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INVESTIGATION OF CAVITATION DAMAGE OF A MECHANICAL PUMP IMPELLER IN HIGH TEMPERATURE POTASSIUM

by

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prepared for

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ABSTRACT

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A three-vaned mixed flow centrifugal impeller was water tested with an acrylic lacquer coating to determine the effects of vane tip clearance on the degree of cavitation damage which may be expected in an endurance test in 1400F potassium. A range of NPSH values was investigated at five vane tip clearance settings. The time required to remove the lacquer coating and size of the area removed will be used to tentatively select an NPSH condition for the potassium test.

Author

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INVESTIGATION OF CAVITATION DAMAGE OF A MECHANICAL PUMP IMPELLER IN HIGH TEMPERATURE POTASSIUM

by

R. S. Kulp and J. V. Altieri

I. SUMMARY

This if the first quarterly report prepared under NASA Contract NAS3-6468 and covers the period from December 7, 1964, to February 28, 1965.

The area of investigation covered by this contract is an attempt to limit the damaging effects of cavitation within an impeller. By varying the impeller vane tip clearance, the cavitation bubble size, bubble velocity, severity of the vane tip vortex, and hence cavitation damage may be reduced. Visual observation alone is not sufficient to define variations of any of these parameters. To effectively study the potential of these phenomena to damage an impeller, a cavitation damage sensitive coating of acrylic lacquer was used. The area of lacquer removed and time required to produce the area by cavitation was a comparative index of the severity of cavitation.

An impeller was water tested with the acrylic lacquer coating for five vane tip clearances and four values of NPSH while maintaining a constant shaft speed of 6375 rpm and flow rate of 700 gpm. The vane tip clearances tested were 0.015 inch, 0.025 inch, and 0.035 inch constant clearance, and 0.035 to 0.015 inch and 0.035 to 0.025 inch clearance variable from impeller inlet to discharge. From these data a vane tip clearance and NPSH value that may produce minimal damage at a high suction specific speed will be selected as test conditions in an endurance test in 1400F potassium.

Two identical investment cast Type 316 stainless steel impellers will be used in the tests under this contract. One impeller already machined will be used in the water tests. The second impeller will be machined from the rough casting and after a water check will be used in the potassium test. The use of these two impellers allowed water testing to begin immediately and thus saved time. Existing facilities and turbopump are being used for this investigation. An impeller water test stand and a liquid metal pump test stand will be used without change from their present design. The turbopump will require minor modification to eliminate operating problems encountered in a previous potassium test.

During the quarter covered by this report, the water testing of the impeller with acrylic lacquer was completed. The impeller for the potassium test was machined from the rough casting, and vane surfaces were hand finished to a 10 rms finish. Data from the water tests are being reviewed by NASA and Pratt & Whitney Aircraft engineering personnel for determination of the liquid metal operating point.

II. INTRODUCTION

The generation of electrical power for protracted space exploration missions can be accomplished by several methods. The most promising of these methods from the standpoint of lowest powerplant weight per kilowatt generated (powerplant specific weight) appears to be the nuclear Rankine cycle turbogenerator system. To obtain the desired low specific weight of such a system, the highest efficiency possible of each component must be attained. This means high temperature operation of the reactor, pumps and turbogenerator components. Temperatures of about 2000F for the reactor, and working fluid condensing temperatures approaching 1400F are within the range of current technology. These condensing temperatures, however, demand the use of liquid alkali metals, such as potassium, as the working fluid. Obviously, these temperatures and fluids present problems in the field of rotating machinery which have not been encountered before.

Condensate pumps will be required to operate at or near the condensing temperatures where cavitation and the consequent damage to impellers are ever present possibilities. Cavitation damage occurs in condensate pumps as minute metallic particles chipped from the impeller by the mechanical impact of imploding cavitation bubbles. These metallic particles carried by the fluid stream present a hazard to the system since they may become lodged in bearings and restricted heat transfer passages.

The terms "cavitation" and "cavitation damage" as used in this report have specific meanings. Cavitation refers to the actual bubbles formed by local pressure depressions caused by the impeller. Cavitation damage is the removal of material from the impeller as a result of energy release of bubble collapse.

The evaluation of a pump in cavitation is currently done through the parameter of suction specific speed (N_{SV}). A high value of N_{SV} may indicate extensive cavitation is present. However, the limit of N_{SV} where severe damage will not occur to a pump in cavitation is not known. Expressed mathematically this parameter is:

$$N_{SV} = \frac{N\sqrt{Q}}{(NPSH)^{3/4}}$$

where N is the pump shaft speed in rpm, Q is flow in gpm and NPSH (net positive suction head) is the available pressure, in feet, at the pump inlet above the vapor pressure of the liquid pumped. Symbolically expressed, NPSH in feet is:

$$NPSH = H_T - H_V$$

where H_T, in feet, is the total pressure at the pump inlet and H_V, in feet, is the liquid vapor pressure. H_T is normally fixed by system requirements. However, it can be varied at the inlet of a centrifugal pump by pressure boost devices such as a jet pump. Such devices add weight to the system directly and indirectly by reducing the over-all powerplant efficiency.

NPSH values can also be increased through lowering liquid vapor pressure (H_V) by subcooling the liquid from its condensing temperature to a lower temperature which will allow pumping with a lesser degree of cavitation. Subcooling the liquid requires additional radiator surface to remove the excess heat, which again adds to the total system weight.

It becomes apparent then, that low system weight is aided by optimizing pump operation at its highest permissible suction specific speed consistent with an acceptable level of cavitation damage. Determination of this maximum permissible suction specific speed has been under investigation by Pratt & Whitney Aircraft-CANEL on this contract.

Under a previous contract with the NASA, a mixed flow pump impeller (designated RI-7C3) was extensively calibrated in water and operated in 1400F potassium for 350 hours (Reference 1). In the water phase of the work, the impeller was tested at five flow rates and its cavitation characteristics recorded. Still and high speed motion pictures were taken of the impeller at various cavitating conditions. Sound intensity measurements and recordings of the sound were made to assist in establishing the desired cavitation conditions in the liquid metal test.

The RI-7C3 impeller was installed in a modified turbopump (designated TP-1) and further calibrated in water. On the basis of these calibrations the test conditions were chosen to be a flow rate of 700 gpm, a shaft speed of 6375 rpm and suction specific speed of 20,000 for the endurance test in 1400F potassium. The test was terminated after 350 hours of operation when the hydraulic performance had deteriorated and vibration levels had exceeded preset limits.

