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Report 1487

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DAVID TAYLOR MODEL BASIN

POWERING PERFORMANCE OF A VENTILATED PROPELLER

by

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HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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NOTATION

A	Area, (Chord times unit span)
C_L	Lift Coefficient, $\left(\frac{L}{\frac{1}{2} \rho V^2 A} \right)$
D	Propeller Diameter
e	Efficiency, $\left(\frac{T V}{2 \pi Q N} \right)$
J	Speed coefficient, $\left(\frac{V}{n D} \right)$
K_q	Torque coefficient, $\left(\frac{Q}{\rho n^3 D^5} \right)$
K_t	Thrust coefficient, $\left(\frac{T}{\rho n^3 D^4} \right)$
L	Lift
n	Rotational speed of propeller
P	Hydrostatic pressure (submergence)
P_a	Atmospheric pressure (pressure above water surface)
P_v	Vapor pressure
P_c	Cavity pressure
Q	Torque
Q_g	Volume flow rate of gas supplied for ventilation
Re	Reynolds number
T	Thrust
V	Speed of advance

ρ Mass density

σ_C Cavitation index based on cavity pressure, $\left(\frac{P_a + P - P_c}{\frac{1}{2} \rho V^2} \right)$

σ Cavitation index based on vapor pressure, $\left(\frac{P_a + P - P_v}{\frac{1}{2} \rho V^2} \right)$

ABSTRACT

In an effort to achieve supercavitating performance at relatively low speeds, ventilation of an SC propeller was investigated. Tests were run with a two-bladed SC propeller ventilated through holes in the propeller blades.

The results of the tests show that ventilated propellers operate with a fully developed cavity at speeds too low for supercavitating operation. Powering performance was found to be dependent upon the cavitation index based on cavity pressure.

INTRODUCTION

Supercavitating propellers, which are desirable for high-speed vessels, may also be of interest in a speed range too low for supercavitating operation. In this speed range (20-40 knots), conventional propellers usually cavitate with a resultant thrust breakdown. Therefore, to have good propeller performance in this speed range, it is desirable to have a fully cavitating SC propeller. Ventilation, i.e., the continuous introduction of a gas into the propeller cavity, is one method of producing a fully developed cavity at relatively low speeds.

In order to keep the cavity ventilated, air which is lost from the cavity into the stream must be continually replaced. Some basic studies have been made on the air loss from the cavity behind a flat disc perpendicular to the flow.^{1,2,3} For the disc it has been found that once trailing vortices appear, it is impossible to supply enough air to make any further increase in the cavity pressure. Some studies have also been

¹ References are listed on page 10

made on ventilated foils operating near a free surface.^{4,5} The foils were ventilated when their trailing-vortices reached the surface and thus no air flow measurements were taken. The tests of both the disc and the foils show that trailing vortices provide a funnel through which large quantities of air will flow. Since propellers also have trailing vortices it is likely that a large amount of air will flow through the vortex tubes. Due to restrictions in the supply piping the air that can be supplied to the propeller is limited and hence the air should be judiciously distributed on the blade.

In order to investigate the problems associated with ventilating a supercavitating propeller, a research program was initiated at the David Taylor Model Basin under SR 009 01 01. During the initial investigations the powering performance of a two-bladed SC propeller with flat-faced sections was studied. This report presents the results of the initial phase, specifically the powering performance of the ventilated propeller for conditions of a fully developed cavity. Ventilation is shown to lower the speed at which a fully developed cavity occurs. Correlation of the performance of SC and ventilating propellers has been found through the cavitation index.

DESCRIPTION OF PROPELLER

The SC propeller used for this investigation was TMB propeller 3671A (Figure 1) altered for ventilation by putting holes in the blades. This propeller was specifically designed to produce a large cavity, therefore the propeller sections chosen were flat-faced sections operating at high angles of attack. The method described in reference 6 was used to design this propeller utilizing lift and drag data from references 7 and 8. The section at 70 per cent radius was designed to operate at a 7-degree angle of attack with a lift coefficient of 0.21. The propeller design conditions were: a thrust coefficient of 0.039, a speed coefficient of 0.75, an efficiency of 41.7 per cent, and a cavitation index of 0.4. The low design efficiency, which is characteristic of flat-faced sections operating at high angles of attack, was accepted so that the model propeller would

cavitate fully at the speeds obtainable with the test equipment. Table 1 gives the physical characteristics of the propeller.

TABLE 1
Physical Characteristics of Propeller 3671-A

Number of Blades	2
Exp. Area Ratio	0.154
MWR	0.173
BTF	0.055
P/D(At 0.7R)	1.500
Diameter	14.000 in.
Pitch (At 0.7R)	21.000 in.
Rotation	R.H

Since there was no information available concerning the effect of the location of the holes on ventilation, the hole positions were chosen arbitrarily. Hole 1 was located as near the tip of the propeller as possible in order to ventilate the tip vortex. Hole 2, which was larger than hole 1, was placed near the hub and towards the trailing edge of the blade in order to ventilate the cavity behind the blade (Figure 2).

DYNAMOMETER AND AIR SUPPLY SYSTEM

The TMB 35-horsepower dynamometer, fitted with an air supply system, was used for the tests. A schematic diagram of the air supply system is shown in Figure 3. Calibrations of the thrust and torque elements were made in order to insure that there were no errors in these measurements due to the air seal.

The calibrations for determining cavity pressure (P_3) were made with the propeller blades exhausting air into the atmosphere. The atmosphere was used as an infinite cavity of known pressure. The relation between the pressure ratio (P_3/P_1) and rate of air flow (Q_g) was thus obtained. During tests and calibrations the temperature of the air varied less than

5 degrees Fahrenheit, and so no correction for temperature was made. A correction for density change and supply pressure was made to all air flow readings so that all air volumes discussed in this report are at standard conditions (NTP).

