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Preliminary Study

THE EFFECTS OF ATMOSPHERIC PRESSURE UPON
THE WATER ENTRY BEHAVIOR OF A MISSILE
HAVING A HEMISPHERICAL NOSE
AND FLARED-CONE TAIL

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OF THE
HYDRODYNAMICS LABORATORY
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Hydrodynamics Laboratory
California Institute of Technology
Pasadena, California

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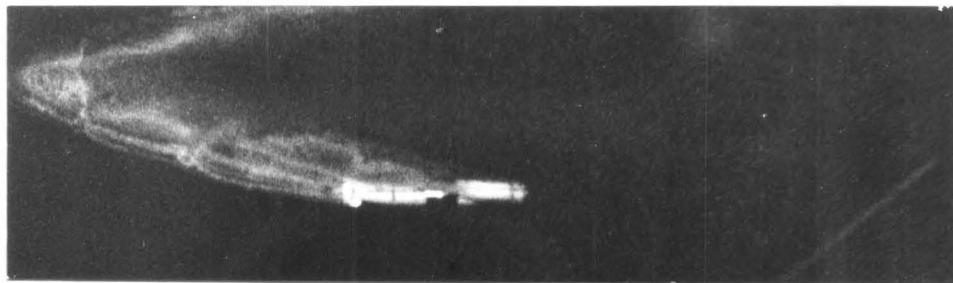
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FOREWORD

This memorandum is an informal report on an experimental investigation made as a special task at the request of the Naval Ordnance Test Station, Pasadena Annex. One part of this task was the investigation of the shape of the entry cavity and the orientation of the model within the cavity.

In the body of the report no mention is made of the considerable amount of experimentation and development that had to be done on the illumination and photography of the cavity before this study could be made. The photographs obtained heretofore in the Controlled Atmosphere Launching Tank, of which a sample is shown below, were good enough for tracking the model and for determining its orientation. The image of the cavity was, however, quite faint and ill-defined, and the interaction between model and cavity was not clearly visible. A comparison of the photograph below with Figs. 2, 5, 7, and 11 of this report shows the improvement in cavity photography obtained so far. This improvement was achieved by doubling the energy input per flash for several of the flash lamps, and by sealing these lamps in individual lucite housings mounted on adjustable supports so that the lamps could be placed in the interior of the tank as required for proper illumination of the cavity.



The writer believes that this development is worth mentioning since it makes available a considerable amount of useful information in addition to any that could be obtained before. One example of a number of possibilities that are now open is a study to correlate the forces and moments, as measured in the Free Surface Water Tunnel on nose and afterbody shapes within a cavity, with the dynamic behavior of free flying models as observed in the Controlled Atmosphere Launching Tank.

Joseph Levy
Section Chief

INTRODUCTION

At the request of the Naval Ordnance Test Station, Inyokern, Pasadena Annex, several tests were made at the Hydrodynamics Laboratory, California Institute of Technology, under contract NOrd 9612 to supplement the investigation being made at the Naval Ordnance Test Station (NOTS) under NOTS Task Assignment Re 3d-454-1-52.

The NOTS study refers to air-launched missile shapes which oscillate in the cavity during the cavity phase of the underwater trajectory. The purpose of the study is to correlate the behavior of these missiles in terms of distance traveled between the contacts of the tail of the missile with the cavity wall. It is hoped that this parameter can ultimately be used to predict missile stability. In order to decrease the number of variables, the study was begun with only two nose shapes: the hemisphere and a subcalibre flat plate having the same drag coefficient as the hemisphere. The various tail sections used on the cylindrical body section were flared cones of half angles ranging between 0° and 22.50° . Five slenderness ratios from 5.5 to 9.5 were investigated. The slenderness ratio was varied by increasing the distance from the cg to the tail. The distance from the cg to the nose was held constant and the weight and moment of inertia were the same for all of the models.* Since it is not possible to vary the air pressure in the open model tank at NOTS, it was desirable to make a few tests in the Controlled Atmosphere Launching Tank (CALT) at the Hydrodynamics Laboratory to see if the behavior of these missiles was altered by changing the air pressure (i.e. changing the cavitation number).

PURPOSE

The purpose of the launchings made in the CALT was to determine whether the behavior of the missile with the hemispherical nose used in the NOTS tests was significantly altered by change in air pressure. The tests

* Report in progress at NOTS

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were made only with the missile having a hemispherical nose, because the hemisphere is known to be more sensitive to pressure than is the flat plate.*

The original NOTS request, Memo NP45-P8083/A1-1(5), required that the Hydrodynamics Laboratory launch a 2-in. diameter missile weighing 3.56 lbs. at an air pressure of 1/6 atm and entry velocity of 163 fps. The entry conditions, the time-position of the cg during underwater flight, and, if possible, photographic records of the cavity size and shape were requested.

Preliminary results from NOTS tests with 1-in. diameter missiles made at any entry velocity of approximately 150 fps indicated that the missile struck the top of the cavity after one or two lengths of underwater travel. This was surprising because the 1-in. diameter torpedo models with hemispherical noses launched with the same entry conditions struck the bottom of the cavity first. The fact that an unusual bulge occurred on the back of the cavity lead to the belief that the flared tail of the missile hit the water at entry hard enough to rebound to the top of the cavity. Therefore, the NOTS request was modified to include large, detailed photographs of the model and cavity during the first two lengths of underwater travel. The purpose of these photographs was to see if the tail of the model slapped the water at entry, and if the tail did contact the water, it was of interest to know whether the degree of contact was affected by reducing the air pressure in the model system.

Ten launchings were made in the CALT and one single-flash photograph was taken during each run at times varying between 2 and 15 milliseconds after entry. Air pressures of both 1 and 1/6 atm were investigated in these tests. Entry conditions were recorded with the high-speed motion picture cameras, and the underwater photographs were taken with a 10-in. lens on a 5-in. x 7-in. plate camera mounted on an underwater viewing window in the launching tank. Illumination was provided by two Edgerton flash lamps housed in lucite cans and located near the point of entry. It was later found that with the lights developed for the single flash photographs and the launching tank motion picture cameras, it was possible to obtain

* Unpublished data from Dr. J. Waugh, NOTS

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good cavity pictures during the entire underwater trajectory. Therefore, one additional launching was made at each air pressure and photographed at a rate of 420 exposures per second. The entry conditions of the launchings are listed in Table 1. The entry velocity was reduced to 120 fps and the weight of the model to 2.64 lbs. because a 3.56-lb. model at 163 fps would have overloaded the launcher on the CALT. The pitch velocity during the air flight was caused by inaccuracies in the temporary planetary gears which were used on the launching wheel while new precision gears were being cut.

TABLE I - ENTRY CONDITIONS

Completely Recorded Launchings
(One test at each pressure)

	<u>1 atm</u>	<u>1/6 atm</u>
Entry velocity	123 fps	122 fps
Trajectory angle	18.7°	19.0°
Pitch angle at entry (nose up)	0.2°	0.5°
Pitch velocity (nose up)	95 deg/sec	170 deg/sec

Launchings Recorded with Single Photograph Only
(Average of 10 launchings made at air pressures
of both 1 and 1/6 atm)

Entry velocity	121 fps
Trajectory angle	20.0°
Pitch angle at entry	1.7°
Pitch velocity (nose up)	85 deg/sec

THE MISSILE

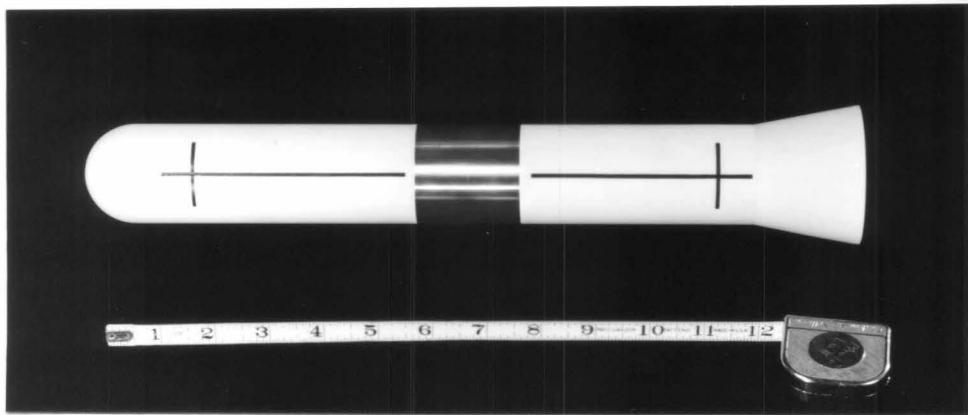


Fig. 1 - Two-inch diameter missile launched in the
Controlled Atmosphere Launching Tank

The missile launched in the CALT consisted of a hemispherical nose and a flared-cone tail of 11.25° half-angle on a 2-in. diameter cylindrical body section (Fig. 1). The slenderness ratio of the model was 7.5. The center section was supplied by the HDL and the other parts were made at NOTS. The dimensions of the model and its physical properties are listed below.

Physical Properties of Missile

Length	15.000 in.
Diameter	2.001 in.
Length of cone	2.000 in.
Cone half-angle	11.25°
Radius of hemisphere	1.000 in.
Displacement	48.8 in. ³
Weight	2.647 lbs
C.G. (aft of nose)	7.498 in.
Moment of inertia	0.2397 lb ft ²

ACCURACY OF DATA

Difficulty was encountered in analyzing the underwater data because the cavity distorts the model and sometimes obscures it. However, the x and y coordinates of the model image were determined to ± 0.1 dia in most cases and to ± 0.2 dia under the most unfavorable conditions. No

attempt was made to correct for the small, unknown distortion of the bubble. The z coordinate was not measured because the model did not yaw perceptibly from the launching plane. The inclination of the model axis was measured to $\pm 1^\circ$ in most cases and to $\pm 2^\circ$ under unfavorable conditions.