Post-test examination showed the impeller had contacted the scroll causing considerable wear on the impeller vane tips. Rubbing contact was not concentric on either the impeller or the scroll. The exact cause of this contact has not been satisfactorily determined. The rubbing contact produced varying tip clearances which resulted in different degrees of cavitation on each impeller vane. The major cavitation damage was concentrated in the rear flow channels of the impeller with some single event pitting found on the pressure surfaces of the inlet with lesser amounts on the suction surfaces of the vanes. The rear channel damage appeared to be in direct proportion to the amount of vane tip clearance produced by the eccentric rotation of the impeller. The vane tip clearance effect appears to be significant in controlling cavitation damage. Determination of tip clearance effects in water tests, selection of vane tip clearance and NPSH for the potassium test and an endurance test of not more than 1000 hours in 1400F potassium are the goals of this current work.

The difficulty, cost, and time consuming effort required to perform liquid metal experiments demanded that a means of predicting cavitation damage effects in water tests be found. The problem was under study for CANEL's current AEC work for SNAP-50/SPUR program. The desired solution was to find a coating of some kind which would not erode under high velocity water, would adhere to Type 316 stainless steel, and yet, be relatively sensitive to cavitation damage.

For the SNAP-50/SPUR program the technique was first approached from the standpoint of equivalent damage of the coating to that expected at the higher temperatures with Type 316 stainless steel. With this criterion in mind, metallic platings received first consideration. It was soon apparent that very long time cycles were required for coating the impeller and for test operations in water. The criterion of equivalent damage was then dropped, and increased sensitivity of the coating became the primary consideration. This allowed more candidate coatings to be considered, such as epoxyes, epoxy paints, enamel paints and machinists' layout dyes.

The candidate coatings were screened for effectiveness using a small rotating disk cavitation damage test rig. A 5.28 inch diameter Type 316 stainless steel disk containing four inducer holes was used. The disk, as shown in Figure 1, could screen up to eight coatings at a time, four on each side. The test rig featured visual observation and quick turn around. A photograph of the test rig in operation is shown in Figure 2, and a complete discussion of the program and results is given in Reference 2.

The coating showing the most promise was a gold colored acrylic lacquer. The lacquer showed good adhesion, could be applied in extremely thin coats (0.0005 inch), and gave excellent definition of the potential damage area in a short time (Figure 3). Since the rotating disk cavitation damage test is an accelerated method of cavitation damage testing, fast response times were required of the coatings to keep test time on an impeller within reason. No correlation has been made of the time required for cavitation damage to occur in laboratory devices with that of an actual impeller. The question of the time relationship between the disk and an actual impeller was answered by applying the coating technique to a SNAP-50/SPUR impeller (designated RI-16) for additional evaluations. The coating performed excellently (Figure 4). High intensity cavitation produced potential damage patterns, as evidenced by removal of the paint, within 30 minutes. The complete results of this work are reported in Reference 3.

This work on the RI-16 impeller also revealed the fact that suction specific speed, per se, is not a useful parameter for predicting cavitation damage. This was illustrated by initially operating the impeller at 8500 rpm with an N_{SV} of 10,000. The pump shaft speed was then dropped to 4250 rpm at a constant throttle condition and using the laws of dynamic similarity (speed and flow reduced by one-half and pressures reduced by one-quarter) to retain an N_{SV} of 10,000. At 8500 rpm potential damage patterns were generated within one hour. However, at the 4250 rpm point no patterns were found after 12 hours operation. Therefore, suction specific speed by itself will indicate the degree of cavitation present but does not predict when cavitation damage is likely to occur.

III. ENGINEERING PROGRAM

Pratt & Whitney Aircraft-CANEL is conducting an experimental program to explore higher limits of suction specific speed operation in high temperature liquid metal centrifugal pumps. This program is being conducted with the existing mixed flow (RI-7) impeller (as shown in Figure 5) using the acrylic lacquer painting technique described in the Introduction. These water test results will be used to select an operating condition for a subsequent endurance test in 1400F potassium. Existing equipment and facilities will be used to minimize time and cost. In all cases, except for the use of the Water Pump Test Stand, the facilities for the work described in Reference 1 will be reused with little or no modification.

The Impeller Water Test Stand requires no modification under this contract. It was modified for work under CANEL's continuing AEC program and is shown photographically in Figure 6 and schematically in Figure 7.

The TP-1 turbopump will be modified to prevent a recurrence of the rubbing contact of impeller and scroll reported in Reference 1. A bearing housing which incorporates two angular contact bearings in place of the previous single deep groove radial bearing and a heavier service flange will be used. This modified TP-1 turbopump has been redesignated as the KP-1 turbopump and is shown in Figure 8.

The Liquid Metal Pump Test Stand will not be modified but does require reconstruction of the hot trap and liquid metal sampling station. As reported in Reference 1, these items became inoperative during the potassium test. The hot trap valve stuck closed and must be replaced. The sampling station broke in several places due to fatigue of the lines under heavy vibration.

The present test program is composed of the following two phases:

1. Water tests of the RI-7A3 impeller with acrylic lacquer and hydraulic performance tests of the RI-7B3 impeller.

2. An endurance t[illegible] in 1400F potassium using the RI-7B3 impeller in the KP-1 turbopump at a selected value of suction specific speed.

In detail, the Phase I water tests using the RI-7A3 (previous history of this impeller is given in Reference 4) painted with gold colored acrylic lacquer will be run at three values of constant vane tip clearance. For each value of tip clearance the location and pattern of potential cavitation damage will be determined from the pitting patterns recorded on the acrylic lacquer coatings for at least four values of NPSH. Due to time limitations each test point will be run for a total time of 2 hours with observations made every 15 minutes to observe the growth rate of indicated cavitation damage. It is expected that stable patterns will be obtained within this time period. The tip clearance values selected are: 0.015 inch, minimum; 0.025 inch, intermediate; and 0.035 inch, maximum. The NPSH values will be 18 feet, 30 feet, 46 feet and 68 feet with corresponding suction specific speeds of 19,400, 13,100, 9500 and 7000.

Further investigations at two of these NPSH values (18 feet and 30 feet) will be done with vane tip clearance varying from 0.035 inch at the inlet to 0.015 inch at the discharge and 0.035 inch inlet to 0.025 inch discharge. High speed still photographs of the cavitation on the impeller will be taken at each test point. The impeller, with indicated potential damage patterns, will be photographed at the end of each two hour test run.