TEST PROCEDURES

The propeller was first tested in the TMB 24-inch variable pressure water tunnel. These tests were run at 40 fps and the rpm and tunnel pressure were varied to obtain the desired speed coefficient J and cavitation index σ . During the tunnel tests the propeller rpm was varied from 1400 to 3000 rpm and the pressure at the propeller shaft centerline was varied from 4 to 38 feet of water.

The ventilated tests were then performed in the TMB high-speed basin. In the basin the pressure at the shaft centerline was fixed at 38 feet of water. The forward speed was varied from 10 to 26 fps and the rpm from 900-1800 rpm. During all tests the Reynolds number was greater than 1×10^6 .

Table 2 summarizes the tests reported herein.

During the ventilated tests the air temperature (t), air flow (Q_g), and metering pressure (p_1) were measured. The cavity pressure was then obtained from the calibrations shown in Figure 3. Determination of the cavity pressure in this way is reliable only if there is no critical flow (choking) anywhere in the system. Therefore, in order to obtain reliable values of cavity pressure, care was taken during the tests to avoid critical flow.

As an aid in running the tests, Polaroid photographs were taken during each run and developed immediately. These pictures were often used as a guide during the later tests. Still photographs were also taken to aid in analyzing data.

TABLE 2

Test Conditions

Figure	Symbol	Test Facility	Type of Test	J	σ	Hole Condition
5		24" VPWT	Non-ventilating (used as standard test for comparison)	Const.	vary	1 & 2 Plugged
4, 5, 6		High-Speed Basin	Non-ventilating	Const.	vary	1 & 2 Plugged
5, 6		High-Speed Basin	Ventilating	Const.	vary	1 - open 2 - Plugged
4, 5, 6		High-Speed Basin	Ventilating	Const.	vary	1 - open 2 - open
5		High-Speed Basin	Ventilating	Const.	vary	1 - open 2 - open
7		High-Speed Basin	Ventilating	Const.	vary	1 - open 2 - open
7		High-Speed Basin	Ventilating	Const.	vary	1 - open 2 - open
7		High-Speed Basin	Ventilating	Const.	vary	--
8		Open Water	Non-cavitating	vary	--	1 & 2 Plugged
8		24" VPWT	Non-ventilating	vary	Const.	1 & 2 Plugged
8		High-Speed Basin	Compiled from all ventilated tests	vary	Const.	--

RESULTS AND DISCUSSION

The effect of ventilation on propeller cavity formation is shown in Figure 4. From this figure the cavity formation with and without air at 8, 10, and 12 knots can be compared. The effectiveness of ventilation in producing a full cavity at speeds below 12 knots is quite apparent. At speeds above 12 knots the propeller has a fully developed cavity without ventilation.

A composite plot of the powering performance at design J is given in Figure 5. Included in this figure are the data obtained previously from tests in the 24-inch water tunnel. The scatter of the ventilated test data is believed to be due to inaccuracies in obtaining cavity pressure. Equipment, newly developed at TMB, will provide direct measurements of the cavity pressure. This is expected to reduce the scatter of future tests.

The close agreement of the test results shows that the powering performance of supercavitating and ventilated propellers can be correlated through the cavitation index. For the ventilated condition cavity pressure is used instead of vapor pressure.

Figures 6a, b, c show the cavity formation at several speeds and air flows while operating at design J(0.75). These figures are keyed to corresponding powering performance data of Figure 5 and show that the propeller had a fully developed cavity at cavitation indices below 3.7. During this test, ventilation at all speeds above 8 knots increased the cavity pressure enough so that the propeller operated at a cavitation index less than 3.7, and hence all the ventilated data appear below this value in Figure 5.

Figure 7 shows the ventilated performance of the propeller at $J = 0.6$, $J = 0.75$ (design), and $J = 0.9$. This range of J was chosen so that all measured quantities were kept within the range of existing instrumentation. The tests show that at the lower J, where the section angle of attack is increased, ventilation will occur at higher cavitation indices. The tendency to supercavitate, and hence ventilate, at high angles of attack has been shown to occur also on hydrofoils⁷.

Figure 8 shows the performance of propeller 3671A at several σ as a function of the speed coefficient J . Data for nonventilated operation (obtained in the 24-inch water tunnel) and ventilated operation are included in the figure. The "solid" test spots are for ventilated operation. Most of the ventilated data was with air supplied at atmospheric pressure (0 psig) although some data for air supplied at 10 and 20 psig are included.

Figure 8 shows that the performance of a ventilated SC propeller is dependent upon the cavitation index based on cavity pressure. As previously mentioned the scatter of the ventilated test data is probably due to inaccuracies in the cavity pressure measurements.

Figure 8 can also be used to illustrate the effectiveness of ventilation in achieving supercavitating operation. Under the section on test procedures it was stated that the tunnel tests were run at 40 fps. For the $\sigma = 0.4$ tunnel test the net pressure at the shaft centerline was 9.95 ft of water. The ventilated data for $\sigma_c = 0.34$ was obtained in the high-speed basin at 26 fps and a pressure at the shaft centerline of 38 ft of water. These conditions would produce a σ based on vapor pressure of 3.61. The ventilation of the cavity raised the cavity pressure and caused σ_c to be reduced to 0.34.

Figure 8a is the same as Figure 8 with the test spots removed for clarity. The designed K_t of 0.39 and efficiency of 41.7 are shown on the curve. The figure shows that the propeller performed as predicted. The predicted values were calculated as shown by reference 6 with the exception that, since this propeller has flat-faced sections, the lift-drag data from reference 7 and 8 were used.

