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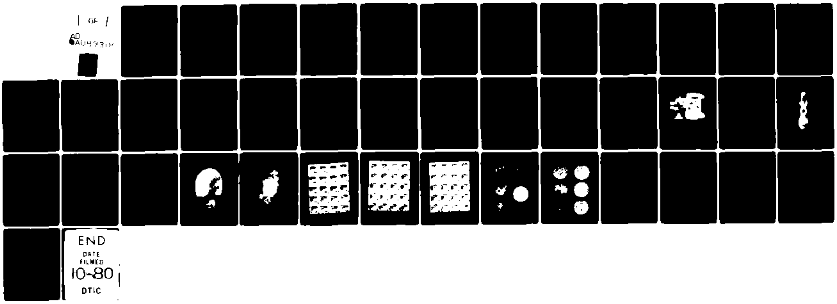

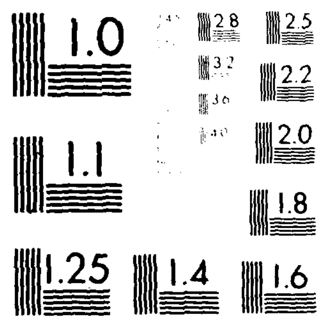


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LEVEL II

DTNSRDC-SPD-0915-01

# DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

AD A089318

THE EFFECT ON BLADE EROSION OF INJECTING AIR AHEAD OF A CAVITATING PROPELLER

THE EFFECT ON BLADE EROSION OF INJECTING

AIR AHEAD OF A CAVITATING PROPELLER

by

Douglas Dahmer
and
Marlin Miller



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SHIP PERFORMANCE DEPARTMENT
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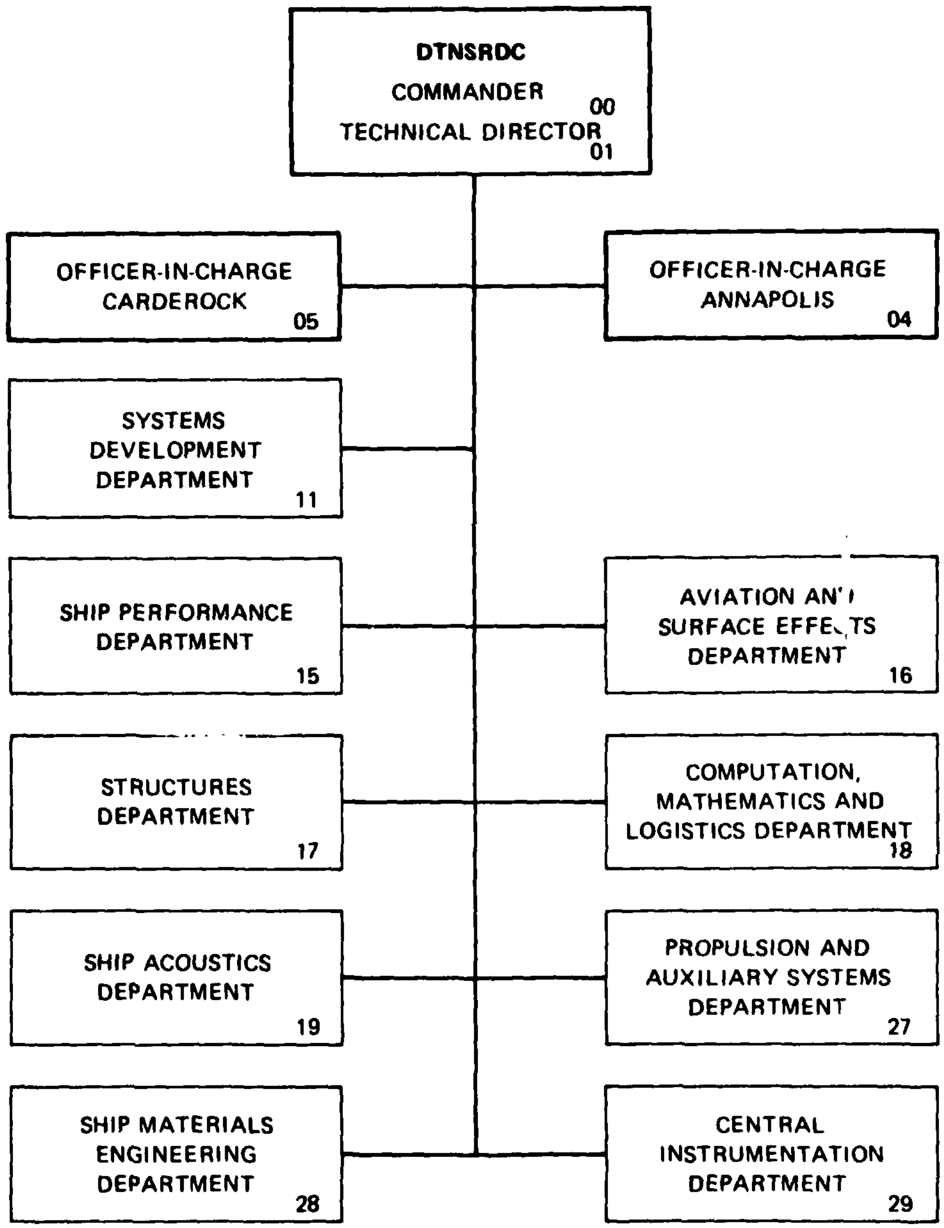

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Experiments are described in which air was injected ahead of a propeller operating at a cavitating condition in a nonuniform wake to determine the effect of air on blade cavitation erosion. Experiments were conducted with no air injected and with air injected at different locations ahead of the propeller for two air flow rates. The experimental technique and data collection method are described.

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The results show that the injection of air ahead of a cavitating propeller significantly reduces the amount of blade erosion.

The amount of erosion was found to be dependent on the location and the amount of air injection.

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## NOTATION

| | |
|---|---|
| $c_{0.7}$ | Propeller blade chord length at 0.7R |
| D | Propeller diameter |
| EAR | Expanded area ratio |
| g | Acceleration of gravity |
| J | Advance ratio, $V_A/(nD)$ |
| $K_Q$ | Torque coefficient, $Q/\rho n^2 D^5$ |
| $K_T$ | Thrust coefficient, $T/\rho n^2 D^4$ |
| n | Propeller revolutions per unit time |
| P | Propeller blade pitch |
| $P_c$ | Tunnel centerline pressure |
| $P_v$ | Water vapor pressure |
| Q | Propeller torque |
| r | Propeller local radius |
| R | Propeller radius |
| $R_n$ | Reynolds number, $C_{0.7}V_{0.7}/\nu$ |
| t | Propeller blade thickness |
| T | Propeller thrust |
| V | Tunnel water velocity |
| $V_A$ | Speed of advance |
| $V_{0.7}$ | Local velocity $\left[(0.7\pi nD)^2 + V_A{}^2\right]^{\frac{1}{2}}$ |
| $\eta_0$ | Propeller efficiency, $JK_T/2\pi K_Q$ |
| $\nu$ | Kinematic viscosity of water |

$\rho$ Density of water

$\sigma$ Cavitation number, $(P_C - 0.7\rho gR - P_V)/\frac{1}{2}\rho V^2$

$\sigma_{0.7}$ Local cavitation number, $(P_C - 0.7\rho gR - P_V)/\frac{1}{2}\rho V_{0.7}^2$

## ABSTRACT

Experiments are described in which air was injected ahead of a propeller operating at a cavitating condition in a nonuniform wake to determine the effect of air on blade cavitation erosion. Experiments were conducted with no air injected and with air injected at different locations ahead of the propeller for two air flow rates. The experimental technique and data collection method are described.

The results show that the injection of air ahead of a cavitating propeller significantly reduces the amount of blade erosion.

The amount of erosion was found to be dependent on the location and the amount of air injection.

## ADMINISTRATIVE INFORMATION

This work was performed as part of the Independent Research Program of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) and funded under Task Area ZR0230101, Work Unit 1544-323.

## INTRODUCTION

A propeller operating under cavitating conditions runs the risk of damage by cavitation erosion. Solutions to the erosion problem have ranged from attempting to design the propeller so that the types of cavitation which cause erosion are reduced or eliminated to the use of protective coatings. It is known that if air is injected into a cavity the collapse of the cavity will be cushioned and erosion can be reduced or prevented.[1,2] This method has been used on ducted propellers with considerable success.[3,4] It would be desirable if this method could be used on conventional propellers, but there is no simple, inexpensive way to inject air directly into the cavity. The use of air to reduce erosion on conventional propellers would be possible, however, if air bubbles in flow upstream of the propeller would be entrained in the propeller cavitation in sufficient quantities to cushion the cavity collapse. Experiments were conducted to determine whether this means of introducing the air would be effective in reducing blade erosion.

The experiments described in this report were conducted in the DTNSRDC 36-inch water tunnel. A propeller was operated at a cavitating condition in a nonuniform wake produced by a strut ahead of the propeller. Air was emitted from the strut at various positions and air flow rates. Soft aluminum discs located on the propeller blade were used to measure the cavitation damage during the various conditions. It was found that erosion was significantly reduced for certain conditions of air emission. This report describes the experiment, presents the results, and recommends some further experiments to determine the effect of various parameters.

## EXPERIMENTAL APPARATUS

All experiments were conducted in the 36-inch water tunnel facility at DTNSRDC. The test arrangement consisted of a strut installed in the open jet test section of the tunnel ahead of a two-bladed propeller (Figures 1 and 2). Air was emitted from tubes located on the trailing edge of the strut.

The propeller used in these experiments was DTNSRDC Propeller No. 4123. The propeller has two blades and is 24-inches (0.61 m) in diameter. A drawing and table of the geometry of the propeller are presented in Figure 3 and Table 1, respectively. Pressure gages were installed on the back of one blade and soft aluminum inserts were installed on the back of the other to reduce the time required to produce erosion. The locations of the gages and inserts are shown in Figure 4. Recesses for pressure transducers and/or strain gages which had been used in previous, unrelated experiments can be seen in the photograph. These were filled with an epoxy compound for the present tests. The method used to select the locations of the inserts and gages will be discussed later.