The distance between the contacts of the tail with the cavity wall was taken as the geometrical distance between the location of the cg of the missile at consecutive contacts between the tail and the water. Since the tail usually contacted the cavity wall between exposures, it was necessary to estimate the point at which contact occurred. It is believed that the accuracy with which these distances can be estimated varies between $\pm 1/2$ dia at the beginning of the trajectory to $\pm 1/8$ dia at the end where the missile is moving more slowly.

RESULTS

Similarities of Behavior at Air Pressures of 1 atm and 1/6 atm

Changing the air pressure from 1 to 1/6 atm made no major difference in the behavior of the missile used in these tests. At both air pressures the missile oscillated in its cavity while traveling along a nearly straight trajectory lying close to the extension of its air path. Large bulges appeared on the cavity each time the tail of the missile struck the water (Fig. 2). The maximum difference between the underwater trajectories was less than 3 dia (Fig. 3). The total distance traveled during the first 1/4 second of underwater flight was the same at both air pressures, and the instantaneous velocity as a function of time was also equal (Fig. 4).

At both air pressures the tail of the model hit the water as it entered (Fig. 5), and the configuration of the cavity was very similar during the first 36 milliseconds after entry. Fig. 6, which was traced from projections of the motion picture data, shows outlines of the cavities 36 ms after entry and the outlines of the tail cavities as a function of time during the first 36 milliseconds of underwater flight. The similarity of the tail cavities suggests that the tail of the missile struck the water with approximately equal force at both air pressures.

When only the hemispherical nose of the missile is in contact with the cavity wall, the line of separation between the missile and the cavity

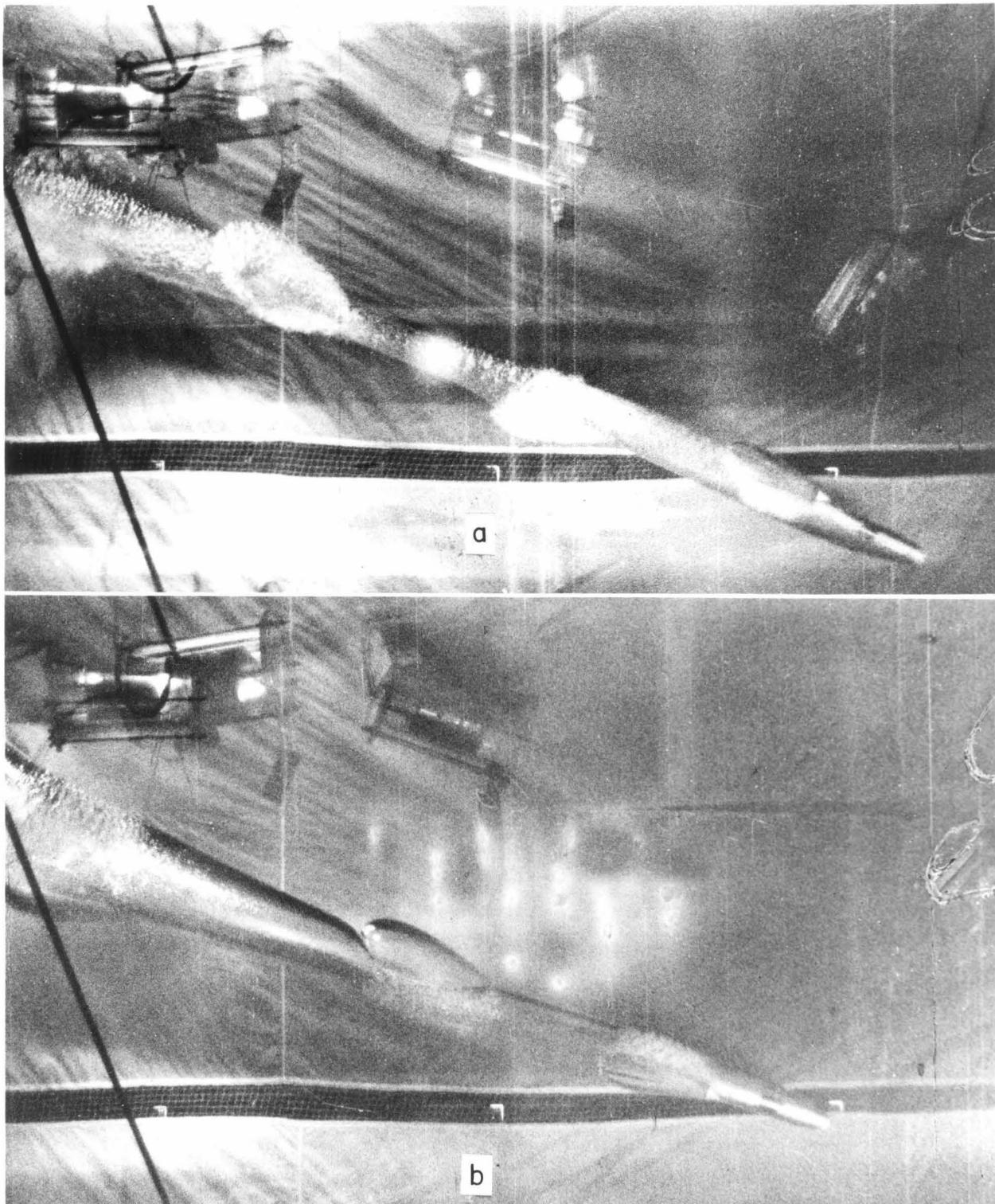


Fig. 2 - The missile and cavity 140 milliseconds after water entry
(a) air pressure: 1 atm
(b) air pressure: 1/6 atm

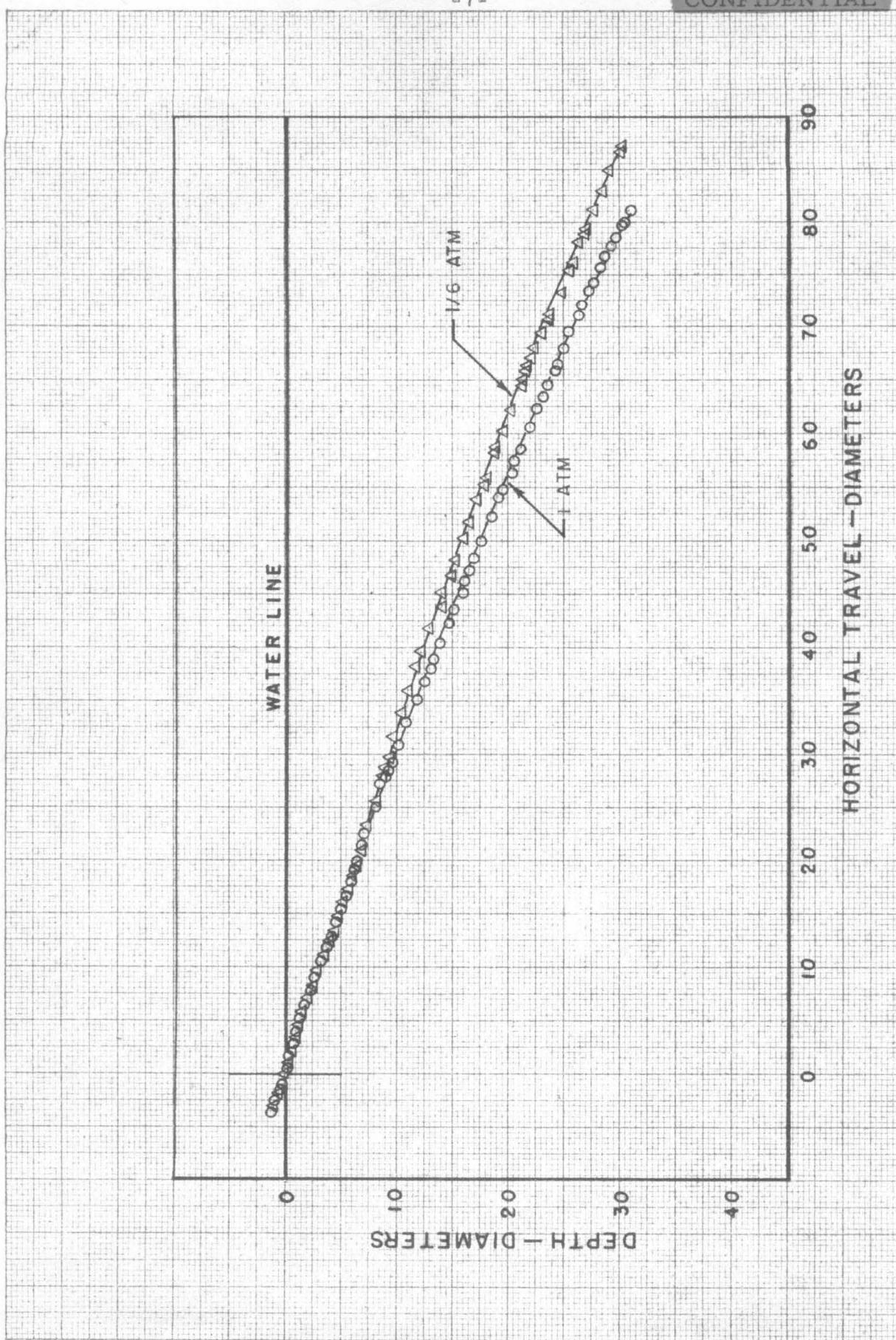
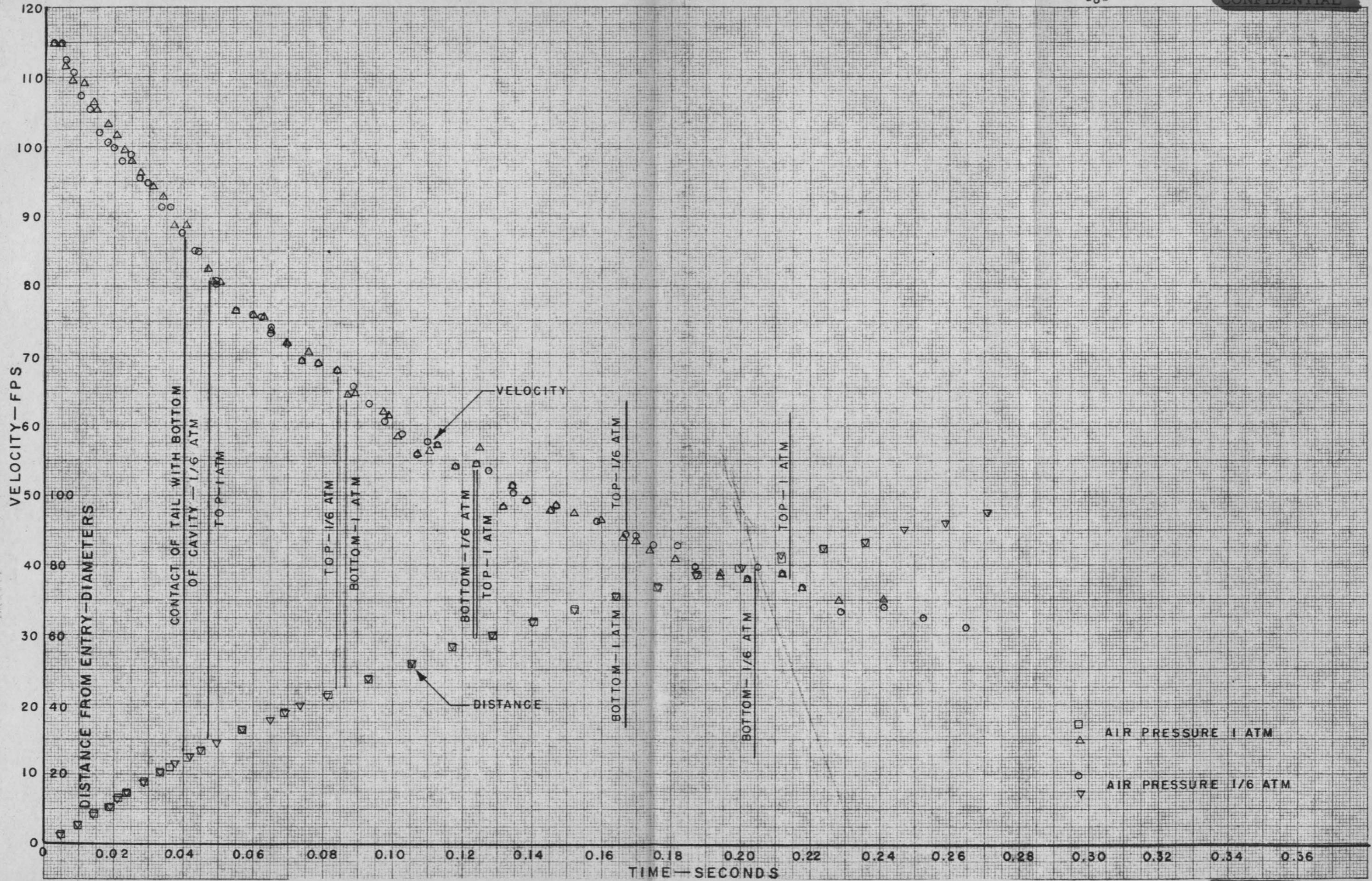