CONCLUSIONS

The data presented in this report clearly indicate the effectiveness of ventilating supercavitating propellers at low speeds to induce a fully developed cavity.

Correlation of the power performance through cavitation index (based on cavity pressures) has been obtained. In general, the air supplied to the cavity raises the cavity pressure and thus reduces the cavitation index. Hence a fully developed cavity can occur at speeds too low for supercavitating operation.

It was found that raising the supply air pressure will reduce the cavitation index as long as the mass flow of air is increased. If the supply pressure is raised too high, say above 20 psig for these tests, choking occurs in the supply system and further increasing the supply pressure does not affect the propellers. The location of the holes was not thoroughly investigated; however, it was found that unless the natural cavity enclosed the air supply hole, full ventilation did not occur.

FUTURE INVESTIGATIONS

From the information contained in this report, it has been concluded that ventilation of SC propellers is a feasible means of inducing a fully developed cavity at relatively low speeds. However, in order to gainfully apply ventilation, several aspects of ventilation must be further investigated experimentally and theoretically.

The tests reported herein show considerable scatter; this has been attributed to indirect measurement of cavity pressure. Newly developed instrumentation will provide direct measurement of the cavity pressure and hence, reduce scatter. As soon as manufacturing of this equipment is completed tests will be performed in which the cavity pressure will be measured directly.

In the present investigation it was found that the powering performance can be correlated through the cavitation index. This allows the prediction of the thrust and torque when the cavitation index is known. At this time, however, it is not possible to predict the cavitation index at which a ventilated propeller will operate since the relationship between propeller loading, air entrainment, and cavity pressure are not known.

Hence they must be obtained. Future investigations will thus consist of a theoretical study of the mechanism of air entrainment and an associated experimental study to investigate the air entrainment of simple shapes and foils*. The information thus obtained will be used to develop a design method for ventilated propellers.

* These experiments are currently being performed by the Research and Propeller Branch of the David Taylor Model Basin.

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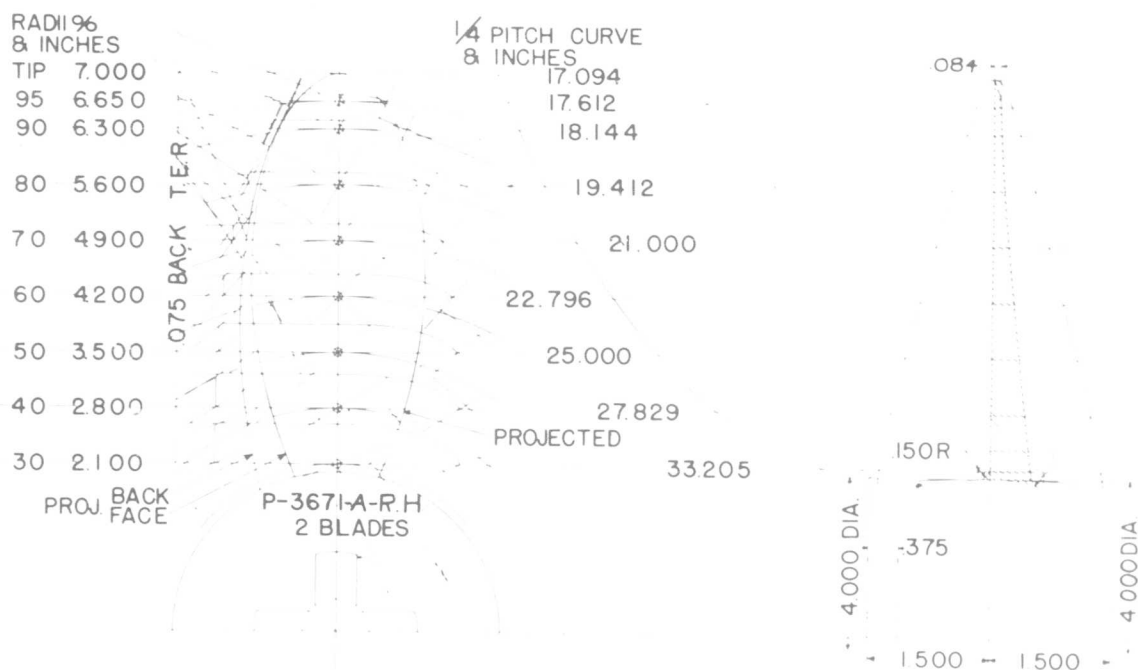
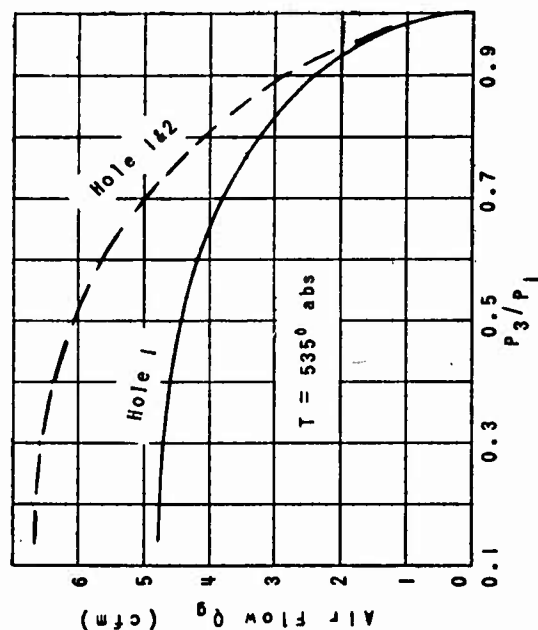