The RI-7B3 impeller will be machined to adapt it to the KP-1 turbopump while the RI-7A3 is undergoing water tests. The vane tip arc of the RI-7B3 impeller will not be machined until tests of the RI-7A3 impeller are completed and the data reviewed by P&WA and NASA personnel. The data review will select the vane tip clearance and operating conditions for the high temperature liquid metal test. When these conditions are determined, the RI-7B3 vane tips will be cut to provide the desired vane tip clearance in the KP-1 turbopump. The RI-7B3 impeller will then be water tested in the Impeller Water Test Stand to determine its hydraulic and cavitation performance. Tests will be conducted for the three flow rates of 680, 700, and 720 gpm at a shaft speed of 6375 rpm. Noise intensity measurements will be made of the impeller in cavitation for each of these flow rates. Still photographs and high speed motion pictures will be taken for at least five values of NPSH for each of these flow rates.

The KP-1 Turbopump (modified from the TP-1 turbopump) is shown in Figure 8. The turbopump was modified to provide a more rigid shaft assembly to eliminate or drastically reduce suspected shaft bending. These modifications centered about the lower bearing, service flange and impeller attachment bolt. The deep groove radial bearing of the TP-1 turbopump described in Reference 4 was eliminated and two angular contact bearings substituted. This change was done through substitution of the bearing housing from another CANEL designed pump (NP-1) which has a shaft nearly identical to the TP-1. Adaptation of the bearing housing to the TP-1 turbopump of Reference 4 was made through the service flange of the NP-1 pump. This adaption also provided a more rigid assembly since the NP-1 pump service flange is much heavier.

The impeller attachment bolt was lengthened to pass through the minimum cross section of the dynamic seal area of the shaft. Stress calculations at this area indicated a marginal bending stress situation existed. The longer attachment bolt passing through this minimum area would serve to strengthen the shaft in the bending mode.

The Liquid Metal Pump Test Stand will be rebuilt. The hot trap and liquid metal sampling station will be rebuilt and installed.

Prior to liquid metal operations, the RI-7B3 impeller will be cleaned with the inlet surfaces smoothed to approximately a 10 rms finish. Inspection of the impeller will be done and will include weight measurements, mechanical inspection, X-ray and fluorescent inspections; photographs at magnifications of two and four times size and rubber molds of the vane surfaces will be taken.

IV. PROGRESS DURING THE QUARTER

The water test phase of the RI-7A3 impeller was completed, and review of the data by Pratt & Whitney Aircraft personnel was started. The RI-7B3 impeller was machined, except for the vane tip arc. Vane surfaces are being hand finished to provide the required 10 rms finish.

Discussion of the RI-7A3 impeller water testing will be subdivided to clearly delineate the effects noted under each of the operating vane tip clearance conditions. Operation of the Impeller Water Test Stand will be discussed first to show the changed operating procedure from that of previous work in this stand (Reference 1).

A. Impeller Water Test Stand

The Impeller Water Test Stand, as shown in Figure 6 and schematically in Figure 7, was modified between the period of testing under the previous NASA contract to the start of testing under the present one. The significant change was the incorporation of a retention tank and vacuum pump. The tank was installed to retain the demineralized and deaerated water of the test loop while the impeller was changed or modified between cavitation tests. In previous operation of the stand, the water was drained away and an entirely new fill was required. Preparation of the water for cavitation testing took about three days to complete. The addition of the retention tank system decreased the loop turn around time to approximately one day. Transfer of the loop water was accomplished under partial vacuum by pumping the water to and from the retention tank. Some additional deaeration under vacuum conditions could be done in the retention tank.

The photographic arrangement for the cavitation tests of the RI-7A3 impeller is shown in Figure 9. A 35 mm camera was used to take the pictures. The light source was two high intensity microflash units which supplied a light flash of 0.5 microsecond duration. The lights were fired by a pulse from the shaft speed pickup which was amplified and synchronized through the time base generators of two oscilloscopes. The firing pulse was also fed to a stroboscope to orient the timing with the particular vane on the impeller to be photographed. The time base of the oscilloscopes could be adjusted to allow photographing of each of the three vanes at the same cavitation condition. Variations in cavitation from vane to vane could thus be recorded.

Sound intensity measurements were obtained by completely enclosing the clear plastic housing in a wood box covered with sound proofing tile. The sound intensity meter microphone was inserted in a hole in the box to obtain intensity readings. In this manner extraneous noise from the test cell was minimized.

The RI-7A3 impeller was prepared for testing by filling surface porosity and vane tip shroud pin holes with epoxy resin. (The shroud pin holes resulted from previous RI-7A3 impeller testing where a shroud was used. No tip shroud was used in this test program.) All surfaces were smoothed to original contours and the impeller installed in the test stand. Vane surfaces were not smoothed beyond the "as cast" condition.

The gold colored acrylic lacquer used in the tests is a commercially available product supplied in aerosol cans. The lacquer color is obtained by bronze powder suspended in a vehicle which contains about 4% acrylic ester resin. The lacquer is sprayed on the impeller which has first been wiped with a cloth containing acetone. No special preparation of the impeller surface was found to be needed. However, care should be taken that dust particles do not lodge in the wet lacquer. These particles will be surface irregularities which will become secondary cavitation generators in the water test.

Installation of the RI-7A3 impeller was identical to that of Reference 1. This previous installation is shown in Figure 10. A dial indicator was used to observe deformation of the plastic housing under impeller discharge and loop datum pressures.

B. Vane Numbering Convention

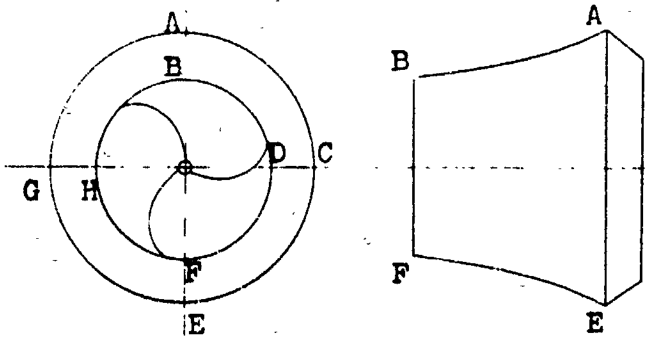
In the following discussion of the cavitation frequent reference is made to the impeller vanes by number. A consistent numbering system for vane and channel designations was used. With reference to Figure 14, the following convention was adopted. The only vane terminating at the hub with the leading edge directly opposite a bolt locking pin hole was chosen as vane 1. The vanes were then numbered in clockwise rotation.