Fig. 3 - The underwater trajectories

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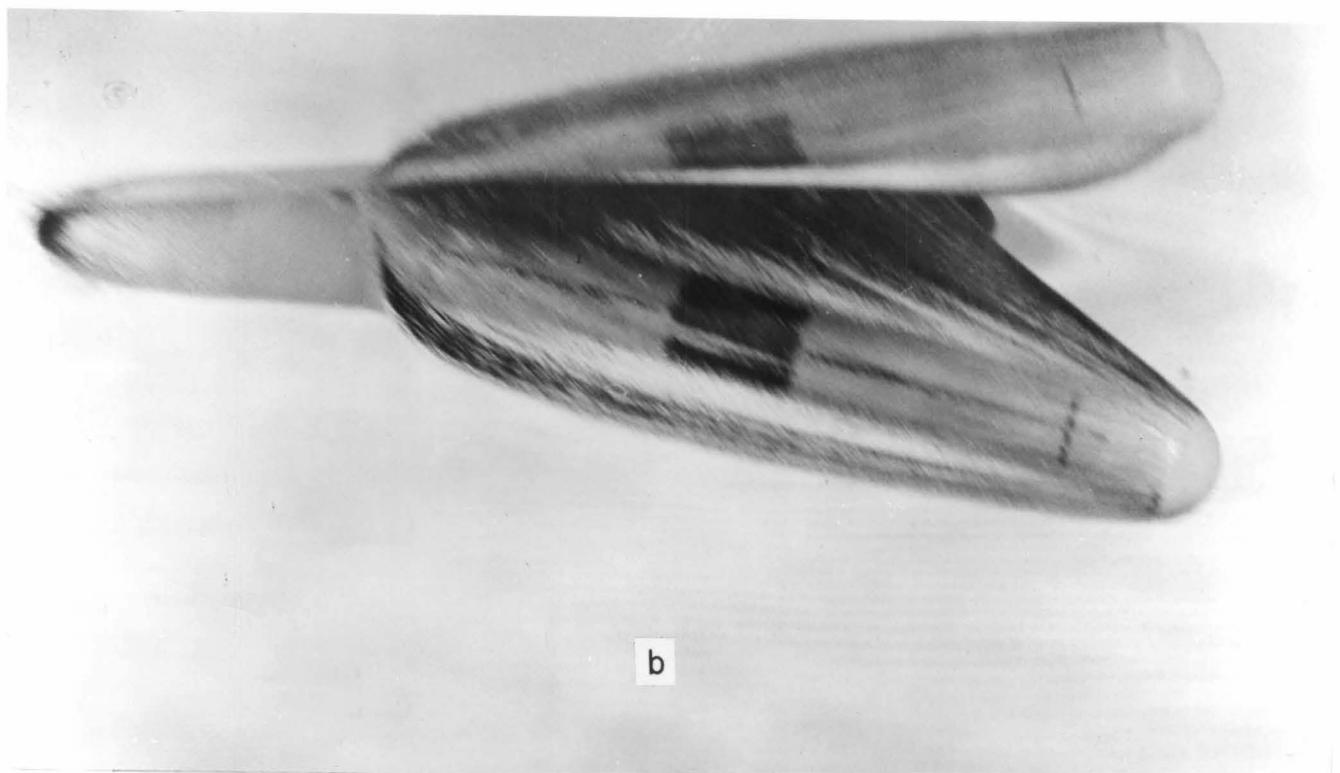
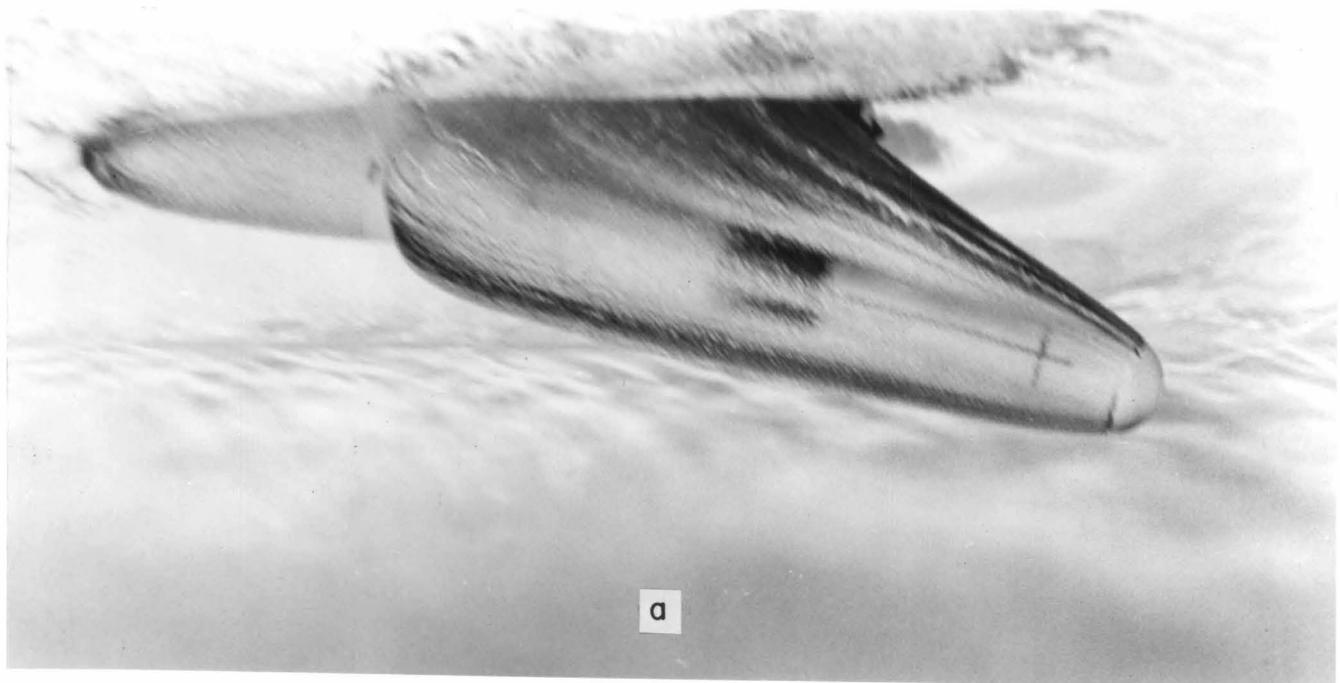


Fig. 5 - Single flash photographs showing the cavity as
the missile enters the water
(a) air pressure: 1 atm, 3-1/2 dia from entry
(b) air pressure: 1/6 atm, 2-1/2 dia from entry