Figure 1 - Drawing of Propeller 3671A



Figure 2 - Propeller 3671A Showing the Holes in the Blades

P_1 - Supply Air Metering Pressure
 P_3 - Pressure at Holes on Propeller Blades
 (cavity pressure during tests)



AIR FLOW CALIBRATION

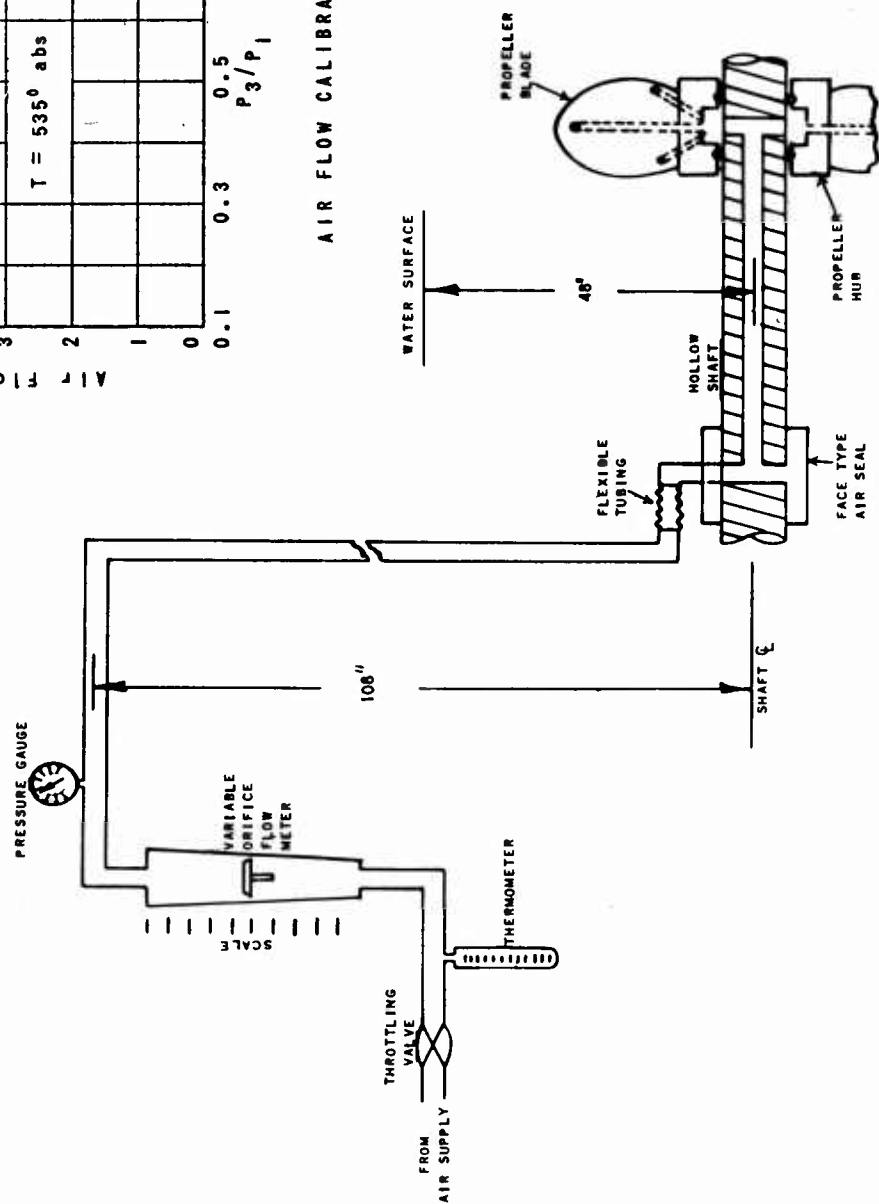
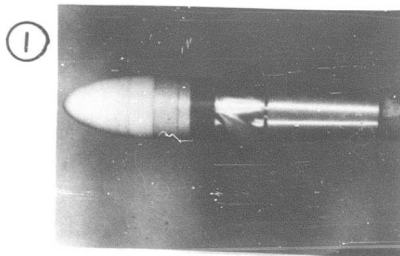
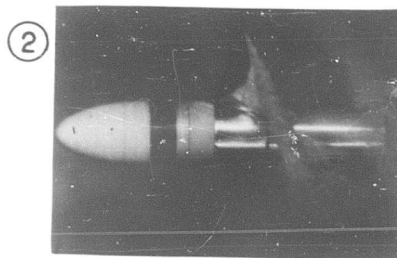


Figure 3 - Schematic Diagram of Air Supply System

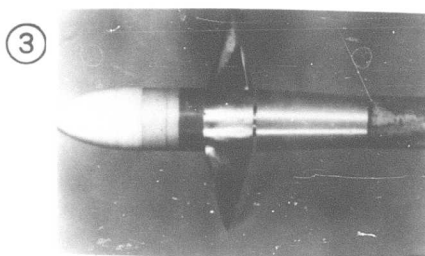


non ventilated



ventilated

$V = 8$ knots (hole 1&2; 14.7psia)
 $n = 15.4$ rps

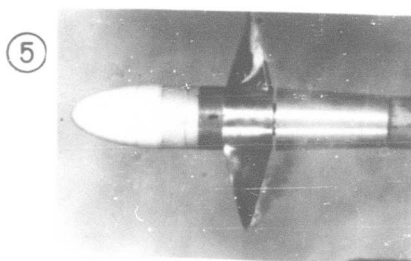


non ventilated



ventilated

$V = 10$ knots (hole 1&2; 14.7psia)
 $n = 19.5$ rps



non ventilated



ventilated

$V = 12$ knots (hole 1&2; 14.7psia)
 $n = 23.1$ rps

Figure 4 - Effect of Ventilation on Propeller Cavity Formation at Design J (0.75)