Channel designations in the impeller are designated by the vane numbers forming the channel. The number of the vane whose suction surface forms the channel is given first. For example, channel 32 would be the channel between the suction surface of vane 3 and the pressure surface of vane 2. Thus, the remaining channels would be channel 13 and channel 21.

C. Vane Tip Clearance - 0.015 inch (nominal) Constant

The RI-7A3 impeller was initially installed with a nominal vane tip clearance of 0.014 inch that was essentially constant throughout the tip arc. A variation of approximately 0.004 inch was present due to tip contour eccentricity with the impeller centerline. Installation accuracy was held within ± 0.001 inch. Actual measured values of the installed clearance are given in the following sketch:

INSTALLED VANE TIP CLEARANCE



POS.	Dim.
A	0.016
B	0.016
C	0.014
D	0.014
E	0.018
F	0.018
G	0.018
H	0.018

The impeller's hydraulic and cavitation performance were obtained after the initial installation. These data are shown in Figures 11 and 12, along with that obtained in all subsequent tests.

The impeller was removed from the stand after obtaining performance data and painted with the gold colored acrylic lacquer. When the lacquer dried, the impeller was reinstalled and clearances rechecked. The first test point was then run for two hours with visual checks of lacquer removal at 15 minute intervals at an NPSH value of 18 feet. The impeller operating at this condition is shown in Figure 13. Back channel cavitation appears mild and essentially confined to the mid-channel. Leading edge cavitation was variable in degree from vane to vane. Figure 13 shows primarily the cavitation present on vane 3, which was the mildest; however, the extensive cavitation from vane 1 is evident in the channel between the pressure surface of vane 3 and suction surface of vane 1 or channel 13.

Lacquer removal on suction surfaces is shown in Figure 14 and on pressure surfaces in Figure 15. The extensive lacquer removal on vane 3 on both surfaces is attributed partially to carry-over of the heavy cavitation cloud on vane 1. The inner cavitation track on vane 3 was believed caused by a heavy cavitation cloud generated along the leading edge near the hub which shed bubbles downstream. All damage patterns showed no increase in size after 1.5 hours of operation.

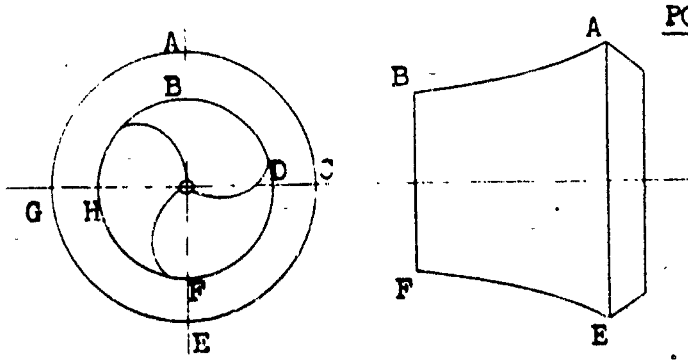
The impeller was removed from the stand, and an attempt to fair the leading edge near the hub was made to eliminate the inner cavitation track on vane 3. The impeller was then repainted, reinstalled, and operated at the same point to determine the effects of fairing. Some changes in the leading edge cavitation cloud near the hub did occur but the effect on the damage pattern was obscured by spill-over from vane 1 (Figure 16).

The effects of higher values of NPSH at the 0.015 inch vane tip clearance were generally lesser amounts of lacquer removed as NPSH was raised. These effects were evident on both pressure and suction surfaces. Figures 17 through 23 show the cavitation clouds on the impeller and indicated potential damage patterns for NPSH values of 30 feet, 46 feet and 68 feet. No pressure surface photographs for NPSH values of 46 feet and 68 feet were taken since no lacquer was removed from these surfaces. No increase in the area of paint removal was noted after approximately one-half hour of operation at NPSH values of 30 feet, 46 feet and 68 feet.

D. Vane Tip Clearance - 0.025 inch (nominal) Constant

At the completion of the 0.015 inch clearance runs the impeller was removed and 0.010 inch was machined from the vane tip arc. This provided a vane clearance of approximately 0.025 inch on reinstallation. The machining operation removed most of the 0.004 inch eccentricity between vane tips and impeller centerline present in the 0.015 inch tests. The actual installed clearance values are given in the following sketch:

INSTALLED VANE TIP CLEARANCE



POS.	Dim.
A	0.028
B	0.024
C	0.027
D	0.024
E	0.025
F	0.023
G	0.025
H	0.023

With the impeller cleaned, repainted and installed, test conditions were established at an NPSH value of 18 feet. Again visual checks of lacquer removal were made at 15 minute intervals throughout the 2 hour test period.

The typical cavitation pattern at the NPSH of 18 feet test point is shown in Figure 24. The inlet cavitation patterns appeared more uniform from vane to vane than for the corresponding point at 0.015 inch clearance. This is attributed to the reduced eccentricity and larger vane tip clearance.

The lacquer removal patterns at the end of the 2 hour test period are shown in Figure 25. The excessive lacquer removal in the center of the vane suction surfaces was partly caused by vortex patterns generated from dust particles trapped in the lacquer during the painting process. This is shown more clearly in the closeup view of Figure 26 where the surface roughness and cavitation originators can be seen. Paint removal on the pressure surfaces is shown in Figure 27.

Cavitation patterns at an NPSH value of 30 feet are shown in Figure 28. Lacquer removal patterns, indicative of potential damage are shown in Figures 29, 30 and 31. The rear channel cavitation of Figure 28 does not appear as intense as that at 18 feet (Figure 24). However, lacquer removal from the pressure surfaces is greater at the 30 foot value of NPSH than for the 18 foot value. These two points were rerun to verify this finding, and identical results were achieved. A check of the sound intensity curve indicates a higher sound intensity level for an NPSH of 30 feet. No conclusion is drawn at this time as to the significance of these facts.

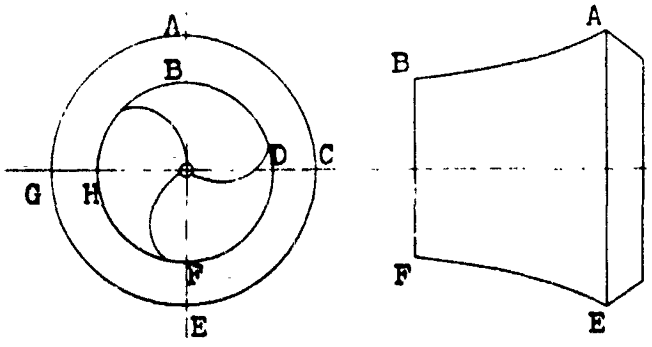
Cavitation patterns and lacquer removal patterns for NPSH values of 46 feet and 68 feet are shown in Figures 32, 33, 34 and 35. After two hours operation at an NPSH of 68 feet, no lacquer was removed from either pressure or suction surfaces. This corresponds to a suction specific speed of approximately 7000.