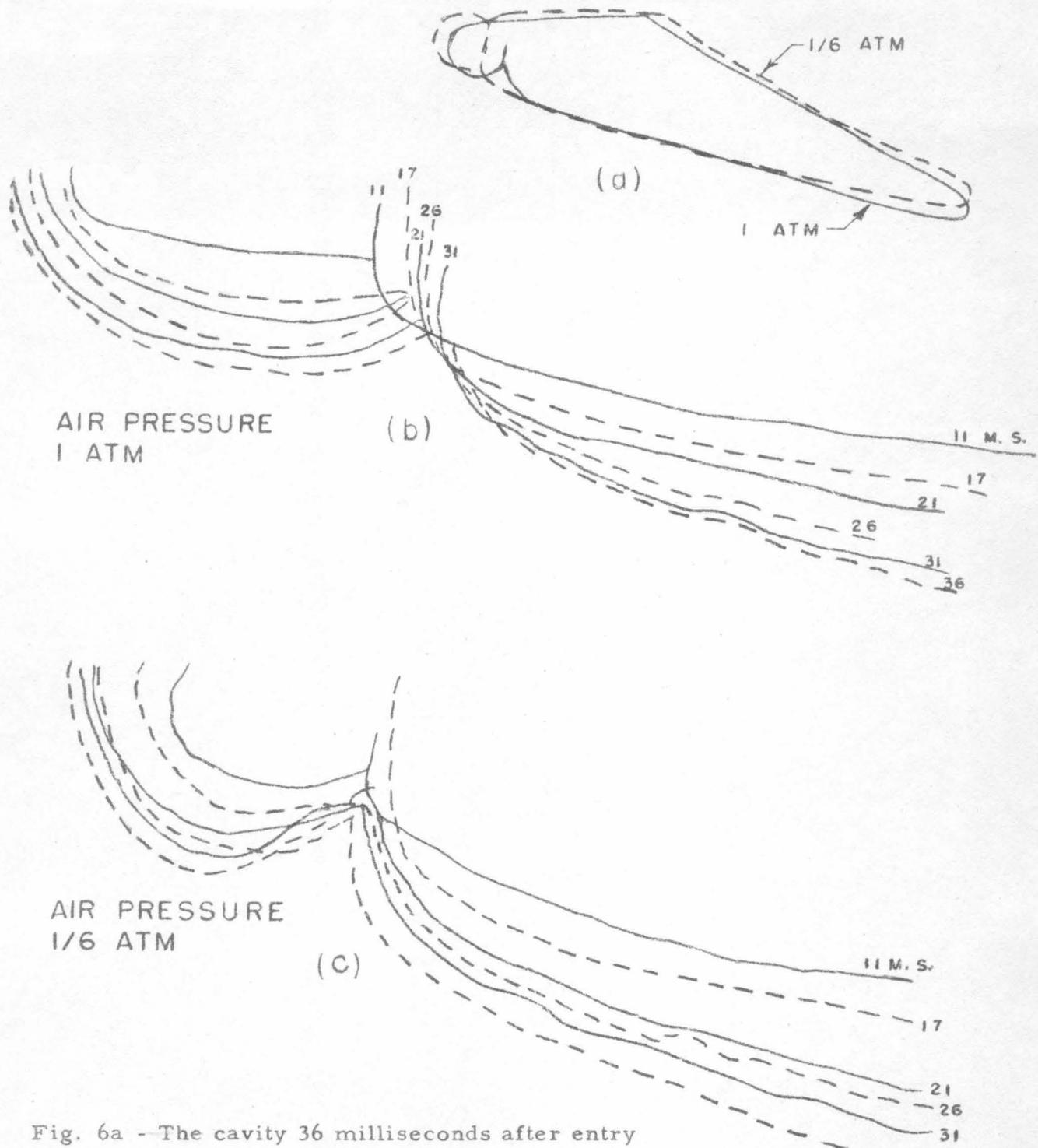


Fig. 6a - The cavity 36 milliseconds after entry

6b - The tail cavity as a function of time during the first 36 milliseconds of underwater flight; air pressure: 1 atm

6c - The tail cavity as a function of time during the first 36 milliseconds of underwater flight; air pressure: 1/6 atm

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is a more sensitive index of pressure effect than is the trajectory. Separation will occur where the pressure on the missile is equal to the pressure in the cavity. The presence of low pressure regions (underpressure) on the nose is accompanied by a change in pressure distribution which causes an aftward shift in the separation as may be seen in Fig. 7, which is from another study made with a torpedo model. No asymmetry in the line of separation could be detected in any of the photographs of the NOTS "stability missile" taken in the CALT. (See Fig. 5.)

Changing the air pressure did not significantly alter the distance the model traveled between contacts of the tail with the cavity wall. At both air pressures the distance between contacts decreased as the model traveled along the trajectory (Fig. 8). There was a difference of 5 diameters in the first oscillation distance. The second and third distances were, within the accuracy of measurement, equal, and the fourth oscillation distance differed by about 2-1/2 diameters. The scatter in the oscillation distances determined from several launchings made at full atmospheric pressure at NOTS with a missile 1 in. in diameter, similar to the shape launched in the CALT, is greater than the difference in oscillation distances of the 2-in. dia model launched at the different air pressures. Fig. 8 also shows that the period of the oscillations was not only unaltered by change in air pressure, but was very nearly constant as well. The eight half-oscillations measured were all between 0.037-sec and 0.048-sec duration, a frequency range of 21 to 27 half cps.

At both air pressures the missile oscillated in the pitch (vertical) plane. Fig. 9 compares the relationship between the inclination of the missile and the instantaneous trajectory angle at air pressures of 1 and 1/6 atm. The amplitude of the pitch oscillation and the duration of contact between the tail and the cavity wall were very nearly the same under both pressure conditions. Since the magnitude of the oscillation is limited by the width of the cavity at the tail, it is not surprising to find the width of the cavity at the tail also unaltered by change in air pressure (Fig. 10).

Differences in Behavior at Air Pressures of 1 atm and 1/6 atm

Although striking similarities have been cited in the behavior of the hemispherical-nose missile at air pressures of 1 atm and 1/6 atm, several differences were also noted. Although the tail always struck the bottom of

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the cavity as the missile entered the water, the rebound was different at the different air pressures. At full atmospheric pressure the tail rebounded and struck the top of the cavity, while at reduced pressure the tail bounced clear of the cavity wall but did not swing far enough to strike the top. Instead, it contacted the bottom of the cavity first, (Fig. 11), and hence the missile oscillated 180° out of phase during the two underwater trajectories (Fig. 12). This difference in behavior may have been caused by the greater nose-up pitch velocity of the missile during the air flight of the reduced pressure launching, or it may have been caused by the difference in air pressure above the water surface (underpressure effects). Preliminary whip data taken in the new variable pressure tank at NOTS* with a missile having a hemispherical nose indicate that the difference is probably due to pressure effects rather than entry conditions.

While little difference could be detected in the shape of the cavity during the first 36 milliseconds of the underwater trajectory, large differences became apparent later. The configurations of the cavities at corresponding times ranging from 2 millisec to 720 millisec after entry are shown in Figs. 13 and 14. The apparent rise in the water surface is partially caused by actual rise in the surface and partially caused by motion of the cavity wall toward the cameras. The location of the cameras with respect to the water surface and the launching plane is indicated in Fig. 13.

The cavity made by the missile at $1/6$ atm eventually grows larger and remains smoother than the cavity at full atmospheric pressure. A roughness begins on the bottom of the full pressure cavity 0.06 sec after entry. This disturbance grows and travels downward until approximately $1/2$ sec after entry, and at approximately $3/4$ sec after entry the projection still persists. No projection appeared on the cavity made by the missile launched at an air pressure of $1/6$ atm. Another difference in behavior near the back of the cavity can be seen in Fig. 15, which shows the motion of the intersections of the nose and tail cavities. The intersection of the full pressure cavities moves forward, while at reduced pressure the intersection remains relatively stationary.

The series of photographs in Fig. 16 shows that the low pressure cavity necked down approximately 45 dia from entry and broke into a series of spiral-like bubbles while the cavity was still open at the surface. The deep

* A small variable pressure tank instrumented primarily to measure whip.

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closure of the full pressure cavity was not well defined, but probably occurred later than the closure of the reduced pressure cavity. From the available data it was impossible to determine whether the full pressure cavity remained open at the surface until deep closure occurred.

CONCLUSIONS

1. Reducing the air pressure from 1 to $1/6$ atm made no significant difference in the general behavior of the missile with a hemispherical nose used in the NOTS stability program.
 - a. The underwater trajectories were less than 3 dia apart.
 - b. The total distance traveled from entry during the first $1/4$ sec of underwater travel was equal.
 - c. The instantaneous velocity during the underwater trajectory was, within the scatter of the data, the same.
 - d. At both air pressures the tail of the missile struck the water before the missile was completely submerged.
 - e. There was no significant difference in pitch oscillation distance, frequency, or amplitude.
2. No positive indication of underpressure effect could be detected during the full pressure launchings. The line of separation of the water from the nose of the missile was always symmetrical. However, the fact that the tail struck the top of the cavity first at full atmospheric pressure and the bottom of the cavity first at reduced pressure suggests some transient underpressure effects as the nose struck the water.
3. Further investigation should be made to see whether the difference in phase of oscillation of the missile in the cavity is due to transient underpressure effects.
4. The cavities were very similar during the first 36 milliseconds after water entry, and the portions of the cavities surrounding the missile during the entire underwater flight were the same when the tail of the missile was not in contact with the cavity wall.
5. Large differences occurred in the cavities after the missile had passed.
6. The fact that conditions immediately following entry could be sufficiently different to cause the missile to oscillate 180° out of phase during the underwater trajectory without significantly altering the trajectory indicates that the trajectory is not a sensitive index of comparison.