. Circled Numbers Correspond To Photographs In Figure 6

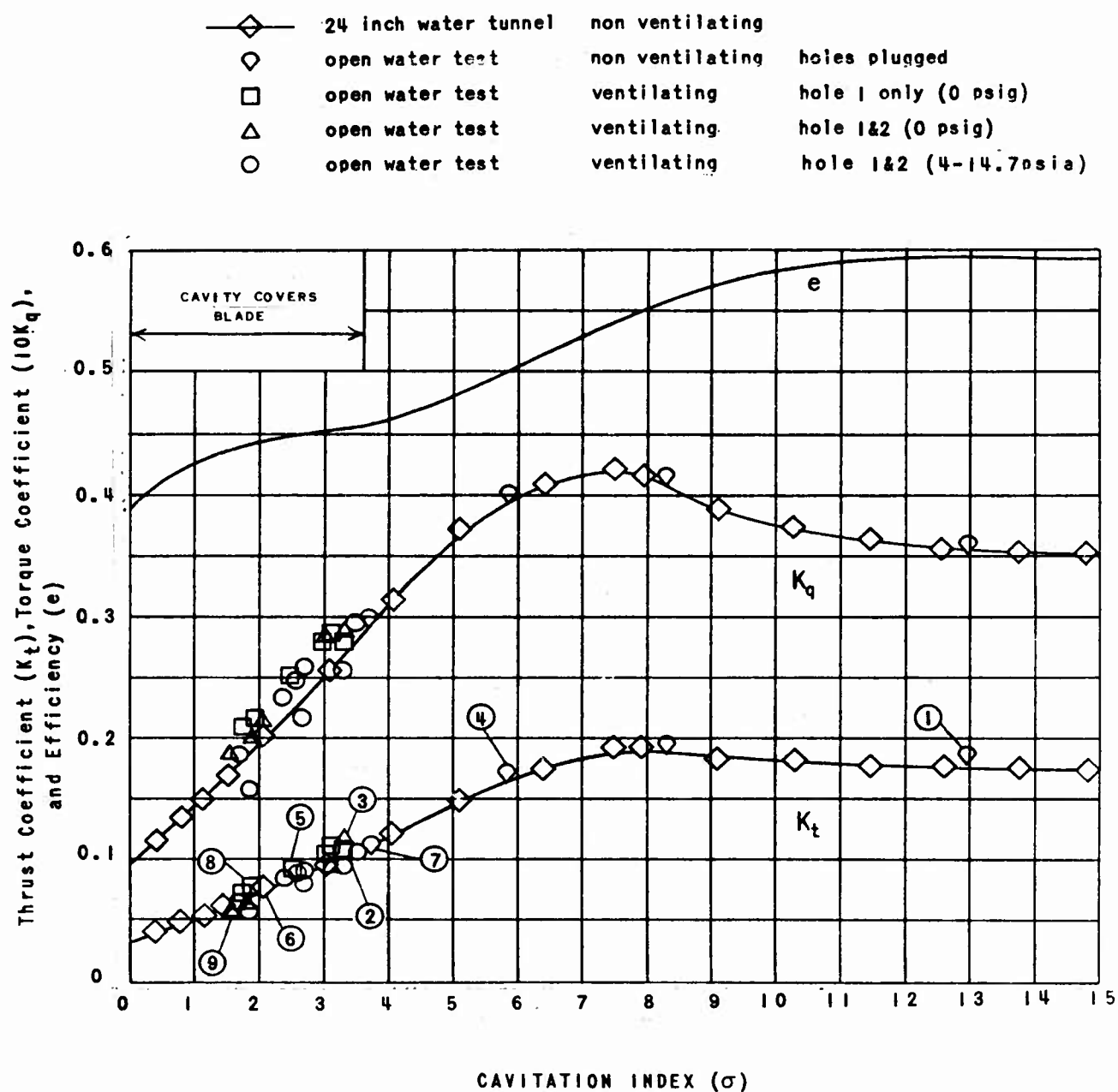
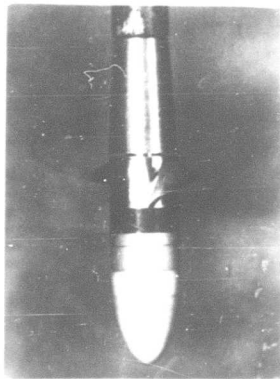


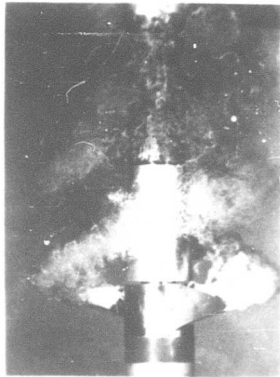
Figure 5 - Powering Performance of Propeller 3671A
at Design J (0.75)

①



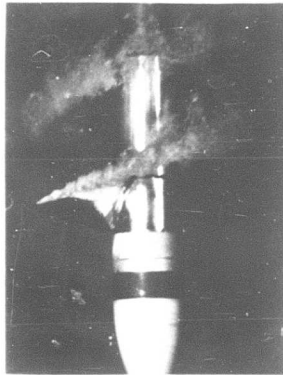
holes closed
 $\sigma = 12.94$

②



hole 1 open
 $\sigma = 3.38$

③



holes 1&2 open
 $\sigma = 3.32$

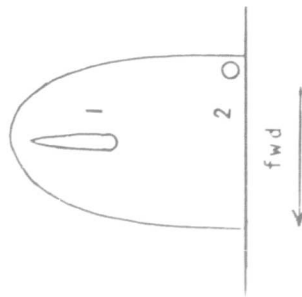
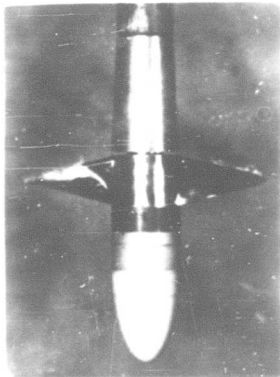