A strut was placed ahead of the propeller to produce a nonuniform wake. The strut is a scaled version of a smaller strut used in the 24-inch water tunnel at DTNSRDC. A drawing of the strut is presented in Figure 5. Expanded metal screening was installed on the strut surface to roughen the surface and produce a stronger wake. The location of the screening is shown in Figure 5. A notch was cut out in the center of the strut to facilitate removal of the fairwater.

Although no wake survey was conducted for the present tests a wake survey was available for the smaller version of the same strut used in the 24-inch water tunnel at DTNSRDC.[5] The results of that survey at the 0.8 radius are presented in Figure 6. The wake for a series 60 hull form, $C_B$=0.6 at the 0.844 radial position is also shown.[6] The comparison shows that the wake is similar to a merchant ship wake but not as deep nor as wide.

Brass tubes were installed in the strut to perform the air emission ~~portion of~~ the experiments. Five tubes were arranged in a rake configuration and were equally spaced 1-5/8 inches (41.3 mm) apart as shown in Figure 5. Two sets of tubes were installed on both sides of the strut such that the tube planes were tangent to the 0.75 radial section of the propeller (also shown in Figure 5). The air was supplied by the pressurized air supply system at the tunnel to the inlet tubes located on both ends of the strut. A flowmeter (rotameter) was inserted in the air circuit so air flow could be measured. Figure 7 presents a schematic of the air emission system.

Aluminum discs were inserted into the suction side of one blade of the propeller at the point where the greatest erosion was expected. They were 0.875 inches (22.2 mm) thick. They were constructed of pure aluminum and after being fitted to the blade and filed to conform to the blade surface contour they were annealed to remove any work hardening. These soft inserts eroded much more rapidly than the bronze propeller metal resulting in a considerable reduction in the time required for the experiments. This is the same technique as that described by Kato in reference 7.

The discs were centered at the 60% chord and 70% radius (see Figure 4). This location was determined by a paint erosion experiment of the type described by Lindgren and Bjarne.[8] In this experiment, the blades were coated by dipping them in the mixture recommended by Lindgren and Bjarne of one part stencil ink and five parts lacquer thinner. After the ink had dried the propeller was run in the tunnel at the planned test condition until a paint erosion pattern was visible. A photograph of the erosion pattern is shown in Figure 8. The disc was located at the point where the erosion appeared to be the greatest. Figure 9 shows a disc in place and the erosion pattern of the blade. It can be seen that the paint erosion pattern correctly predicted the location of erosion of the blade.

Originally the discs were mounted on the blade using one 4-40 screw passing through the blade into the center of the disc. This was found to be unsatisfactory because of the softness of the discs and the intensity of the cavity collapse. With this method the threads in the disc were stripped and the disc unseated after a few minutes of running at the test condition. Three 6-32 screws were used to hold the discs for the remainder of the experiment.

A phosphor bronze disc was also made for the experiment. This disc was used during the long runs when photographs were being taken. Phosphor bronze has a Brinell hardness of 241 as compared to the Brinell hardness of 23 for the aluminum discs which made it suitable for a longer duration test.

Originally, four pressure gages were installed on the back of one blade to try to measure the cavity collapse impact pressure. Two gages were of the diaphragm (semiconductor strain gage) type and two were of the piezoelectric type. Semiconductor strain gage type pressure gages were mounted in two existing holes on the suction side of one blade. One was at 0.8 radius and 0.6 chord and the other at 0.7 radius and 0.8 chord. They were covered with a thin layer of epoxy to make the surface flush with the blade surface. The gages had a 1/4-inch (6.4 mm) diameter stainless steel diaphragm 0.01 inches (0.25 mm) thick and were rated at 120 psi(827KPa). Two piezoelectric gages were constructed using ceramic cylinders about 1/16 inch (1.59 mm) long with wires attached to electrodes on the inner and outer surfaces and coated with a waterproofing compound. These gages were imbedded in epoxy in a cavity in the blade at 0.7 radius and 0.7 chord. Signal conditioners were contained inside the propeller fairwater and the signals were carried outside the tunnel through the existing cable and sliprings.

The locations of these gages were determined by the paint erosion test used to locate the discs. Figure 4 shows the locations of these two types of gages on the propeller. No data were obtained from the gages because during the first run all four gages failed. The cavity collapse pressures were so intense that the surfaces of the diaphragm gages were dimpled and the piezoelectric gages were unseated and torn loose from their wire leads. All gages were removed after this run and the remaining portion of the test was conducted without them.

Photographs were taken of the propeller blade passing through the strut wake. a 60 tooth gear located on the propeller shaft was used to generate a pulse every 6 degrees of shaft rotation. The pulse signal was fed into a shaft position digitizer and camera control NSRDC Type 638 1A to trigger the camera and stroboscopic lights. Photographs were taken at intervals of 5 propeller revolutions plus 6 degrees so that the blade position advanced 6 degrees between each photograph. Twenty frames were taken for each condition for a total of 120 degrees of propeller rotation. Photographs were taken for three conditions of propeller operation: without air emission, with air emission at maximum air flow rate from all five tubes, and with air emission at a reduced air flow rate from all five tubes. The camera setting for all photographs was f4. The camera was situated on the east side of the test section looking downstream.

## EXPERIMENTAL PROCEDURE

The first portion of the experiment was conducted using the number 6 dynamometer on the south shaft of the water tunnel. No-loads (tares) for various tunnel conditions using a dummy hub were taken with the strut in place. The dummy hub was replaced by the propeller and various tunnel conditions were run so that a cavitating condition could be chosen. The conditions used for the remainder of the experiment were: water speed, V=30.7 ft/sec (9.36 m/sec), which corresponds to a venturi differential pressure reading of 6.25 psi (43.0kPa); static pressure at shaft, $P_C$=21.00 psia (144.8 kPa); and propeller rotational speed, N=1385 RPM.

The paint erosion test described earlier was conducted and the propeller was removed and the pressure gages and inserts were installed. All the remaining runs were 10 minutes in duration with the discs in place, the only exception being the run with the bronze disc No. (1) which ran for 5 hours 42 minutes. Table 2 presents a list of all test conditions. Air was supplied at a pressure of 40 psia for all portions of the experiment when air was emitted. The location and the numbering scheme for the air tube pairs is shown in Figures 1 and 2.

An attempt was made to measure the surface roughness of the discs in order to quantify the erosion. The Rank Taylor Hobson Talysurf 10 surface analyzer was used in this attempt but some problems arose. One problem was that the diamond stylus used to scan the surface was so hard that it scratched the surface of the soft aluminum discs. Another problem was that the discs had a curved profile so as to match the blade contour, which made measurement more difficult. This problem could be resolved by using a stylus which measures relative roughness but this method was not attempted because of time constraints.

## EXPERIMENTAL RESULTS

Figures 10, 11 and 12 present photographic sequences of the propeller blade passing through the wake of the strut. The photographs are indicative of the type of cavitation encountered. The increment of blade position between each successive frame is 6 degrees. Figure 10 shows the cavitation with no air being emitted. Figure 11 shows a sequence with all 5 pairs of tubes open at the maximum air flow rate. Figure 12 shows the same tubes open with somewhat reduced air flow. Although the flow rate measuring equipment was not completely suitable for the test, the maximum air flow rate measured with all tubes open was approximately 5.1 $ft^3$/min (0.144 $m^3$/min). The reduced air flow rate with all tubes open was approximately 2.5 $ft^3$/min (0.071 $m^3$/min).

Photographs of the 11 discs used during the experiment are presented in Figure 13. Test conditions are described for each disc. Any further references to the discs will be by the numbers assigned to them in the photographs.

The damage to discs 2, 6 and 7 illustrates the intensity of the impact that the blades were experiencing with no air being injected. These discs showed larger and more pits than any of the discs for which air was injected into the flow. Disc 2 was used in the first successful run without air injection. Disc 6 was run to determine if the increased air content (76%) of the tunnel water, caused by several runs with air injection conducted previously, was affecting the amount of damage experienced by the blades. Disc 6 showed somewhat less damage than disc 2 so the tunnel was deaerated to an air content value of 45% and disc 7 was run. No difference in the amount of damage could be detected between discs 6 and 7 (before and after deaeration, respectively.)

Disc 3 was tested with air injected from all five pairs of tubes. There was a large reduction in damage to the disc as compared to those discs tested without air injection (discs 2, 6 and 7.) This result followed with discs 4, 5 and 8 through 11. All discs for which air was injected into the flow, showed considerably less damage than those tested without air injection.

When it was determined that the injection of air did reduce the damage to the blades, runs were conducted in which air was emitted from the various tube locations. Runs were conducted with air emitted from tubes 1, 3, 4 and 5 at the maximum air flow rate and also from tube 4 at a reduced flow rate (see Table 2 for run sequence.) No tests were run with tube number 2 because of a shortage of test time.

The runs with air injected from tubes 1, 3 and 5 (discs 4, 5 and 8, respectively,) yielded almost identical results. Damage to the discs was less than that experienced by the discs without air injection but was more than the damage that occurred when all five tube pairs were opened. Disc 5 showed slightly less damage than discs 4 or 8 but still not as little damage as disc 3. The disc for which air was injected from tube 4 (disc 9) showed a reduction in damage compared to disc 3. A repeat run was made (disc 11) which yielded the same results. The disc for which air was injected from tube 4 at a reduced flow rate (disc 10) showed approximately the same amount of damage as discs 4, 5 and 8.

