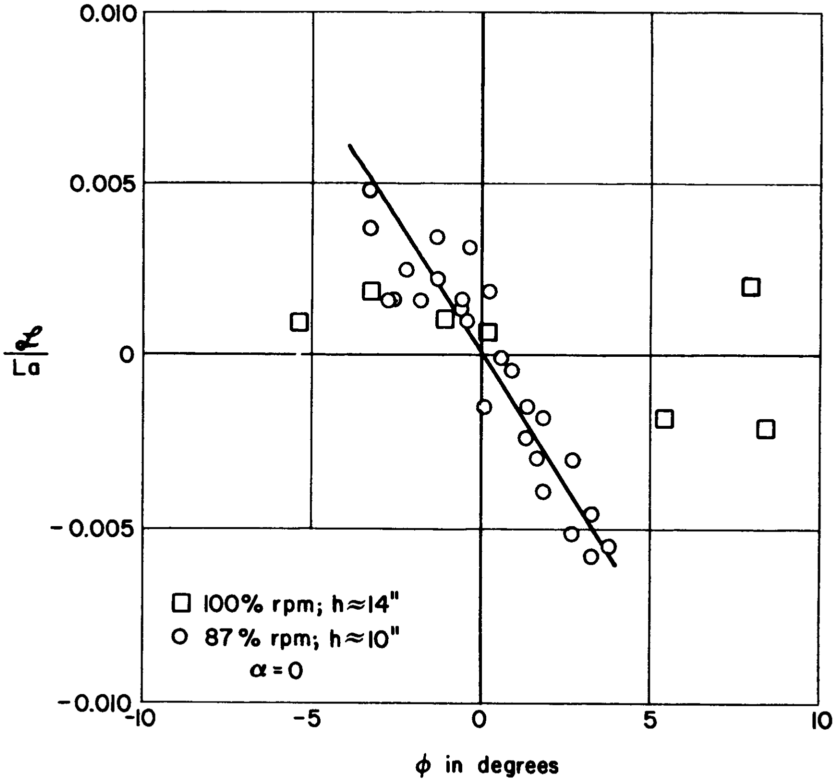


Figure 7 - Roll Stability

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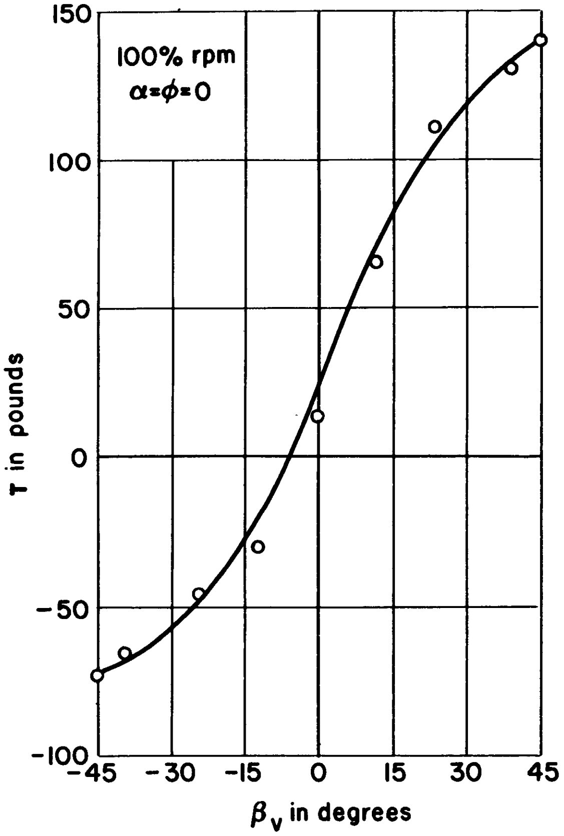