Diagram of Holes in
Propeller Blades

$V = 13.5$ fps
 $n = 15.4$ rps
 $J = 0.75$

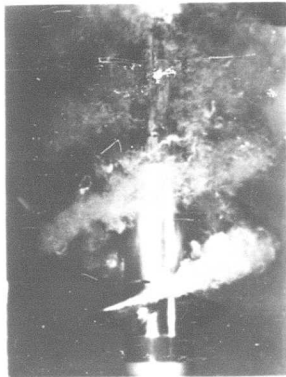
Figure 6a - Comparison of Propeller Cavity Formation at Various Air Flows

④



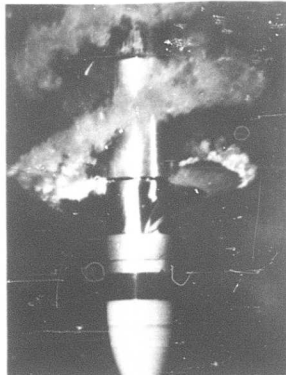
Holes closed
 $\sigma = 5.82$

⑤

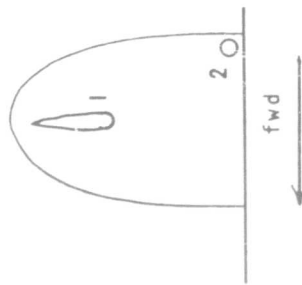


hole 1 open
 $\sigma = 2.50$

⑥



holes 1&2 open
 $\sigma = 2.05$

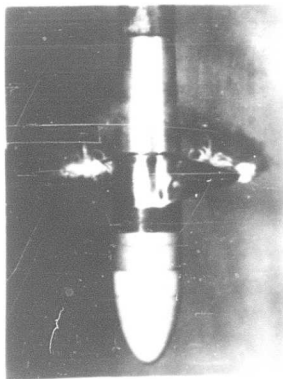


$V = 20.3 \text{ fps}$
 $n = 23.2 \text{ rps}$
 $J = 0.75$

Diagram of Holes in
Propeller Blades

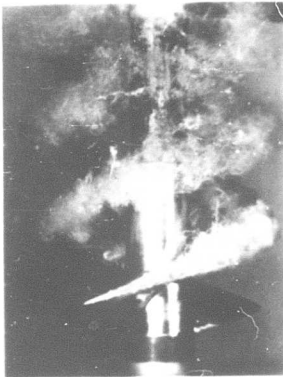
Figure 6b - Comparison of Propeller Cavity Formation at Various Air Flows