Potential cavitation damage areas, as indicated by lacquer removal, were essentially stable after 1.5 hours at an NPSH of 18 feet, three-quarters of an hour at NPSH values of 30 feet and 46 feet.

E. Vane Tip Clearance - 0.035 inch (nominal) Constant

The impeller vane tip arc was again machined removing 0.010 inch to provide a constant vane tip clearance of 0.035 inch after completion of testing at the 0.025 inch clearance. The impeller vane tip radius was not machined correctly because of misalignment of the machining template used to cut the arc. The template was located with the center of the radius too far forward in relation to the impeller. This caused too little material to be removed from the vane tips at the rear of the impeller. Corrective machining was done; but, apparently, the same error was repeated in the opposite direction, causing an overcut by approximately 0.005 inch at the rear of the impeller. This resulted in a variable clearance from inlet to discharge of about 0.006 inch. Measured vane tip clearances at installation are given in the following sketch:

INSTALLED VANE TIP CLEARANCE



POS.	Dim.
A	0.038
B	0.032
C	0.039
D	0.034
E	0.039
F	0.034
G	0.038
H	0.033

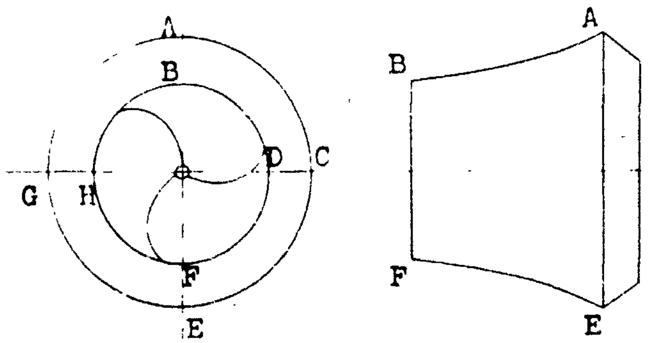
Cavitation patterns on the impeller at an NPSH of 18 feet are shown in Figure 36. Rear channel cavitation is fairly heavy and extends across the full width of channel 13. The extensive leading edge cavitation extends to the flow channel formed by the following vane (channel 21). Potential cavitation damage, as indicated by lacquer removal, is shown in Figures 37 and 38. Considerable areas of lacquer have been removed at several locations on the pressure surfaces with relatively little from suction surfaces. Cavitation patterns and lacquer removal patterns are shown in Figures 39, 40, 41 and 42 for an NPSH of 30 feet and Figures 43, 44 and 45 for 46 feet. No cavitation data was taken at an NPSH of 68 feet at 0.035 inch clearance since no potential damage areas had been found at 0.025 inch clearance. This point was also waived to allow time to operate the impeller with variable tip clearances ranging from 0.035 inch at the inlet to 0.015 and 0.025 inch at the discharge.

F. Variable Vane Tip Clearance - 0.035 Inlet to 0.015 Discharge (nominal)

At the conclusion of the constant vane tip clearance test series, the impeller installation was changed without further machining operations to provide variable clearances. Since the vane tip arc of the impeller at the inlet is tangent to the inlet pipe, a constant inlet clearance is maintained at 0.035 inch. The rear channel clearance can be varied by moving the impeller axially into the housing. In this manner a variable vane tip clearance from 0.035 at the inlet to 0.017 at the discharge was obtained. Due to the machining variations in the tip arc contour, the discharge clearance could not be reduced to the desired 0.015 inch without restricting the impeller mid-section clearance. It was decided to hold to a minimum mid-section clearance of approximately 0.015 inch.

Actual installed clearances, as measured, are given in the following sketch for the impeller inlet and discharge only:

INSTALLED VANE TIP CLEARANCE



POS.	Dim.
A	0.017
B	0.032
C	0.017
D	0.032
E	0.018
F	0.033
G	0.018
H	0.033

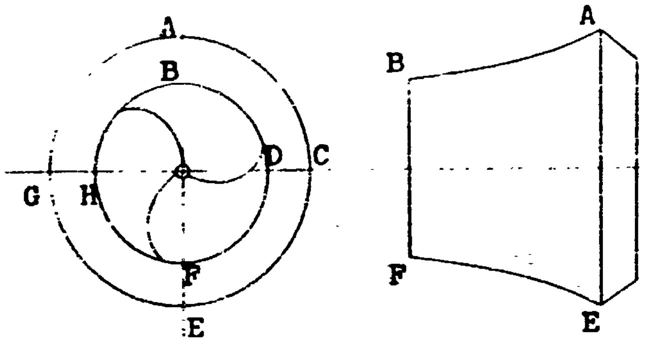
Cavitation patterns on the impeller are shown in Figure 46 at an NPSH of 18 feet. Lacquer removed, indicating potential damage areas, is shown in Figures 47, 48 and 49. The suction surface lacquer removal patterns are similar to, but smaller than, that found at 0.015 inch constant and 0.025 inch constant clearance. The areas of paint removal are more extensive than for the 0.035 inch constant clearance. Paint removal patterns on the pressure surfaces at the inlet were generally more extensive than for any other condition. Rear channels showed very slight patterns. All areas appeared to reach maximum size in approximately one hour.

Cavitation patterns at an NPSH of 30 feet are shown in Figure 50 and potential damage patterns in Figures 51 and 52. Suction surfaces appeared very similar to that found at an NPSH of 30 feet with 0.025 inch constant clearance. Pressure surfaces were milder with no rear channel areas such as those at NPSH 30 feet and 0.025 inch clearance. All areas appeared to reach their maximum size within the first 15 minutes.

G. Variable Vane Tip Clearance - 0.035 inch inlet to 0.025 Discharge (nominal)

The back channel vane tip clearance was increased to approximately 0.027 inch after the tests at 0.017 inch. The increase of back channel clearance was made an even 0.010 inch to correspond to all previous clearance increments. Actual installed vane tip clearance is given in the following sketch:

INSTALLED VANE TIP CLEARANCE



POS.	Dim.
A	0.027
B	0.032
C	0.028
D	0.032
E	0.028
F	0.033
G	0.027
H	0.032

Cavitation patterns on the impeller are shown for NPSH values of 18 feet and 30 feet in Figures 53 and 56. Lacquer removal patterns are shown in Figures 54 and 55 for NPSH of 18 feet and Figures 57 and 58 for NPSH of 30 feet. In general, it can be stated that the increase of 0.010 inch in back channel vane tip clearance over the previous runs produced similar but much smaller areas of lacquer removal. Essentially no rear channel damage patterns were found. Cavitation under these conditions appears quite mild since nearly 1.5 hours were required to reach stable damage patterns.