Table 3 presents data collected after examining the sequential photographs of Figures 10, 11 and 12. Figure 14 presents this same data as sequential sketches of the blade as the cavity passes over the blade. Table 3 and Figure 14 show that the discs are fully covered by the cavity in frames 10 through 13 and partially covered in frames 9 and 14. It can also be seen that during this period of time air emitted from tube 2, 3, 4 and 5 impinges on the cavity. When the cavity is visible but not covering the discs,air from tubes 1, 2, 3 and 4 impinges on the cavity both before and while the cavity covers the disc, and does so for the longest period of time as shown in Table 3. This is significant because discs 9 and 11 (air injected from tube 4) exhibited the least amount of damage. Thus it would appear that it is important that air get into the cavity both before and while the cavity covers the disc (or area of maximum erosion). The damage exhibited by discs 4 and 8, (air injected from tubes 1 and 5 respectively) reinforces this observation. The air injected for these discs entered the cavity either before or while the cavity covered the disc. When these discs are compared to discs 5, 9 and 11, for which air was injected into the cavity both before and while the cavity covered the discs, they showed slightly more damage.

Figure 9 presents a photograph of the bronze disc in the propeller after running 5 hours and 42 minutes without air injection. The blade had been polished before this run. The intensity of the cavity collapse is illustrated by the erosion of not only the disc but also the blade. The location and size of the erosion pattern formed on the blade (Figure 9) matches the erosion pattern formed during the paint erosion portion of the experiment (Figure 8).

## CONCLUSIONS

Experiments which measured the relative damage to discs on the surface of a propeller blade operating in a nonuniform wake under cavitating conditions are described. The conclusions that can be drawn from the results are as follows:

1. The cavitation erosion damage to a propeller blade can be reduced considerably by injecting air into the flow ahead of the propeller.
2. It appears that the air must be emitted from a point, or points, such that it will enter the cavity both before and while the cavity is at the area of maximum blade erosion to achieve the greatest reduction in blade erosion.
3. For the two rates of air flow used in the experiments, the greater rate caused a greater reduction in erosion.

## RECOMMENDATIONS

These experiments are a first step in determining the feasibility of injecting air ahead of a cavitating propeller to reduce blade erosion. Through the problems and successes encountered during these experiments, the authors feel they have gained some insight into the improvements and techniques which can be employed in future experimentation and also the path this experimentation might take. The recommendations, not necessarily in order of importance, are as follows:

1. Develop a procedure for using the Talysurf to obtain quantitative measurements of erosion. If this is not possible, other methods should be investigated.
2. Determine the relationship between the amount of air injected and the amount of erosion for a wider range of flow ratios.
3. Determine the location of air injection that will result in the optimum blade protection.
4. Develop a method to observe erosion and determine the extent of protection over the whole area of the blade subject to erosion damage.
5. Develop a method of measuring the cavity collapse pressures on the blade surface.

This list of recommendations is not intended to be all inclusive. The list contains only those recommendations which may answer some of the important questions that the experiment brought to light.

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## TABLE 1 - PROPELLER 4123 GEOMETRY

Number of blades = 2

EAR = 0.286

Diameter = 24 inches (0.61 m)

Hub diameter = 4.8 inches (0.122 m)

Propeller material = manganese bronze

Projected skew angle = 0

Rake = 0
For all blade sections
Camber = 0

Thickness distribution NACA 66 (MOD)

| r/R | P/D | c/D | t/c |
|---|---|---|---|
| 0.2 | 0.802 | 0.237 | 0.200 |
| 0.3 | 0.804 | 0.269 | 0.156 |
| 0.4 | 0.805 | 0.297 | 0.123 |
| 0.5 | 0.805 | 0.319 | 0.098 |
| 0.6 | 0.804 | 0.334 | 0.077 |
| 0.7 | 0.804 | 0.339 | 0.060 |
| 0.8 | 0.803 | 0.322 | 0.047 |
| 0.9 | 0.803 | 0.258 | 0.037 |
| 0.95 | 0.804 | 0.191 | 0.036 |
| 1.0 | 0.805 | 0.0 | --- |

## TABLE 2 - LIST OF TEST CONDITIONS

### Table 2A - Tunnel Test Conditions For All Runs

Tunnel Centerline Pressure = 21.00 psia (144.8 kPa)

Tunnel Velocity = 30.7 ft/sec (9.36 m/sec)

Propeller RPM = 1385

$R_n$ @ 0.7R = $6.822 \times 10^6$

Local Cavitation No. @ 0.7R, $\sigma_{0.7} = 0.27$

Cavitation No., $\sigma = 3.21$

Torque = 239 ft-lb (324 N-m)

Thrust = 742 lb (3301 N)

$K_Q = 0.0072$

$K_T = 0.045$

$J = 0.665$

$\eta_o = 0.661$

TABLE 2B - TUNNEL TEST CONDITIONS FOR INDIVIDUAL RUNS

| Disc No. | Run No. | Run Time, Minutes | Disc Material | Air Flow Rate | Open Tube No. | Comments |
|---|---|---|---|---|---|---|
| 1 | 3 | 342 | Phosphor Bronze | Zero | None | Photography run |
| 2 | 1 | 10 | Aluminum | Zero | None | |
| 3 | 2 | 10 | Aluminum | Maximum | 1,2,3,4,5 | |
| 4 | 4 | 10 | Aluminum | Maximum | 1 | |
| 5 | 5 | 10 | Aluminum | Maximum | 3 | |
| 6 | 6 | 10 | Aluminum | Zero | None | Run prior to deaeration, air content = 45% |
| 7 | 7 | 10 | Aluminum | Zero | None | Run after deaeration, air content = 45 percent |
| 8 | 8 | 10 | Aluminum | Maximum | 5 | |
| 9 | 9 | 10 | Aluminum | Maximum | 4 | |
| 10 | 10 | 10 | Aluminum | Reduced | 4 | |
| 11 | 11 | 10 | Aluminum | Maximum | 4 | |

TABLE 3 - DESCRIPTION OF AIR IMPINGEMENT AND CAVITY LOCATION FROM SEQUENTIAL PHOTOGRAPHS OF PROPELLER UNDERWAY

| Frame No. | Air Impinges on Cavity? x Yes - No | | | | | Cavity Covers Disc? |
|---|---|---|---|---|---|---|
| | Tube 1 | Tube 2 | Tube 3 | Tube 4 | Tube 5 | |
| 1 | - | - | - | - | - | - |
| 2 | - | - | - | - | - | - |
| 3 | x | - | - | - | - | - |
| 4 | - | x | - | - | - | - |
| 5 | - | x | x | - | - | - |
| 6 | - | x | x | x | - | - |
| 7 | - | - | x | x | - | - |
| 8 | - | - | x | x | - | - |
| 9 | - | - | x | x | x | Partially |
| 10 | - | x | x | x | x | yes |
| 11 | - | - | - | x | x | yes |
| 12 | - | - | x | x | x | yes |
| 13 | - | - | - | x | x | yes |
| 14 | - | - | - | - | x | Partially |
| 15 | - | - | - | - | x | - |
| 16 | - | - | - | - | - | - |
| 17 | - | - | - | - | - | - |
| 18 | - | - | - | - | - | - |
| 19 | - | - | - | - | - | - |
| 20 | - | - | - | - | - | - |

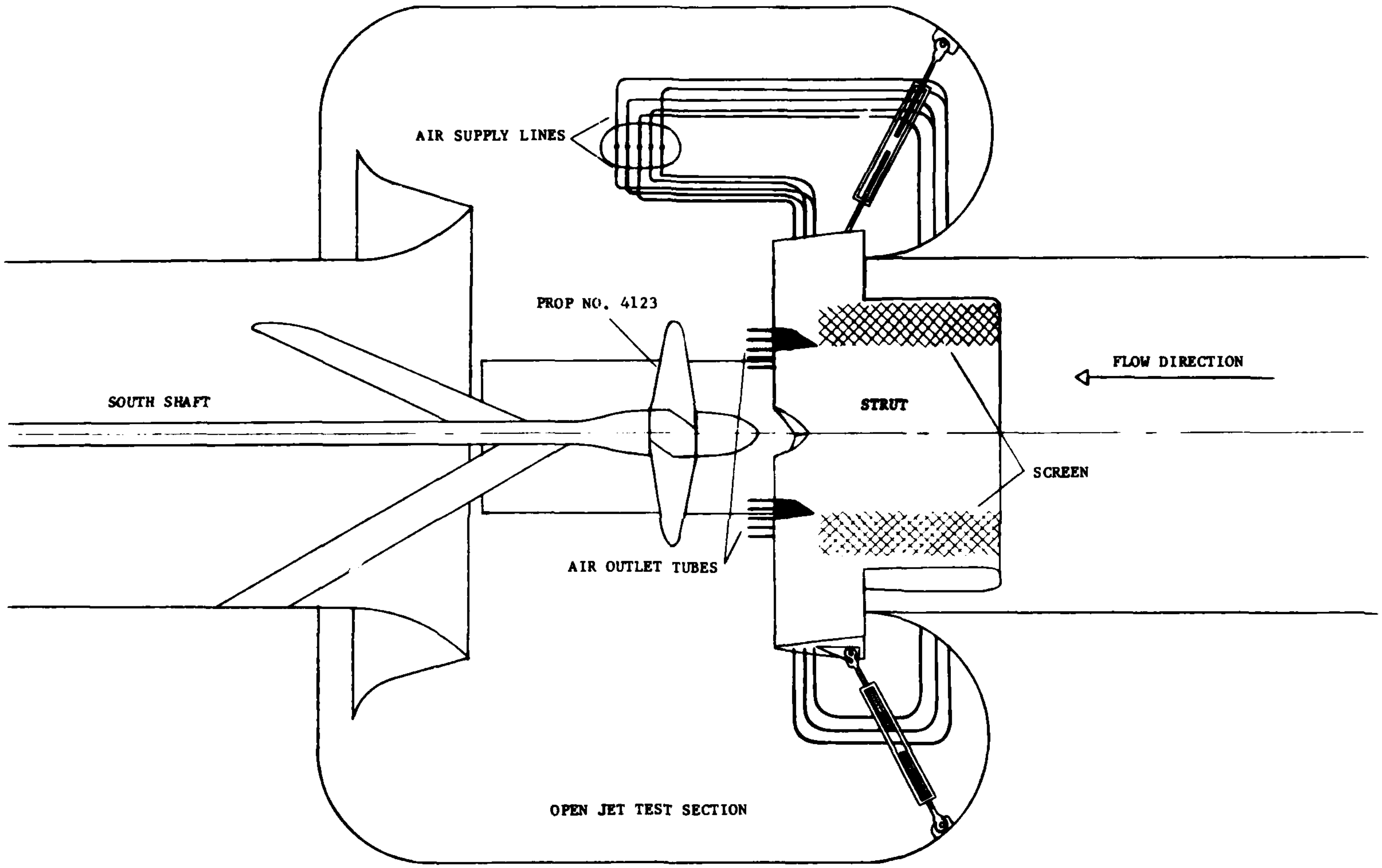



Figure 1 - Sketch of the 36-Inch Water Tunnel Open Jet Test Section With the Strut, Air supply System and Propeller Installed