⑦



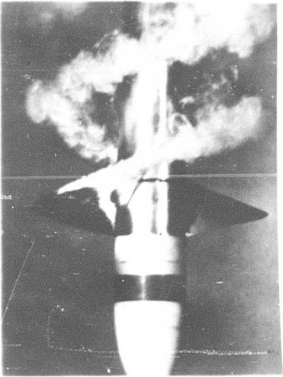
holes closed
 $\sigma = 3.72$

⑧



hole 1 open
 $\sigma = 1.78$

⑨



holes 1 & 2 open
 $\sigma = 1.56$

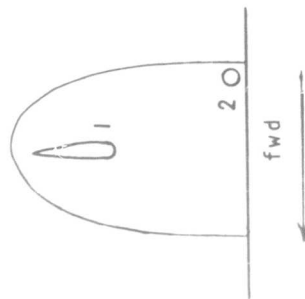


Diagram of Holes in
Propeller Blades

$V = 25.3 \text{ fps}$
 $n = 28.9 \text{ rps}$
 $J = 0.75$

Figure 6c - Comparison of Propeller Cavity Formation at Various Air Flows

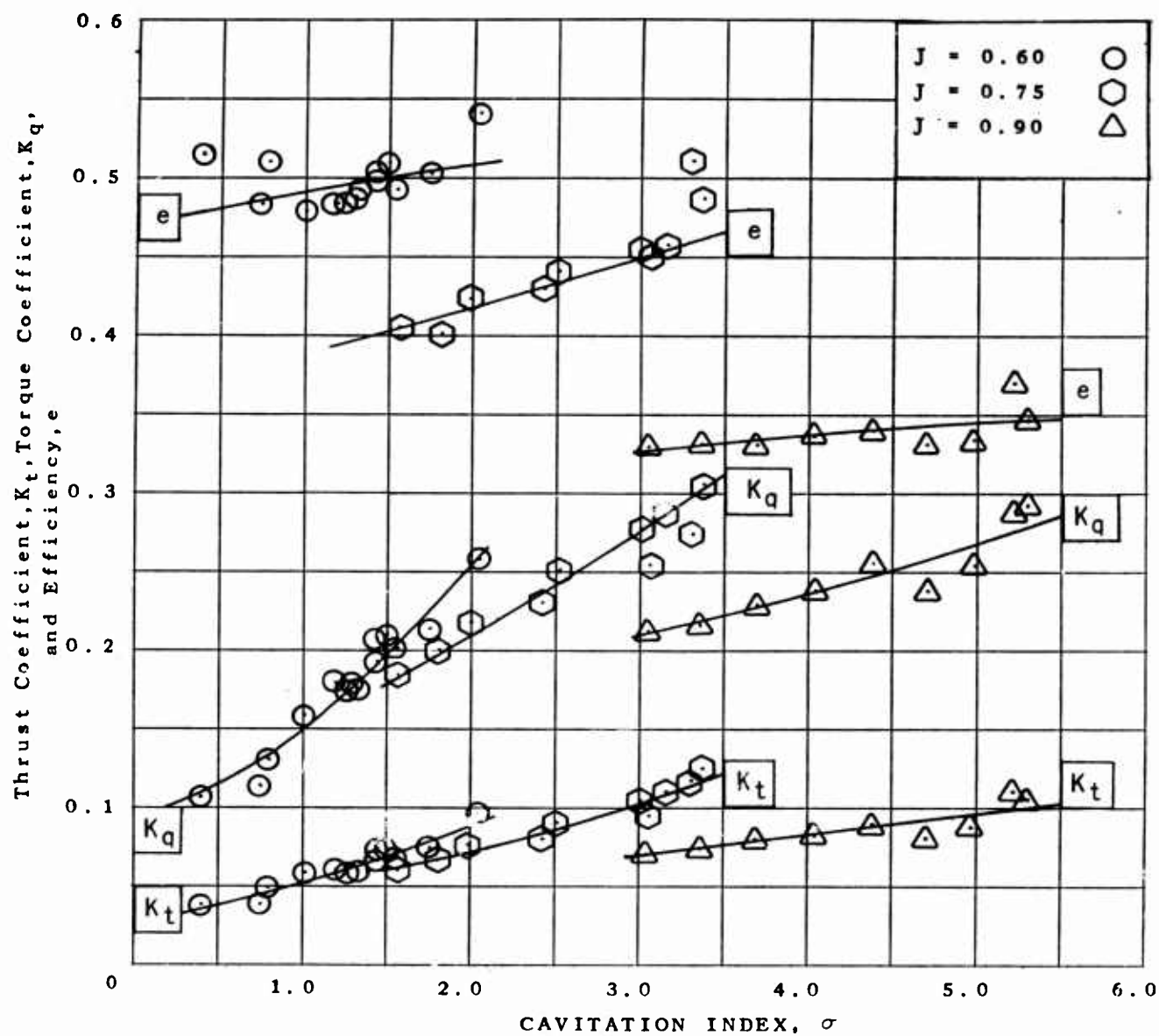


Figure 7 - Powering Performance of Propeller 3671A (Ventilated) at Three J Values

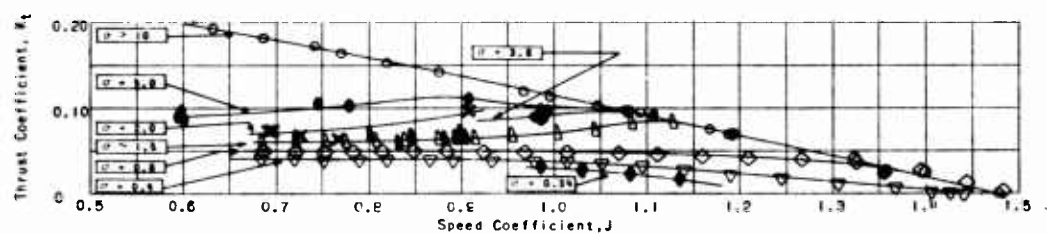
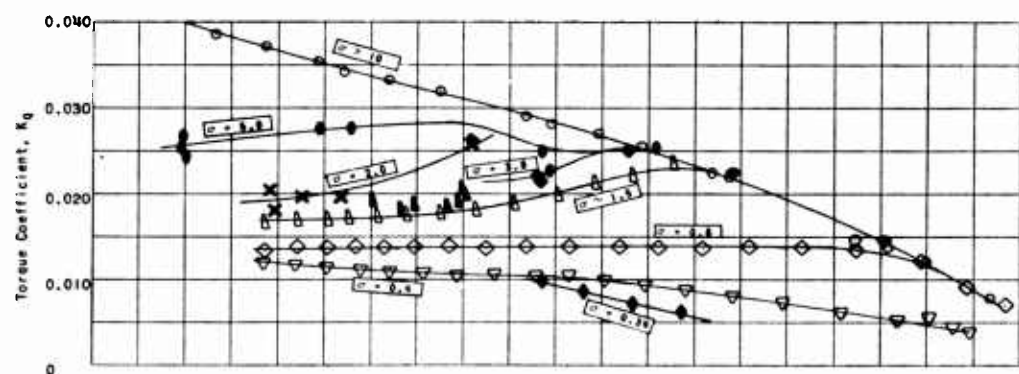
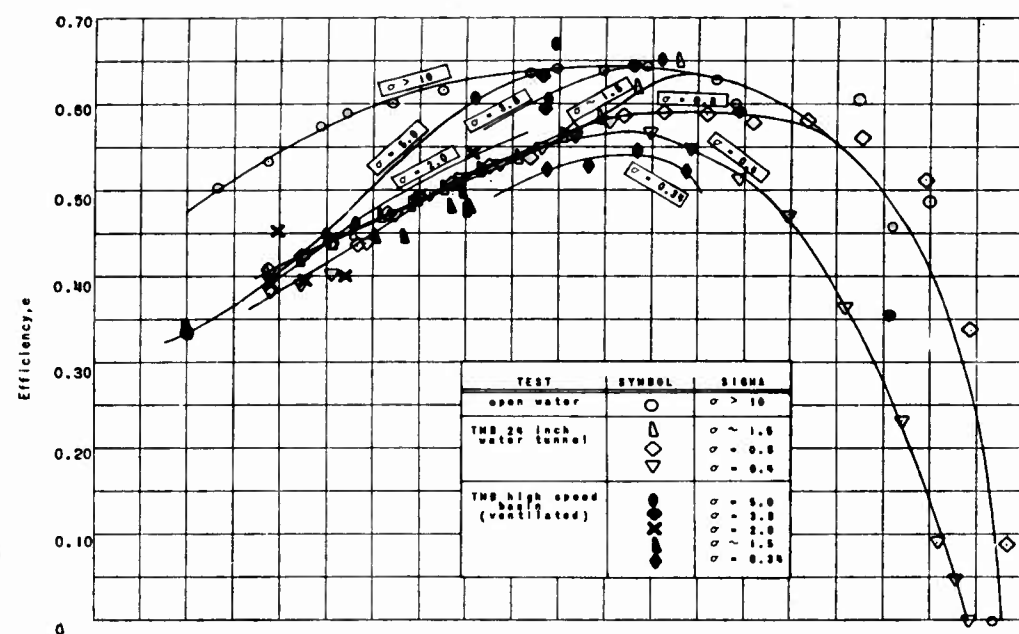