H. Discussion of Tip Clearance Effects

Throughout the test program a definite variation in the amount or degree of cavitation was noted for the three vanes (Figure 59). Vane number 1 consistently produced more cavitation at the impeller inlet at the tip vortex and generally across the suction surface at the inlet. The rear channel cavitation in channel 32 (using convention adopted in Section IV .B) is caused by the flow and pressure gradients of channel 13. Invariably, the channel 32 cavitation bubble patterns and observed paint removal were mildest. This was probably caused by a redistribution of flow in channel 13 due in part to blockage of the channel entrance by vane 1 cavitation.

Cavitation damage testing using the gold colored acrylic lacquer proved very successful. Not only were the areas of potential damage identified, but the relative intensity of the cavitation could be established by the length of time required to produce the patterns (i.e., short time intervals indicate strong cavitation fields).

This test series indicates the importance of vane tip clearance effects on the degree of cavitation damage. Although there was no pronounced change in the amount of cavitation for any given NPSH value, there was a definite change in area of lacquer removed as vane clearances were varied. This was also true for the time required to produce stable patterns of paint removal. For instance, at an NPSH of 18 feet the area of lacquer removed on inlet suction surfaces decreased as the vane tip clearance increased; and the time required to produce the damaged area increased as shown in Table 1. This would indicate that the intensity of cavitation was strong and rather widespread at the tight tip clearance. At the variable tip clearance of 0.035 to 0.025 inch, the cavitation intensity was much weaker since the damaged area was smaller and it took a longer time to produce it.

Table I

Summary of Damage Patterns to Acrylic Coatings

	NPSH 18 ft (N_{SV} 19,400)		NPSH 30 ft (N_{SV} 13,100)		NPSH 46 ft (N_{SV} 9500)		NPSH 68 ft (N_{SV} 7000)	
Clearance	Damaged Area	Time	Damaged Area	Time	Damaged Area	Time	Damaged Area	Time
0.015	very extensive(I)* none (B.C.)	3/4 hour	mild(I) none (B.C.)	1/2 hour	very mild(I) none (B.C.)	1/4 hour	very small area one vane only(I) none (B.C.)	1/4 hour
0.025	extensive(I) mild (B.C.)	3/4 hour	mild (I) extensive(B.C.)	1/2 hour	very mild(I) none (B.C.)	1 1/4 hours	none(I) & (B.C.)	2 hours
0.035	extensive(I) mild(B.C.)	1 hour	mild(I) mild (B.C.)	3/4 hour	very mild(I) none (B.C.)	1 1/2 hours	---	---
0.035 to 0.015	mild to extensive(I) none (B.C.)	1 hour	mild(I) none (B.C.)	1/4 hour	---	---	---	---
0.035 to 0.025	mild to extensive(I) none (B.C.)	1 1/2 hours	very mild(I) none (B.C.)	1 hour	---	---	---	---

*(I) means inlet surfaces
(B.C.) means back channel surfaces

The cavitation on the pressure surfaces in the rear channels of the impeller is very unpredictable, but appears to have a critical point. At the vane tip clearance of 0.025 inch constant, some lacquer was removed at NPSH of 18 feet with much more occurring at 30 feet. The photographs at the NPSH of 30 feet show a lower concentration of bubbles in the rear channel vortex than do those of the NPSH of 18 feet. This unexpected result was double checked and verified. It is postulated that the conditions of pressure (bubble driving force) and tip clearance (bubble size) were just right for the generation of high energy cavitation bubbles which crossed the flow channel and imploded on the pressure surfaces. It should also be noted that the sound intensity curve is nearing its peak at the NPSH of 30 feet and is somewhat lower at the NPSH of 18 feet. Whether this is of real significance or not is not established. It also should be noted that the tip static pressure rise of the RI-7 impeller has a pressure depression in the back channel which triggers cavitation (Reference 1). This pressure rise discontinuity may be unique to the RI-7 design.

The extensive lacquer removal from the suction surface of the vanes at the inlet for a vane tip clearance of 0.015 inch appears to be caused by high pressure gradients in this zone of the impeller. Increasing the vane tip clearance changes the pressure gradients throughout the impeller, since the head rise dropped from 246 feet at 0.015 inch tip clearance to 183 feet at 0.035 inch tip clearance, with a resultant decrease in the area of lacquer removed from the inlet suction surfaces. A partial recovery of the head rise can be effected by closing the impeller tip clearance in the rear channel area without substantially affecting the inlet pressure gradients and lacquer removal. Therefore, it appears that a variable tip clearance from inlet to discharge is the most desirable since head rise is retained without causing pressure gradients in the inlet which could be potentially damaging.

General trends observed from these tests are:

1. Tight inlet vane tip clearances appear to cause heavy inlet suction surface cavitation damage.

2. There appears to be a critical combination of head rise and vane tip clearance for minimum damage in the rear channel areas. At a vane tip clearance of 0.025 inch more extensive lacquer removal was found at an NPSH of 30 feet than for an NPSH of 18 feet in the rear flow channels.

3. The acrylic lacquer coating technique offers a way of predicting the location of cavitation damage. The correlation of cavitation intensity required to produce equivalent cavitation pitting of metal surfaces remains to be established.

4. Surface irregularities are secondary cavitation generators and must be eliminated for high suction specific speed designs.

V. WORK TO BE PERFORMED DURING THE NEXT QUARTER

The RI-7A3 data review will be completed and tentative selection of an operating point for potassium will be made. Water tests of the RI-7B3 impeller will be completed. The RI-7B3 impeller will be thoroughly inspected after the water tests to accurately determine its pretest condition for the hot potassium test.

Machining of parts required for the KP-1 turbopump will be completed and pump assembly started.

Fabrication of the liquid metal pump test stand hot trap and sampling station will be completed and test stand reconstruction will be started.

VI. REFERENCES

1. Kulp, R. S. and Altieri, J. V., Jr., "Cavitation Damage of Mechanical Pump Impellers Operating in Liquid Metal Space Power Loops", NASA Report CR-165, December 1964.