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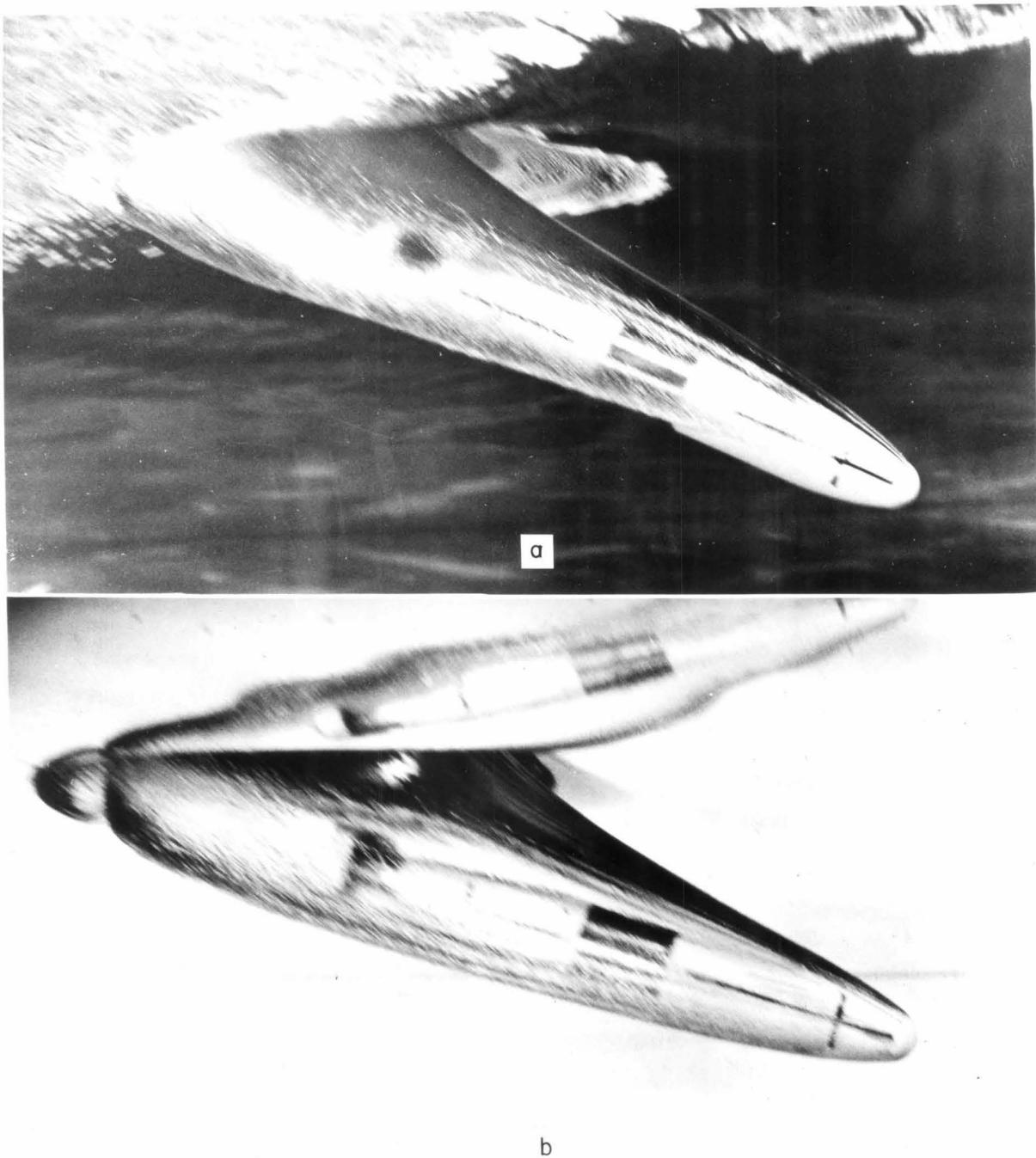


Fig. 7a - Asymmetrical line of separation on nose of 2-in. diameter
Mk 25-W7 torpedo model launched at
full atmospheric pressure

7b - Symmetrical line of separation on nose of 2-in. diameter
Mk 25-W7 torpedo model launched at
reduced atmospheric pressure

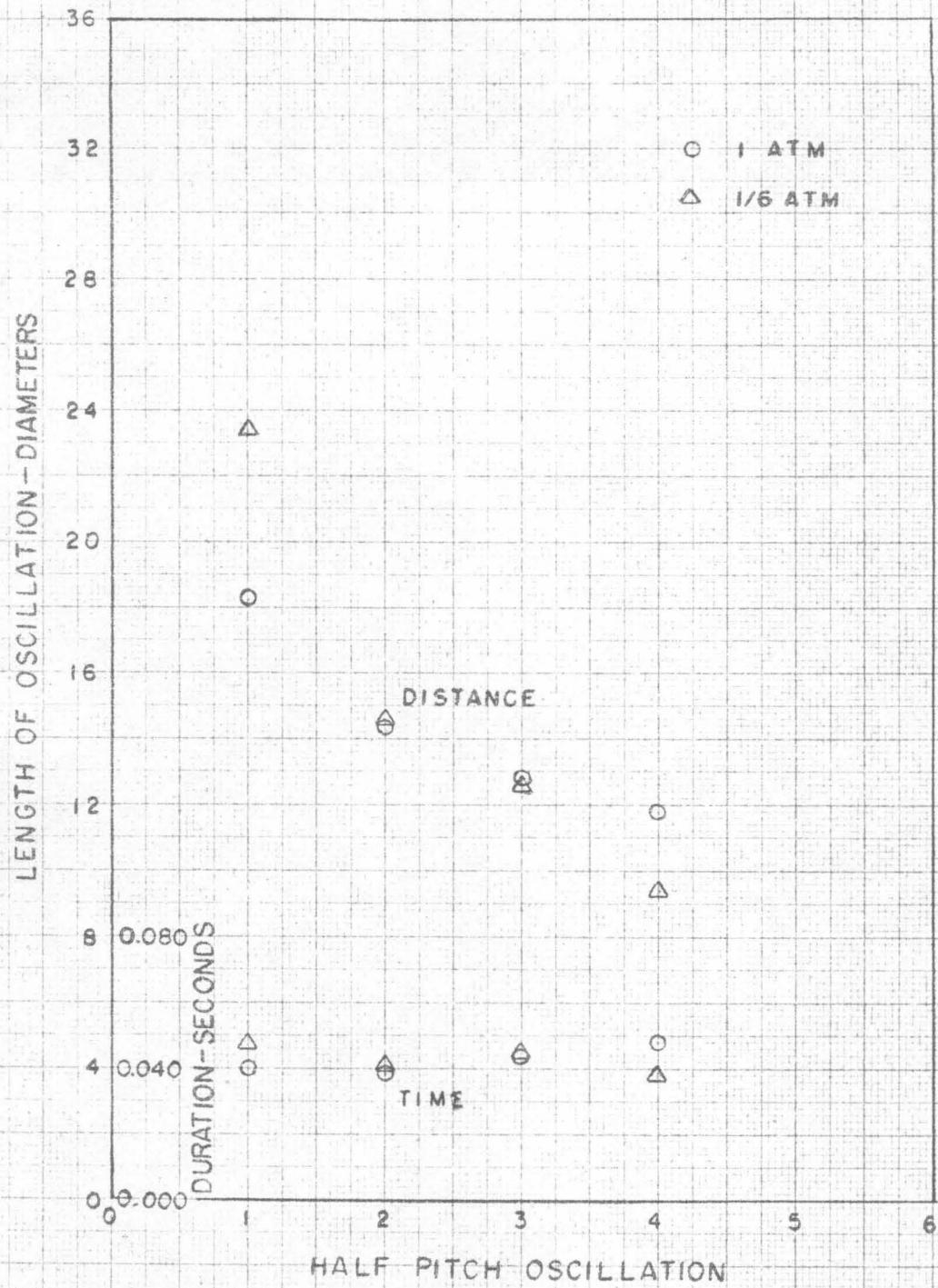


Fig. 8 - Distance and time between successive contacts
of the tail with the cavity wall