Figure 8 - Powering Performance of Propeller 3671A at Various Cavitation Indices

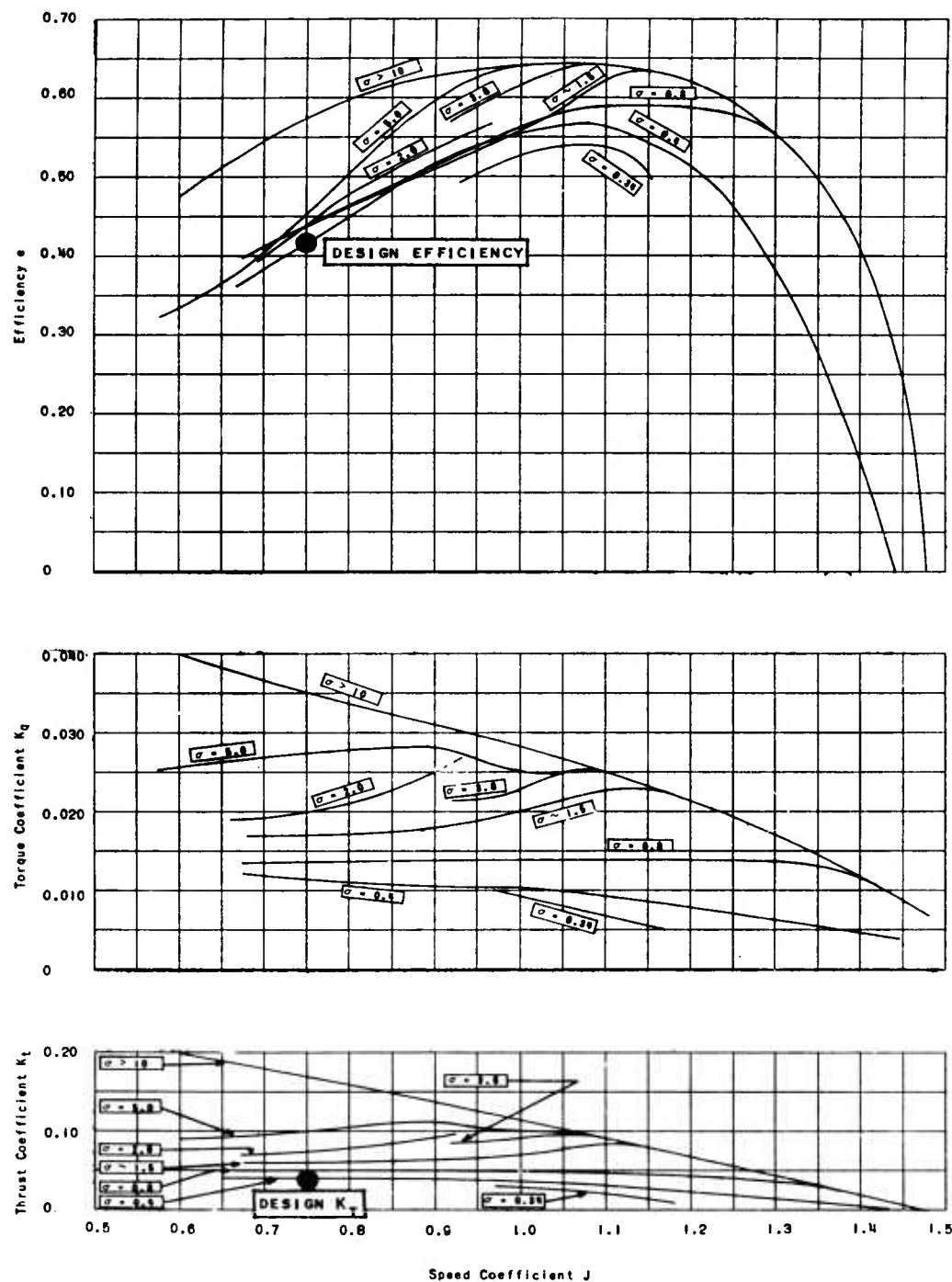


Figure 8a - Powering Performance of Propeller 3671A at Various Cavitation Indices

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In an effort to achieve supercavitating performance at relatively low speeds, ventilation of an SC propeller was investigated. Tests were run with a two-bladed SC propeller ventilated through holes in the propeller blades.

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- I. Supercavitating propellers--Ventilation--Performance
- II. S-R009 01 01

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