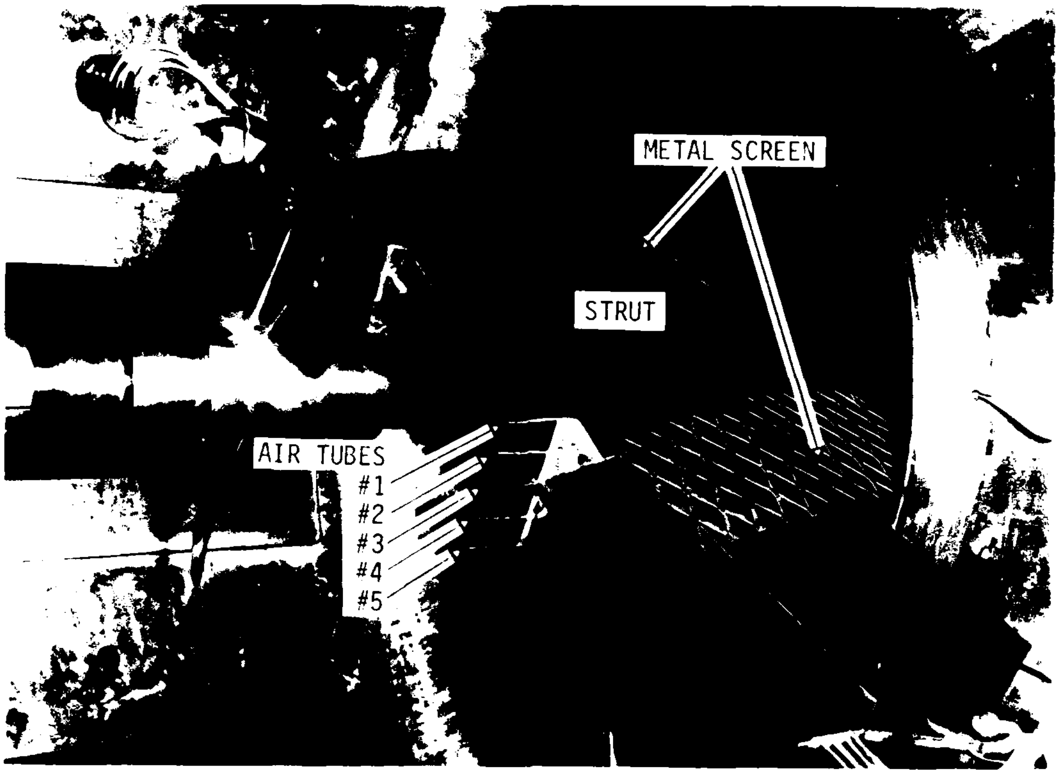



Figure 2 - Photograph of the 36-Inch Water Tunnel Open Jet Test Section With the Strut, Air Supply System and Propeller Installed

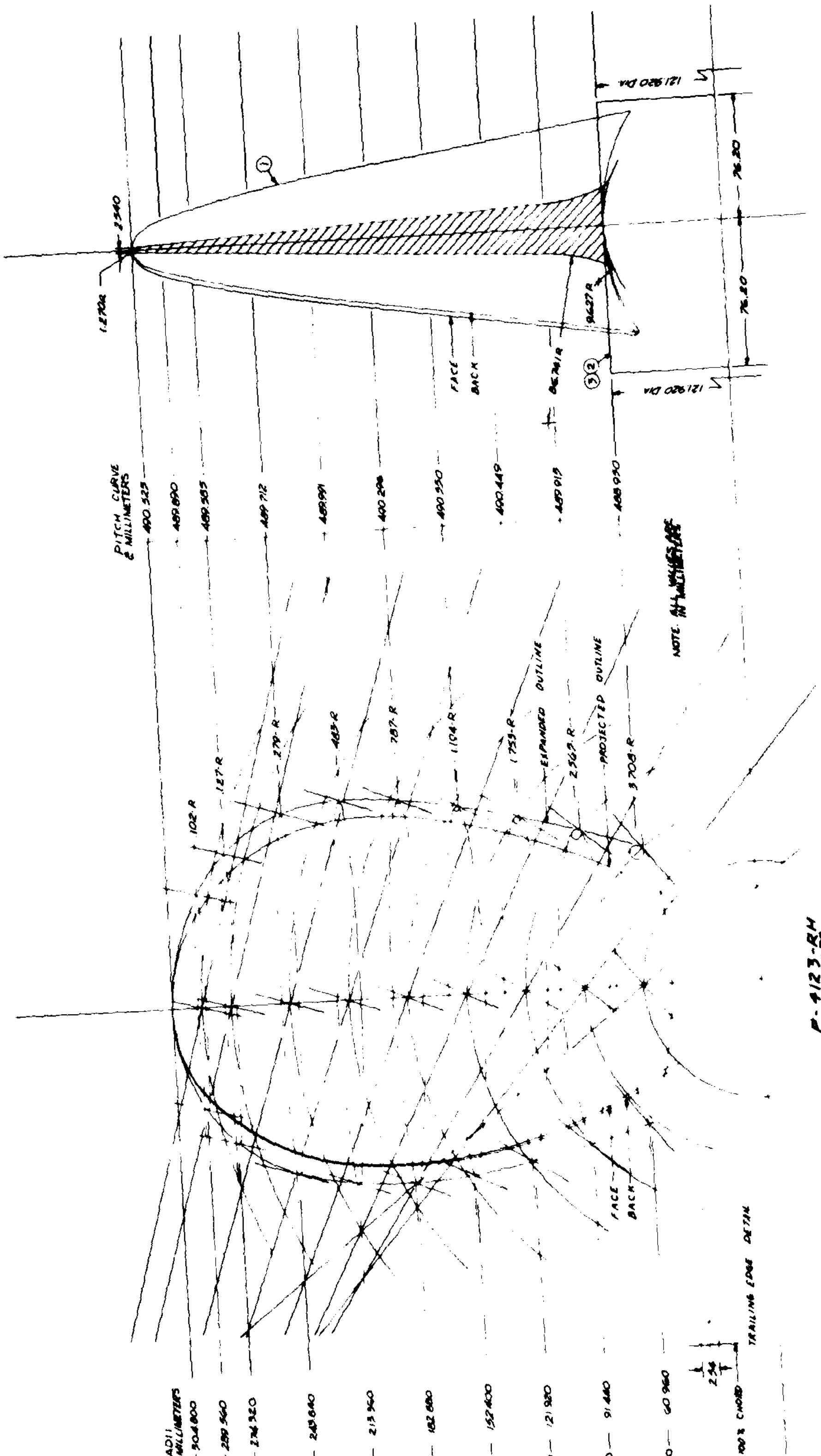
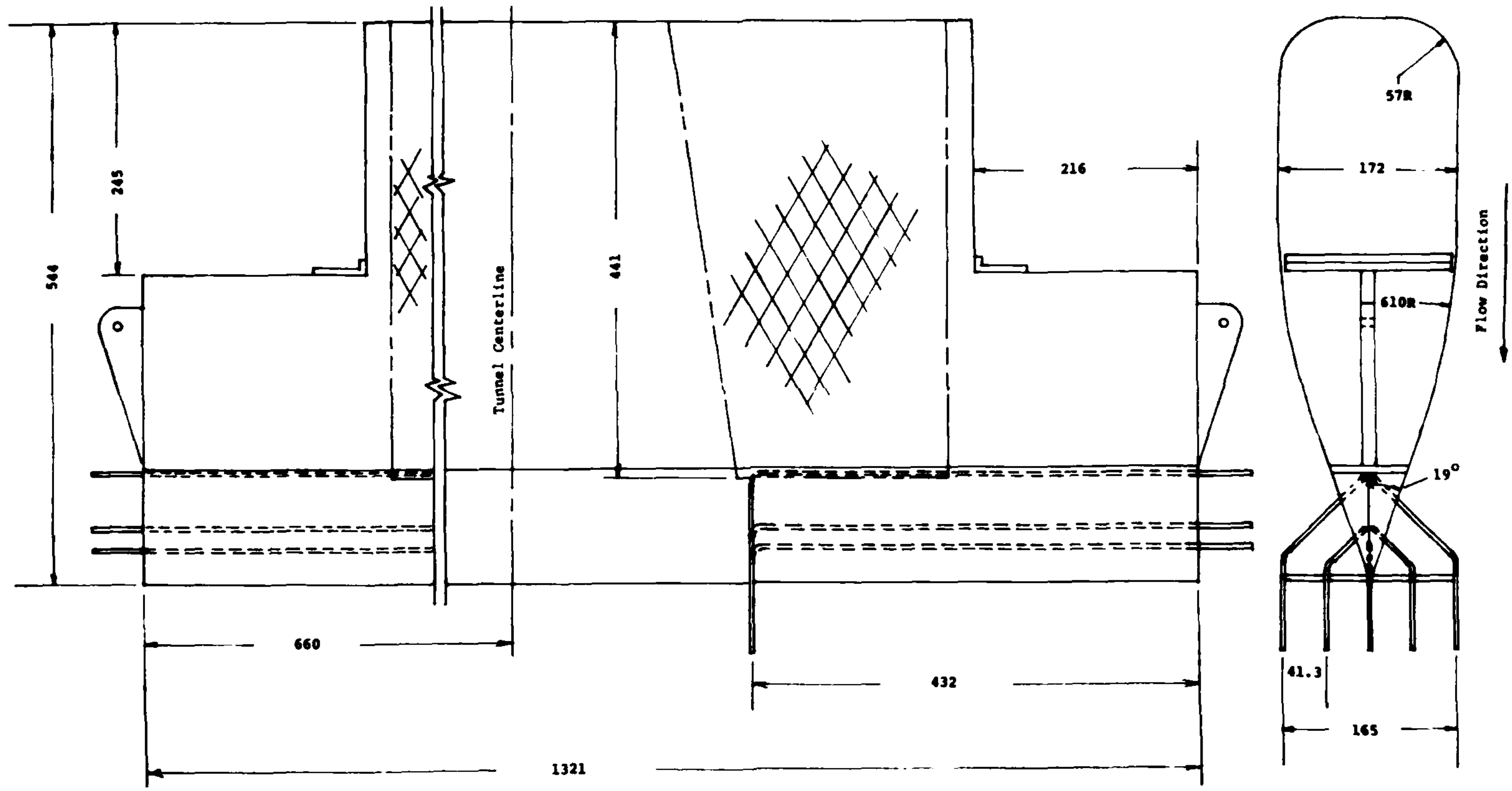