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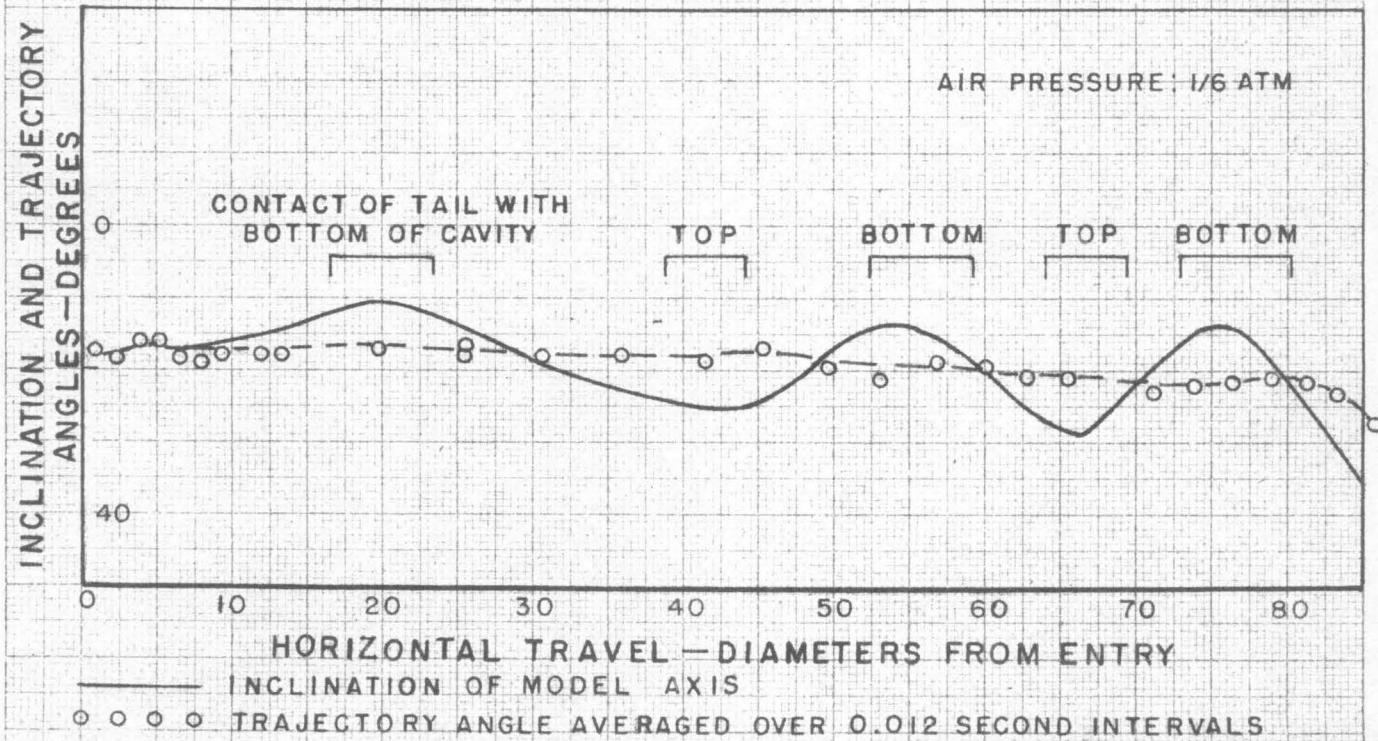
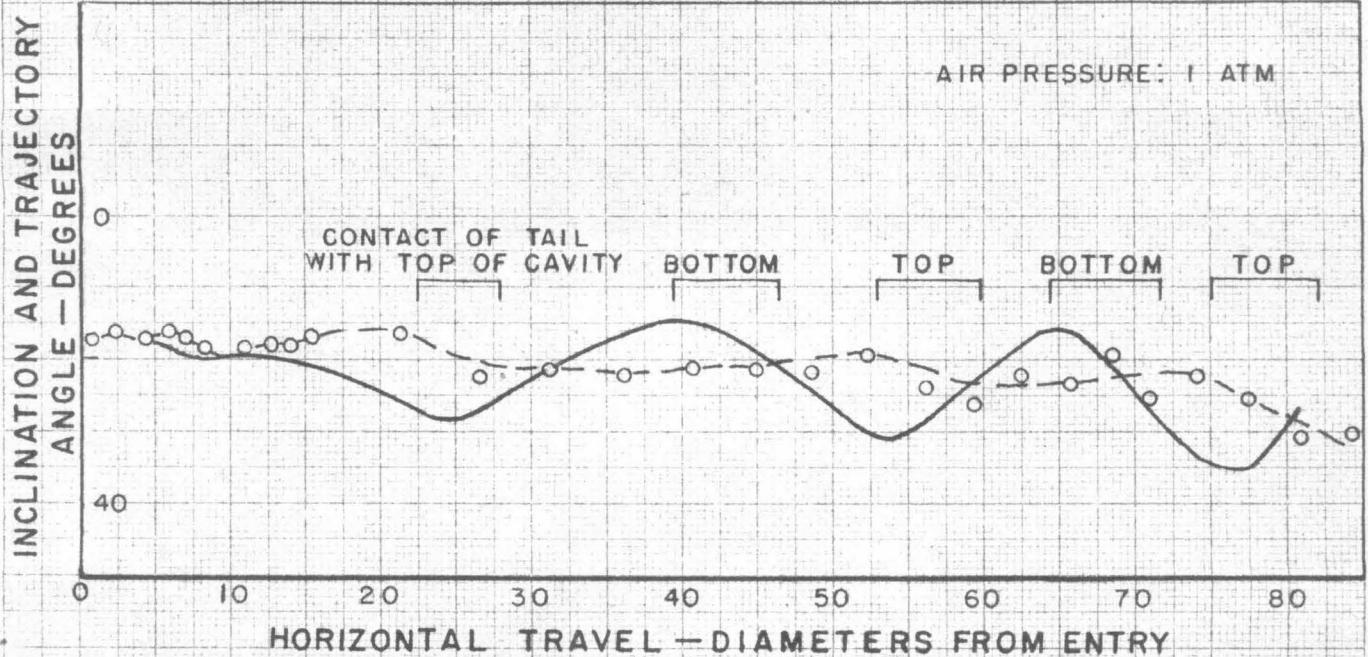


Fig. 9 - Relationship between the inclination of the model axis and the instantaneous trajectory angle

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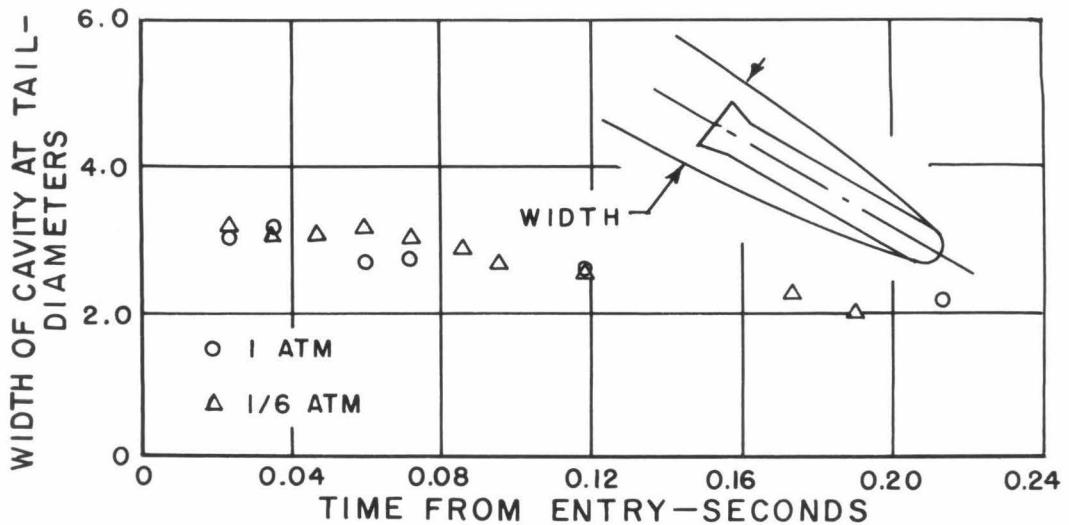


Fig. 10 - The width of the cavity at the end of the missile
as a function of time

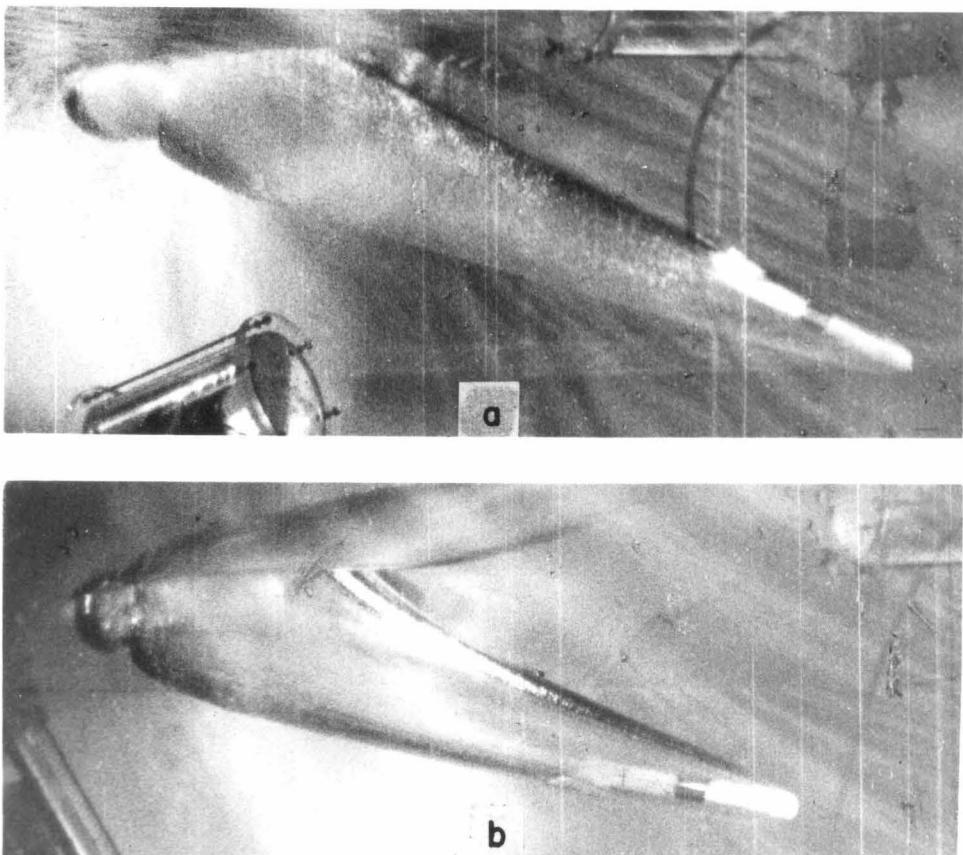


Fig. 11 - The first contact of the tail with the wall of the cavity
(a) air pressure: 1 atm, 48 milliseconds after entry
(b) air pressure: 1/6 atm, 38 milliseconds after entry