2. Noell, G. L., "Cavitation Sensitive Coating Evaluation", Pratt & Whitney Aircraft-CANEL, TIM-878, April 1965.

3. Altieri, J. V., Jr., "Cavitation Tests of Coated RI-16 Impeller", Pratt & Whitney Aircraft-CANEL, TIM-895, April 1965.

4. Kulp, R. S. and Altieri, J. V., Jr., "Investigation of Cavitation Damage of Mechanical Pump Impellers Operating in Liquid Metal Space Power Loops", Quarterly Progress Report No. 1, Pratt & Whitney Aircraft-CANEL, CNLM-5202, October 1963.

FIG 1

4C-5508

COATING EVALUATION ON ROTATING DISK CAVITATION DAMAGE TEST

POSITION	COATINGS	TIME, MINUTES
1	LAYOUT DYE PLUS 3 COATS ACRYLIC LACQUER	0
2	GOLD ACRYLIC LACQUER	0
3	CADMIUM PLATING	16
4	EPOXY	16

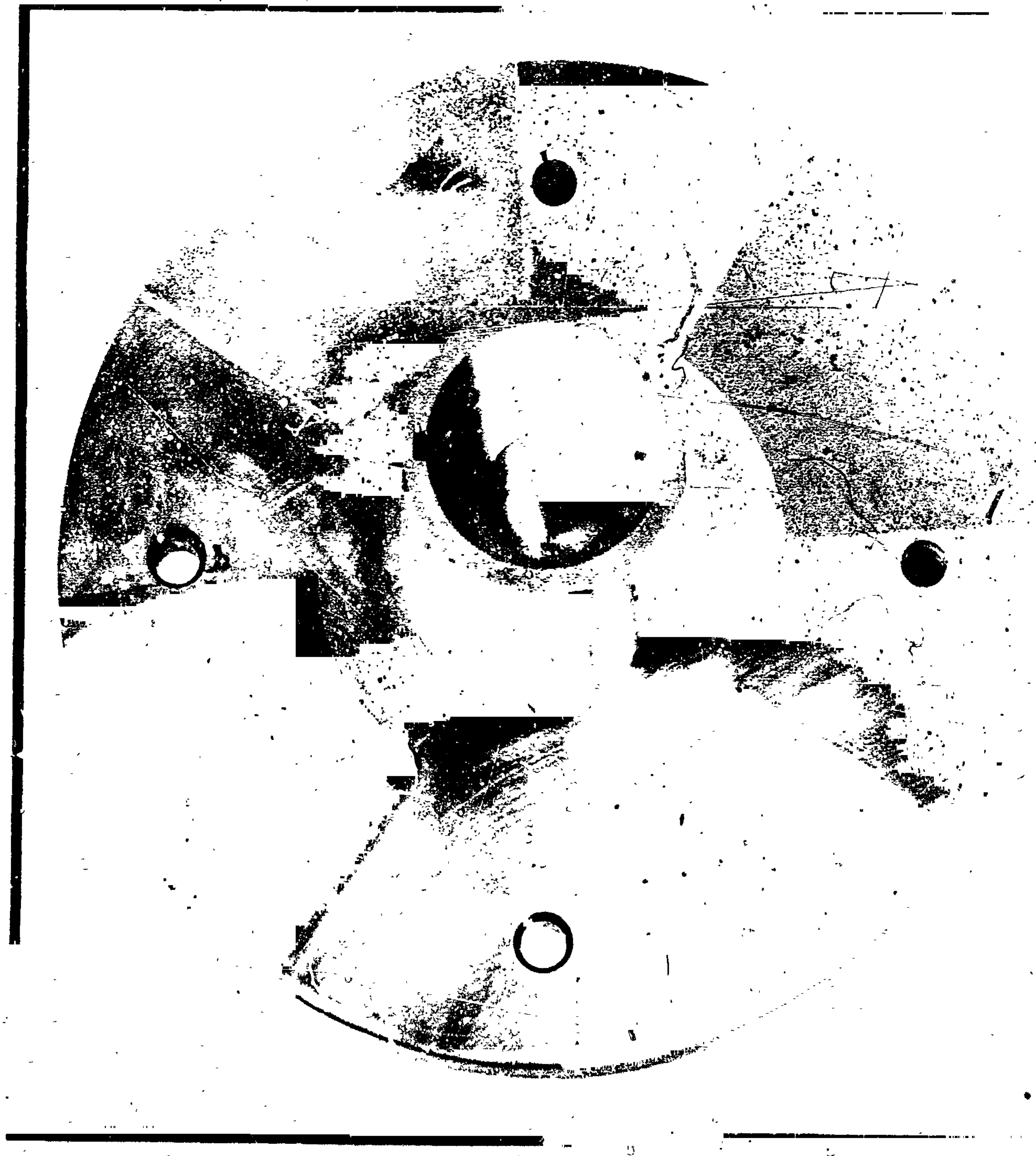
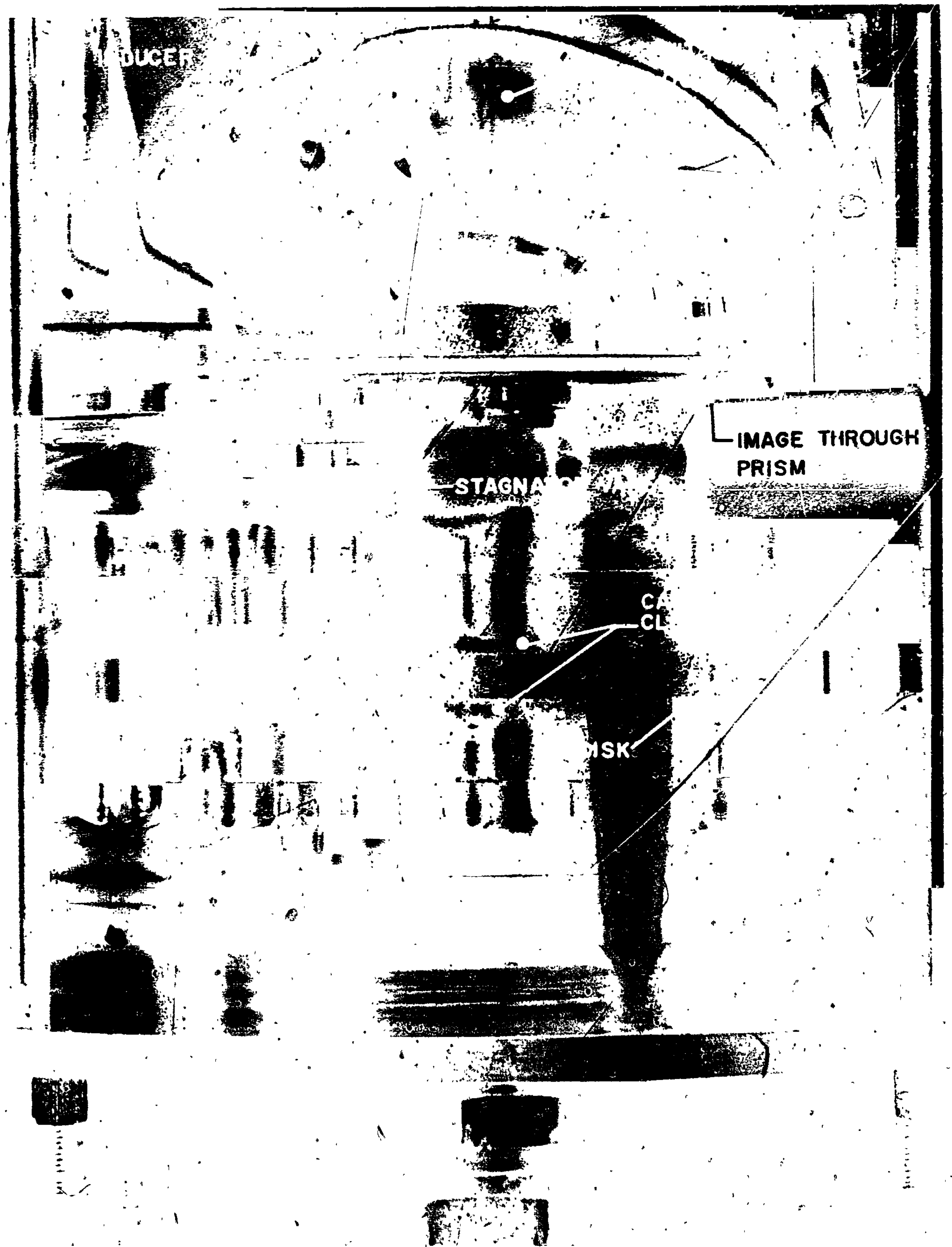