Figure 3 - Drawing of Propeller 4123


Figure 4 - Photograph of Propeller 4123




NOTE: All Dimensions are in Millimeters

Figure 5 - Drawing of the Strut

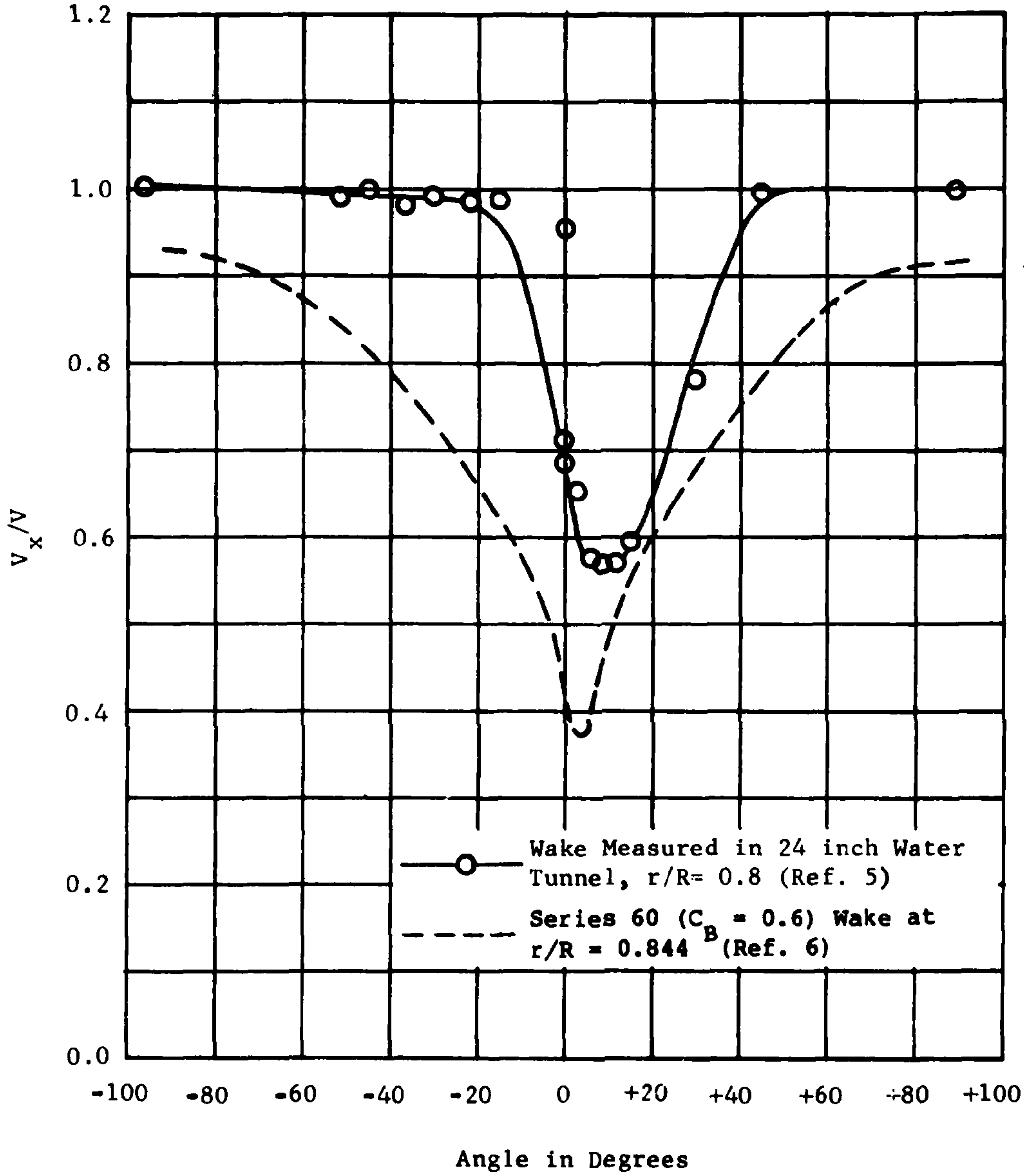



Figure 6 - Comparison of the Circumferential Distribution of Longitudinal Velocity Ratios of a Series 60 Model Hull at r/R = 0.844 and the 24-Inch Water Tunnel Model of the Strut at r/R = 0.8

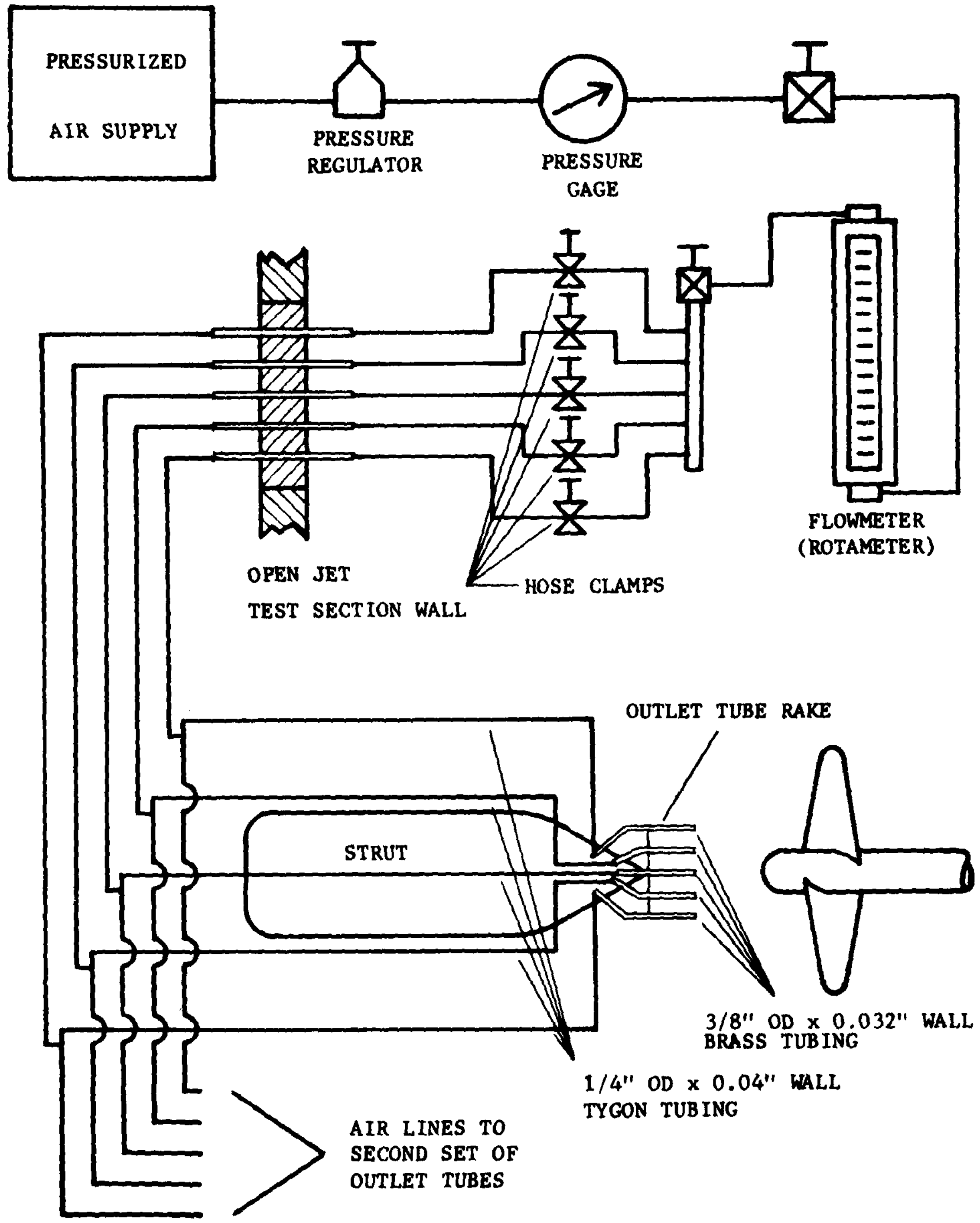



Figure 7 - Schematic of Air Supply System


Figure 8 - Photograph of the Suction Side of the Propeller Blade After the Paint Erosion Test


Figure 9 - Photograph of the Suction Side of the Propeller Blade With Bronze Disc After 5 Hours and 42 Minutes of Run Time


Figure 10 - Sequential Photographs of the Propeller Blade Passing Through the Strut Wake