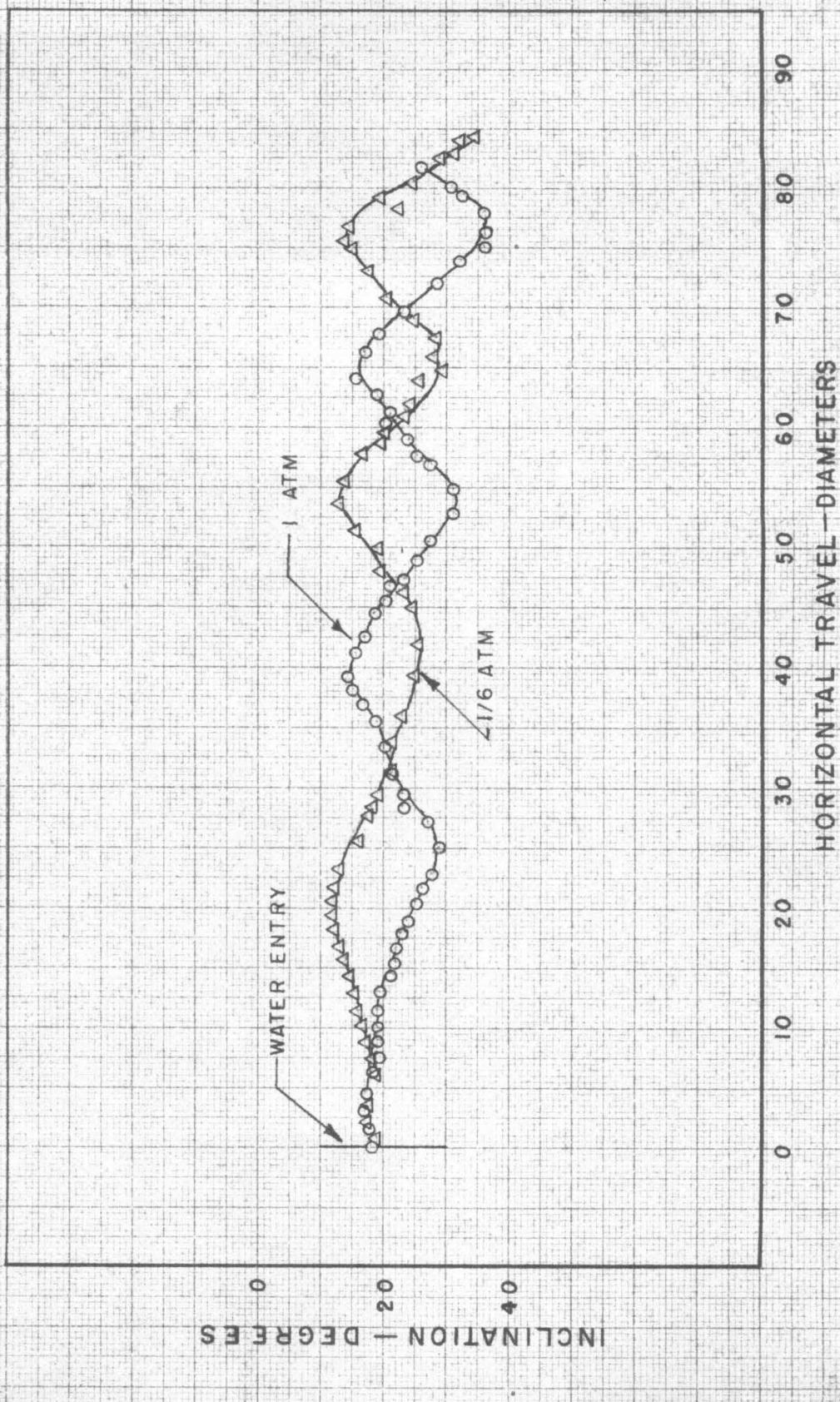


Fig. 12 - The inclination of the model axis as a function of horizontal travel

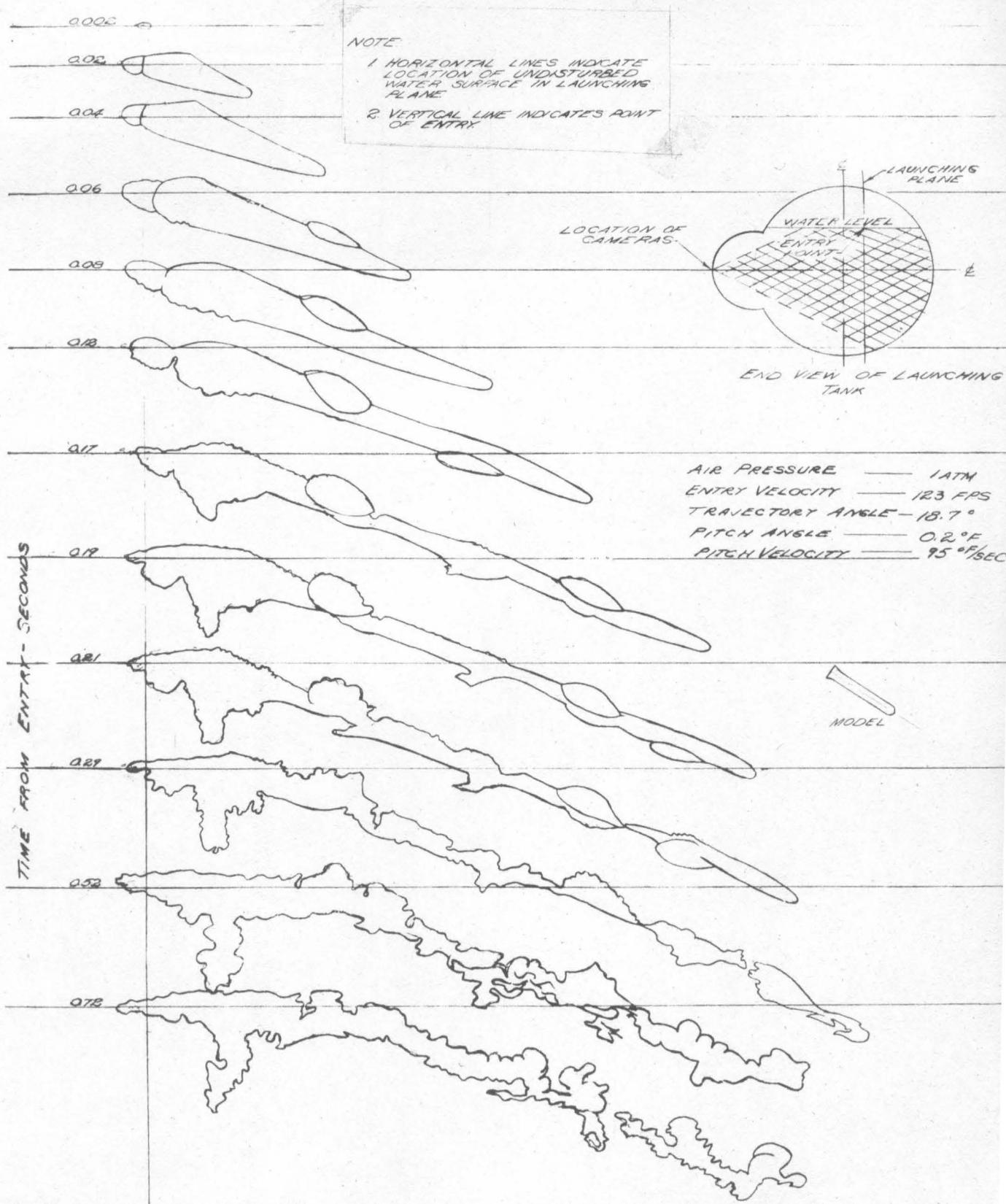


Fig. 13 - The configuration of the cavity as a function of time;
air pressure: 1 atm

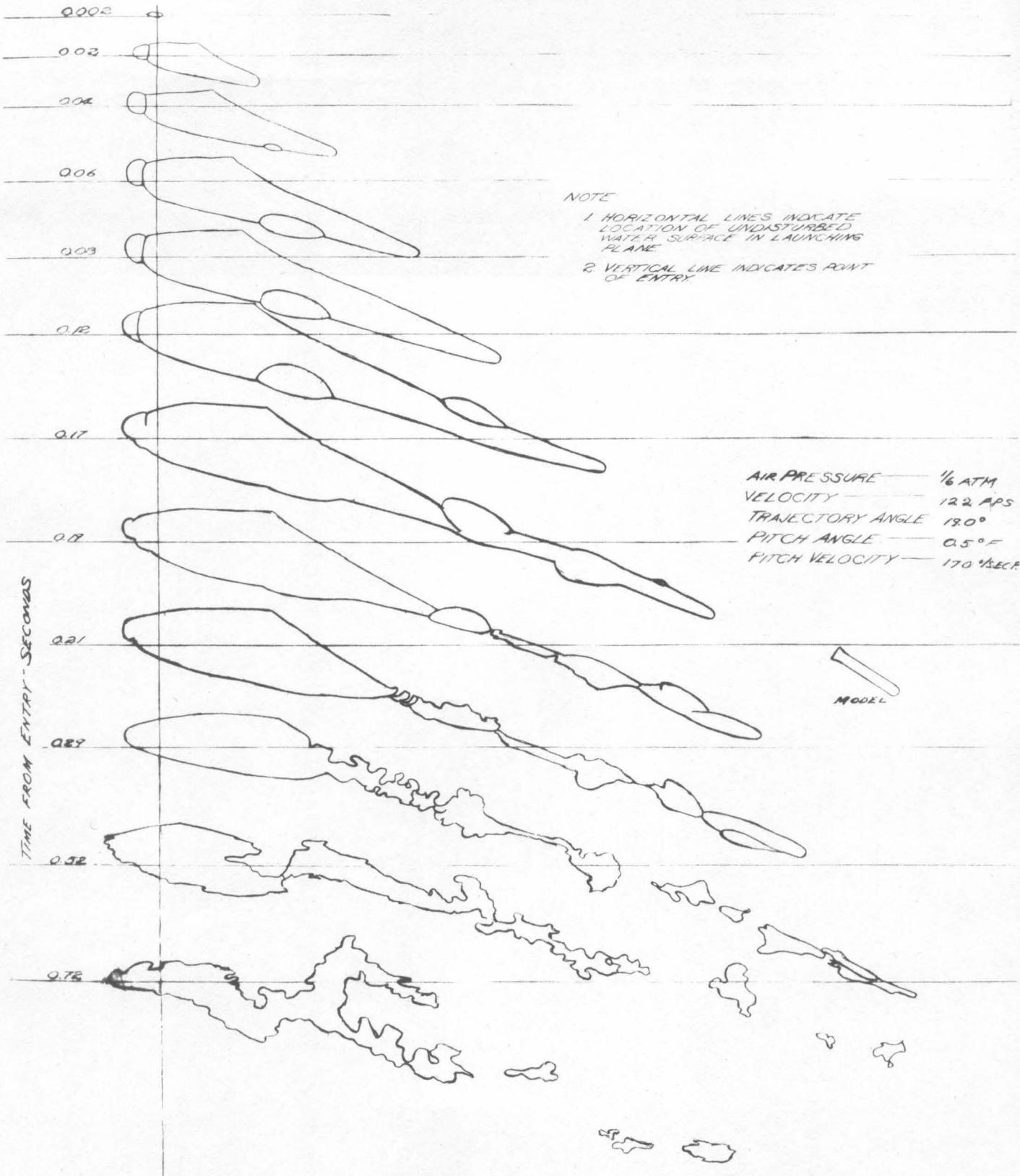


Fig. 14 - The configuration of the cavity as a function of time;
air pressure: $1/6$ atm