Figure 8 - Propulsive Thrust Produced by Collective Vane Deflection

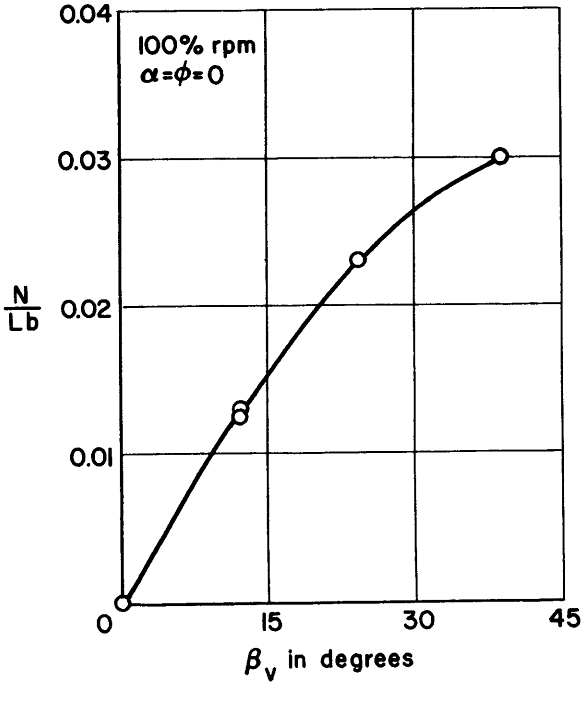

Figure 9 - Yawing Moment Produced by Differential Vane Deflection

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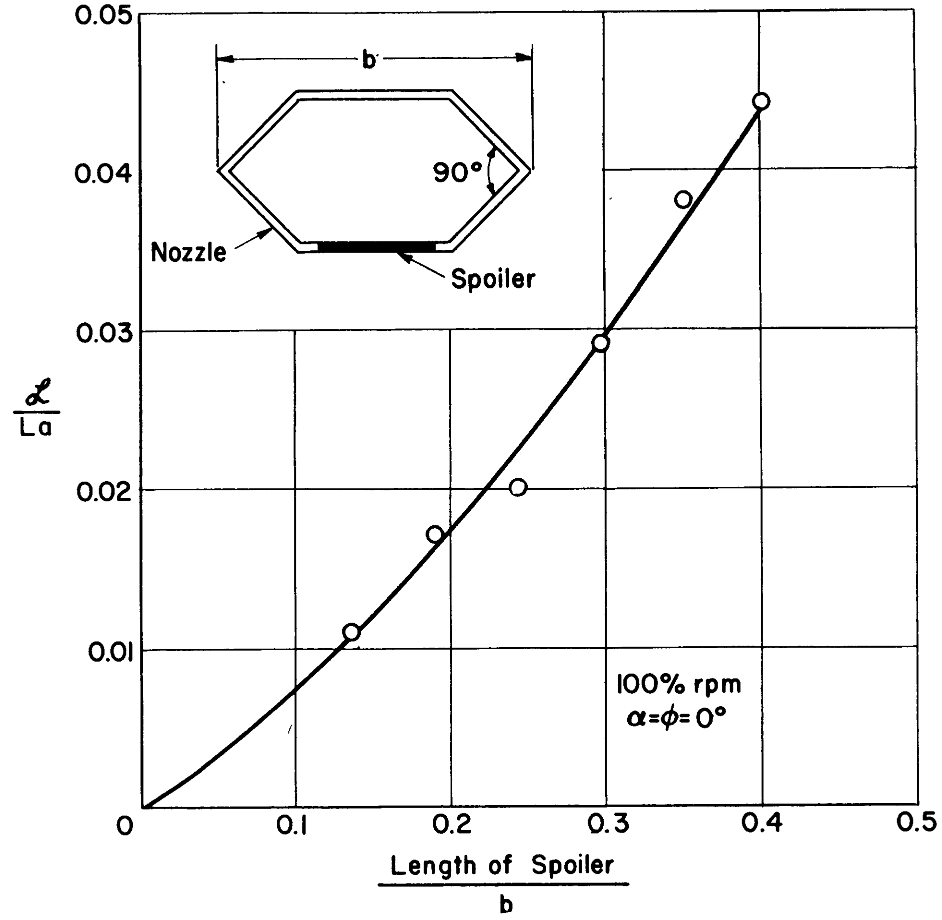
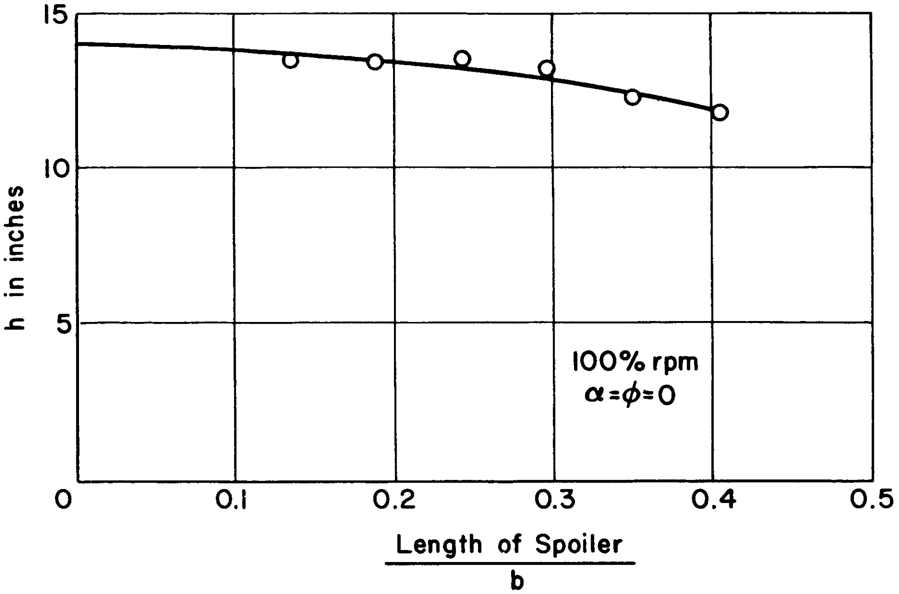


(a) Rolling Moment Produced



(b) Effect on Height

Figure 10 - Effect of a Spoiler Completely Blocking a Section of the Side Nozzle

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