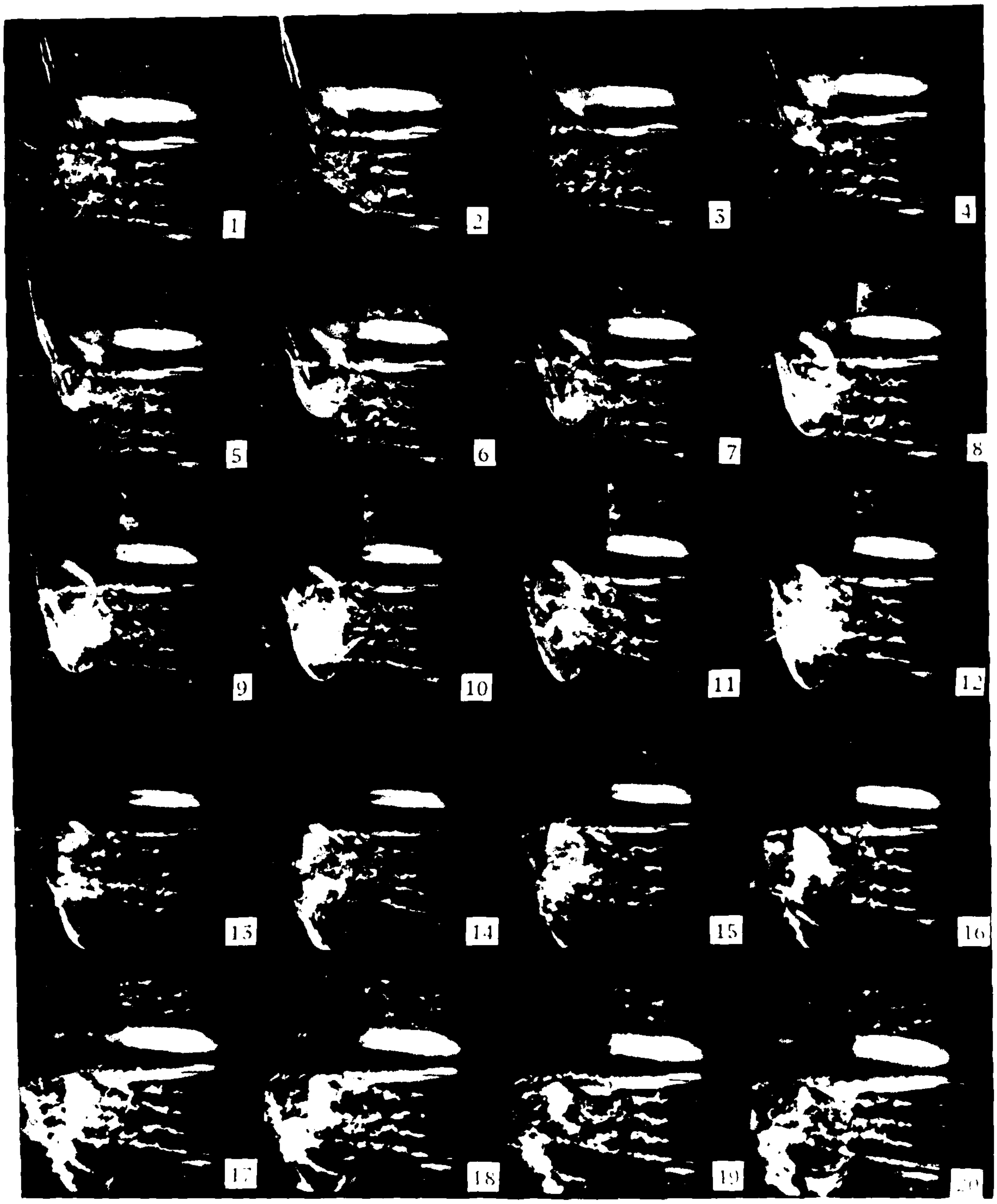
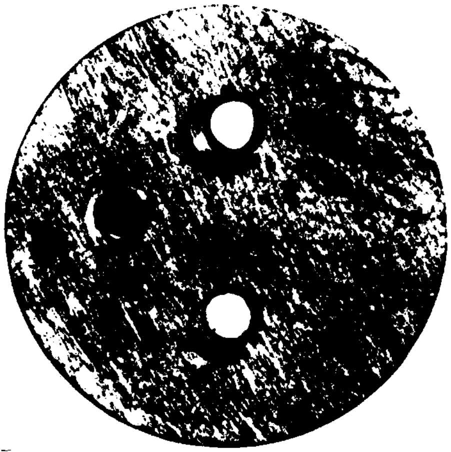
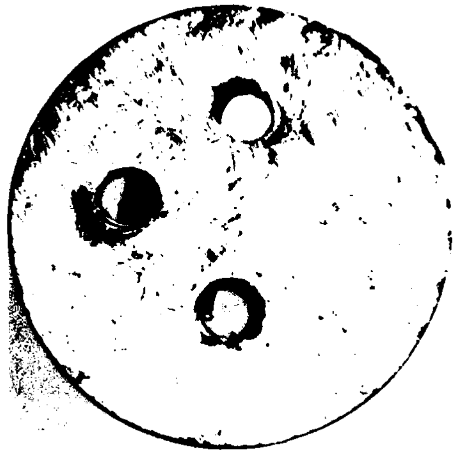



Figure 11 - Sequential Photographs of the Propeller Blade Passing Through the Strut Wake With the Maximum Air Flow Emitted From All Five Tube Pairs

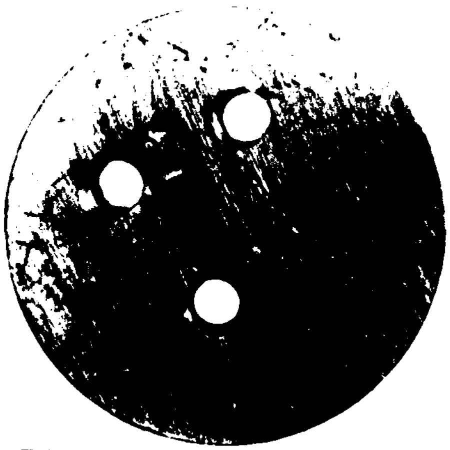

Figure 12 - Sequential Photographs of the Propeller Blade Passing Through the Strut Wake With the Reduced Air Flow Emitted From All Five Tube Pairs



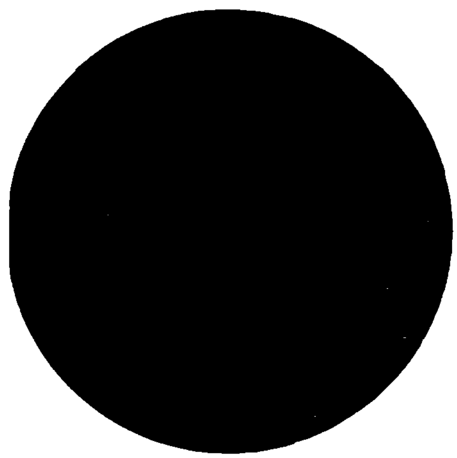
Disc No.9, Tube No.4



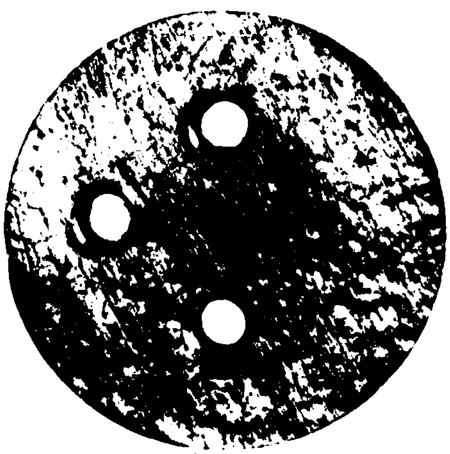
Disc No.8, Tube No.5



Disc No.11, Tube No.4, Repeat



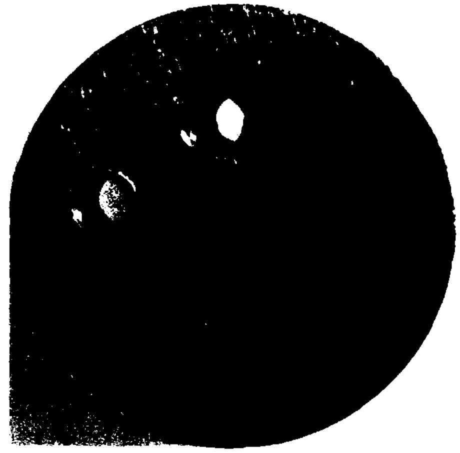
Disc No.1, Bronze, Without Air
5 hours,42 minutes (≈186,000 cycles)



Disc No.10, Tube No.4 Reduced Air

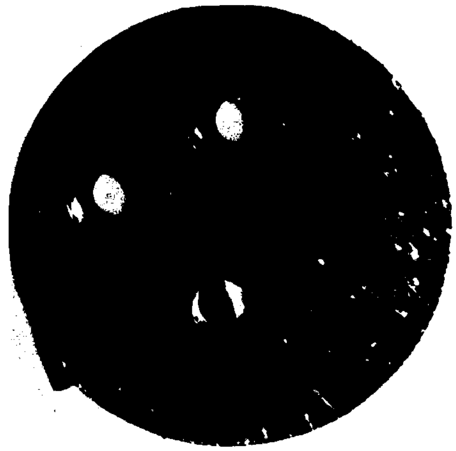
**Figure 13 - Photographs of the Discs Used During the Experiment**