NOTE:

THESE CURVES WERE
ALIGNED BY MAKING
COINCIDENT THE INTER-
SECTION OF THE NOSE
AND TAIL CAVITIES 10
MILLISECONDS AFTER
ENTRY

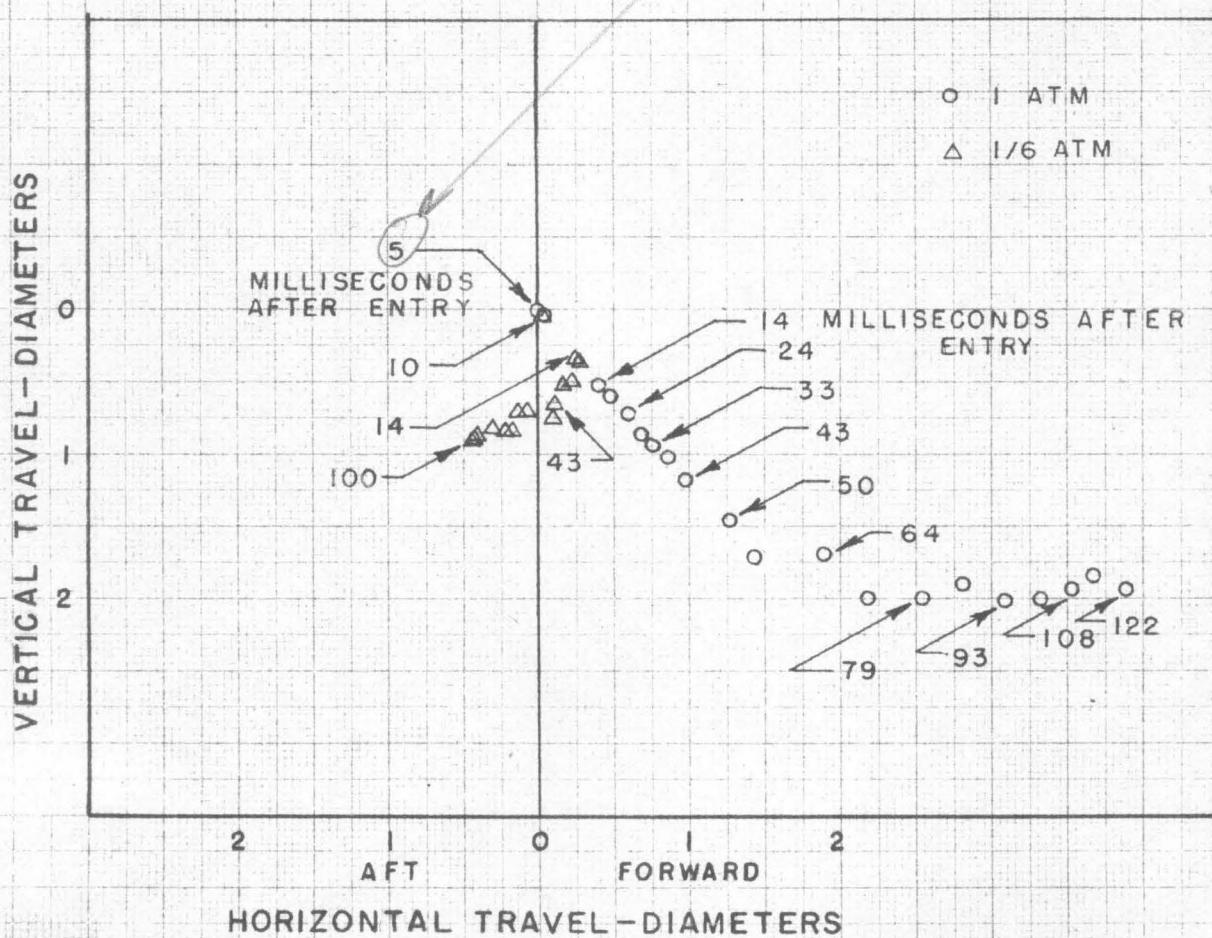
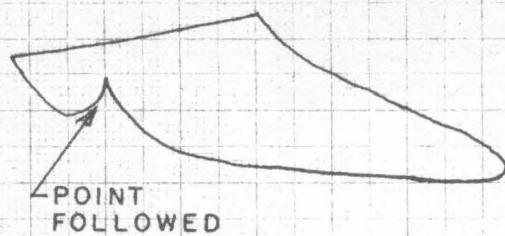


Fig. 15 - Motion of intersection of nose and tail cavities

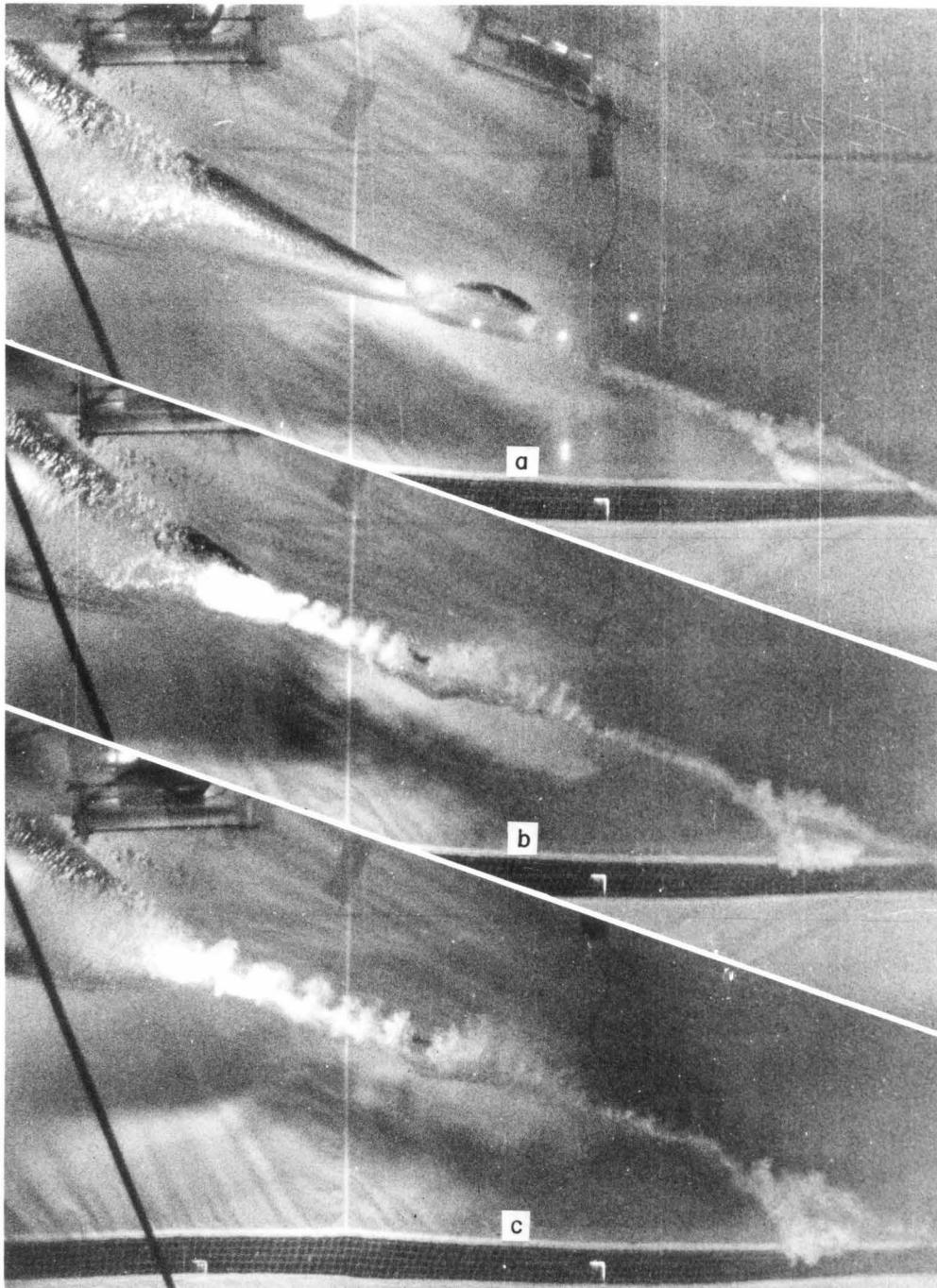


Fig. 16 - Deep closure of the cavity; air pressure 1/6 atm

- (a) 190 milliseconds after entry
- (b) 214 milliseconds after entry
- (c) 238 milliseconds after entry