Disc No.2, No Air

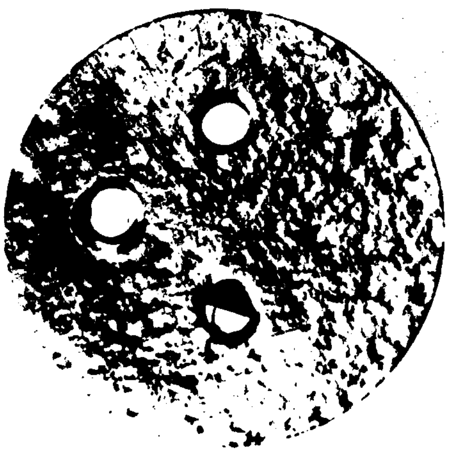


Disc No.3, All Five Tubes

Disc No.6, No Air, Air Content = 76%



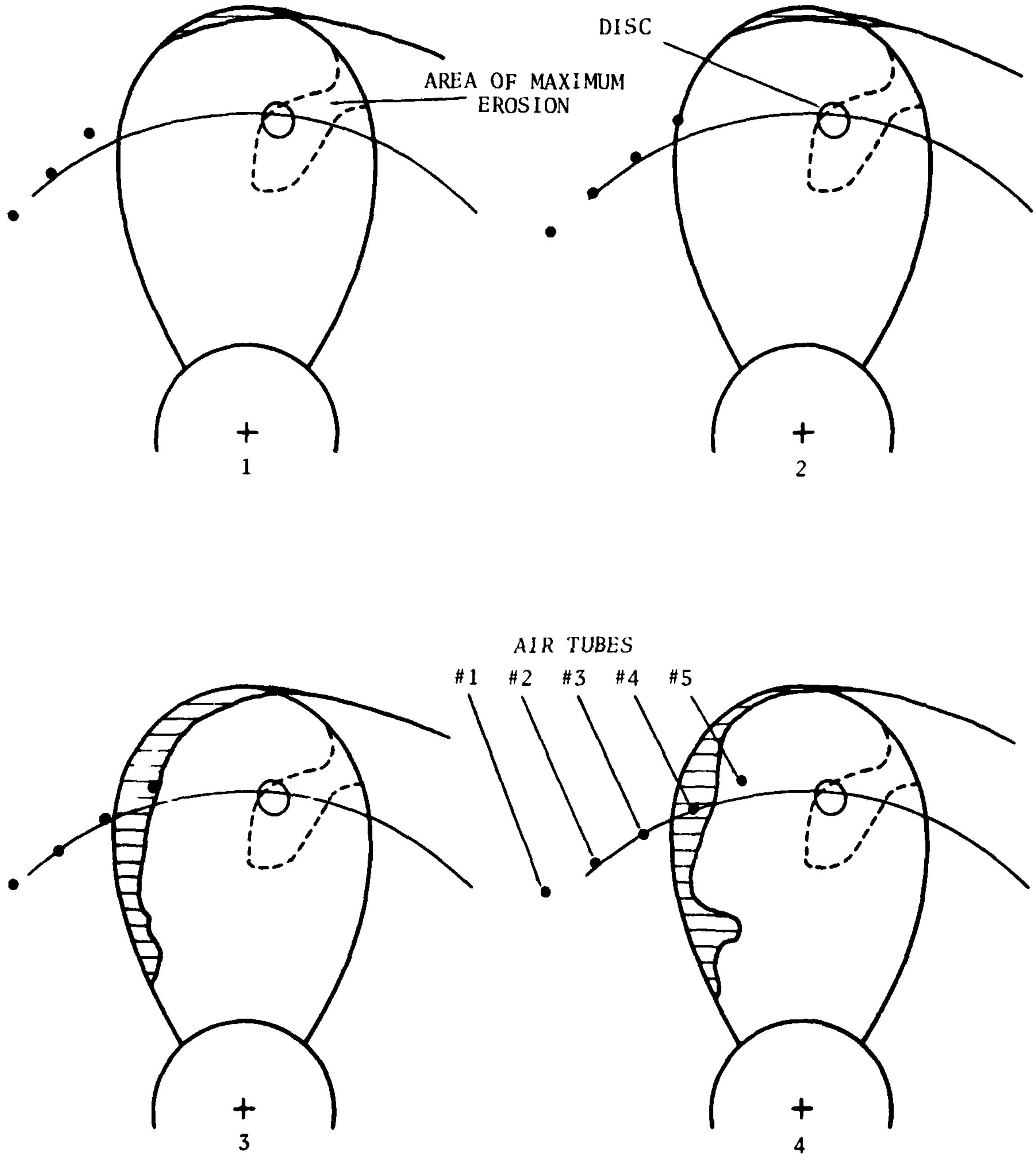
Disc No.4, Tube No.1



Disc No.7, No Air, Air Content = 45%

Disc No.5, Tube No.3

Figure 13 - (Continued)




NOTE: Areas filled with horizontal lines denote cavity sheets.
Areas filled with diagonal lines denote cloud or bubble cavitation.

Figure 14 - Sequential Sketches of the Cavity Passing over the Propeller Blade

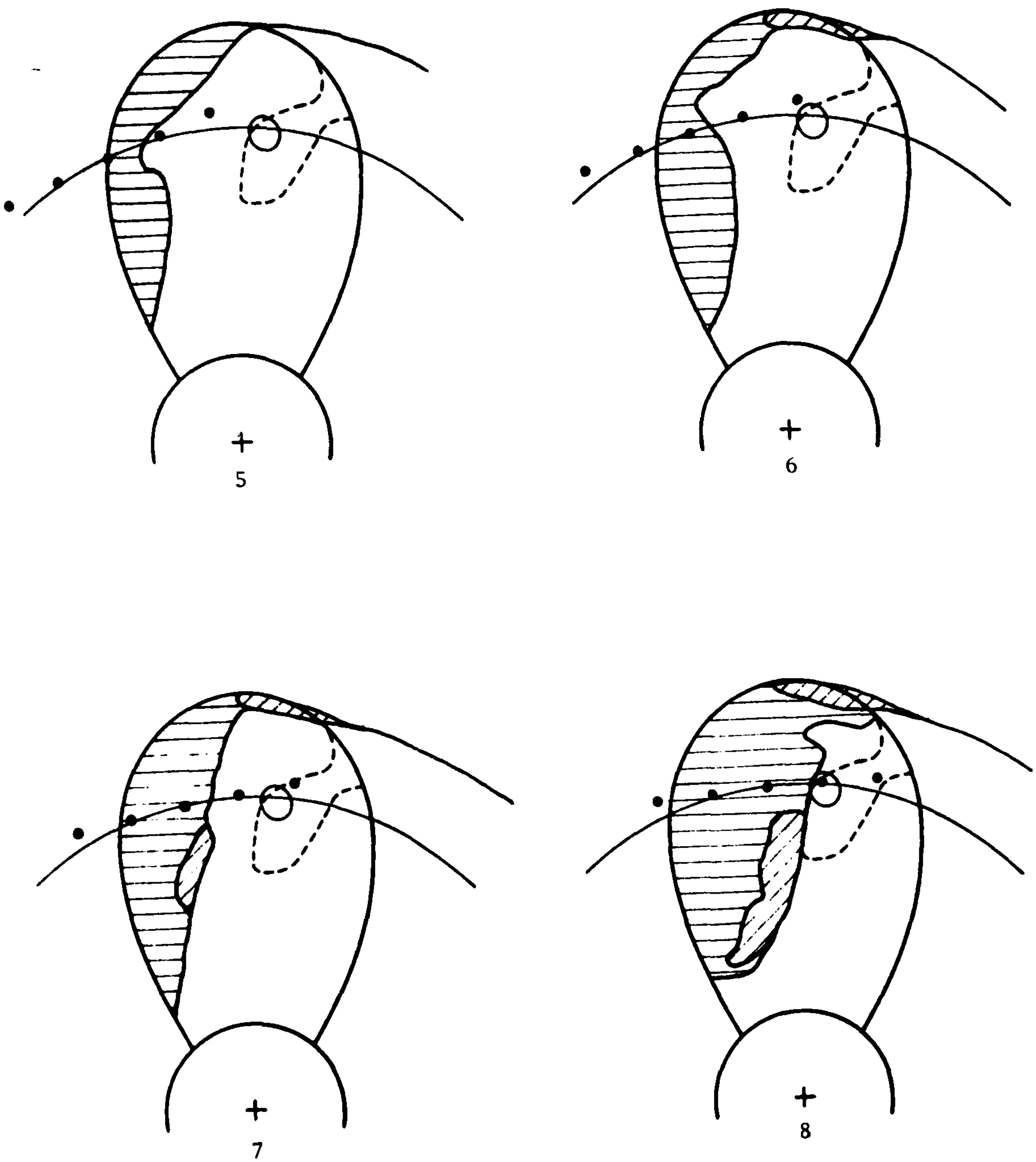



Figure 14 - (Continued)

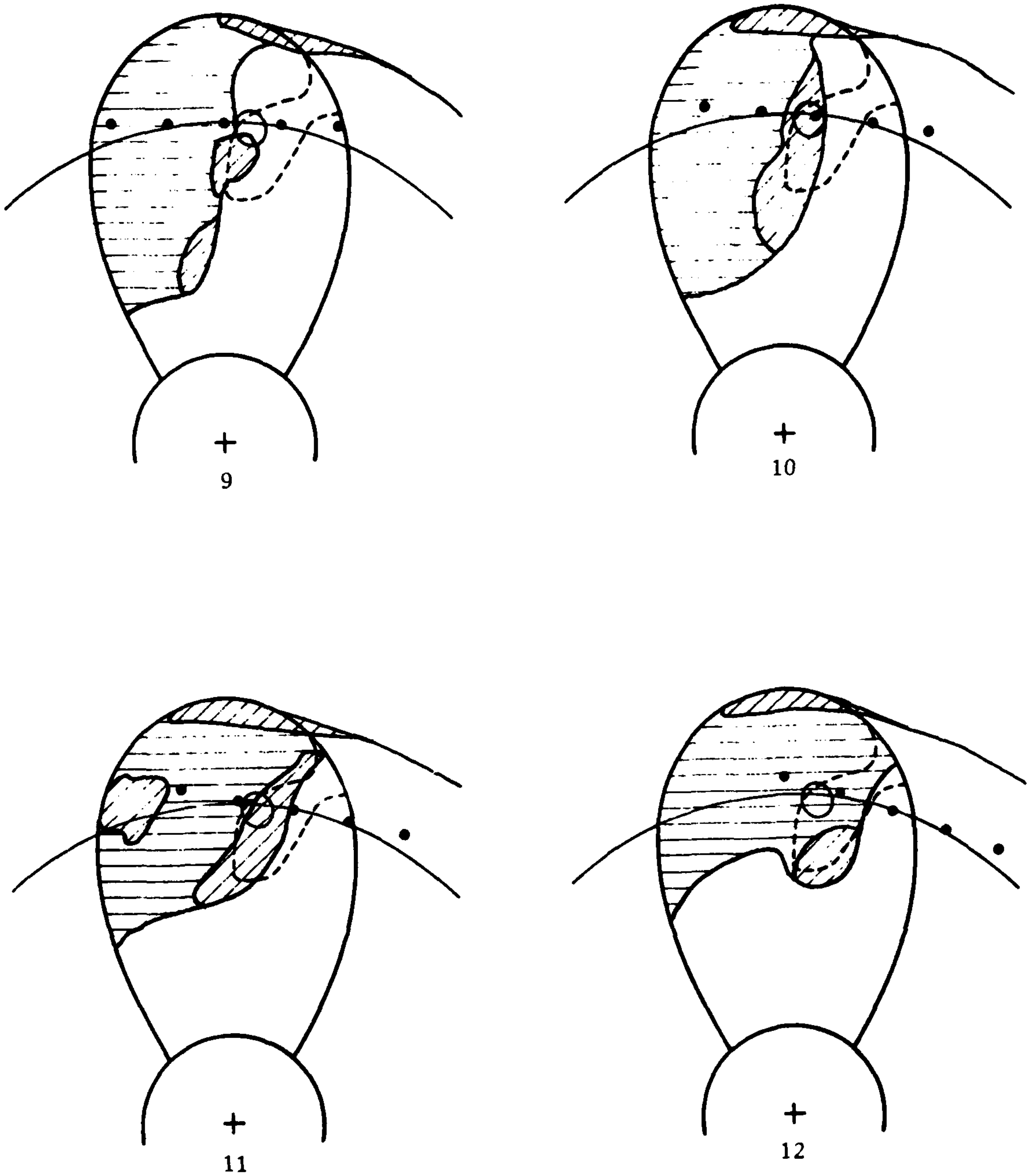



Figure 14 - (Continued)

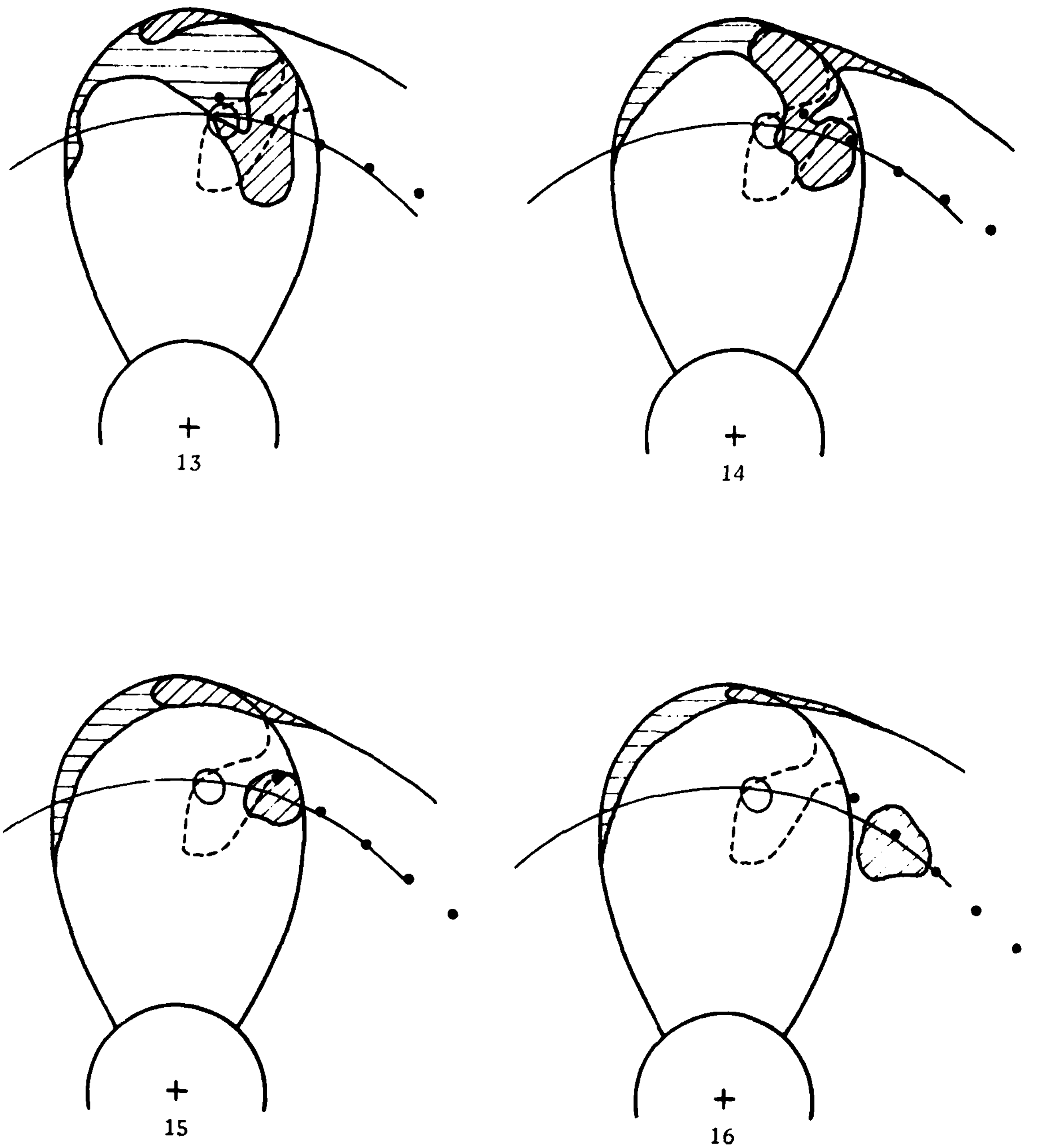



Figure 14 - (Continued)

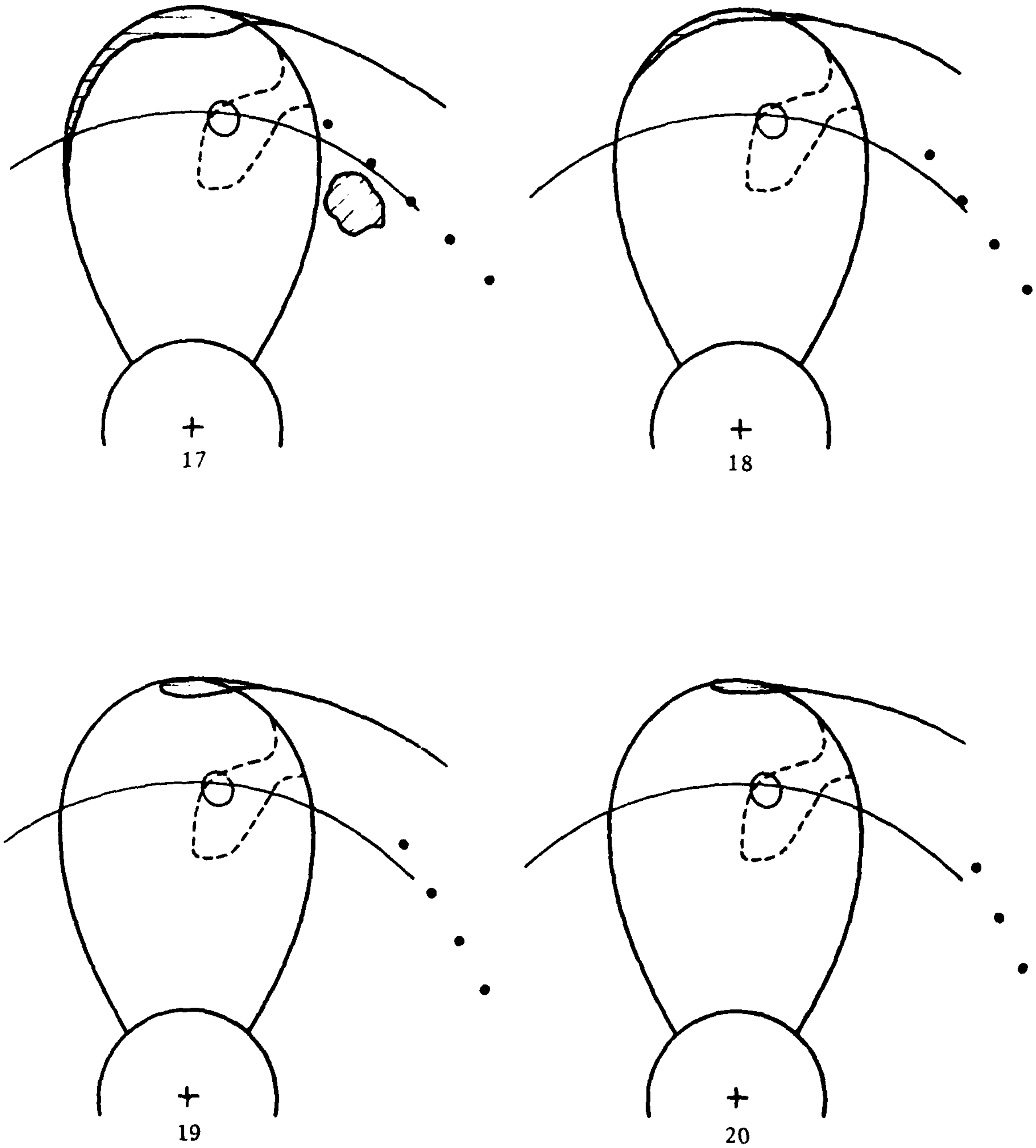



Figure 14 - (Continued)