FIG 2

ROTATING DISK TYPE CAVITATION DAMAGE TEST IN WATER

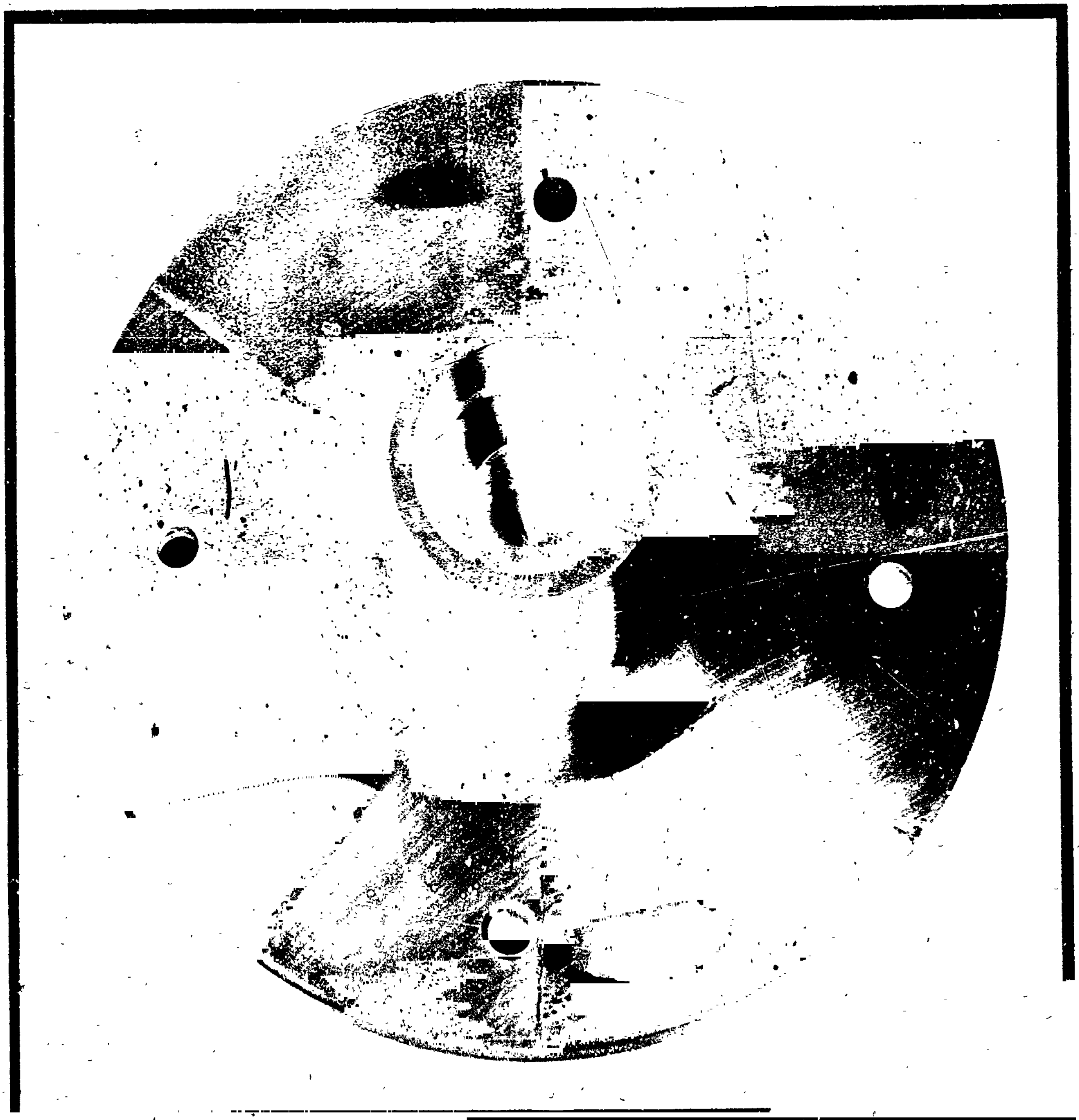


4C-5512

FIG 3

RESULTS OF COATING EVALUATION ON ROTATING DISK

POSITION	COATING	TIME, MINUTES
1	LAYOUT DYE PLUS 3 COATS ACRYLIC LACQUER	14
2	GOLD ACRYLIC LACQUER	14
3	CADMIUM PLATING	30
4	EPOXY	30



C-13824

FIG 4

RI-16 IMPELLER RUN AS PROOF TEST OF GOLD ACRYLIC LACQUER

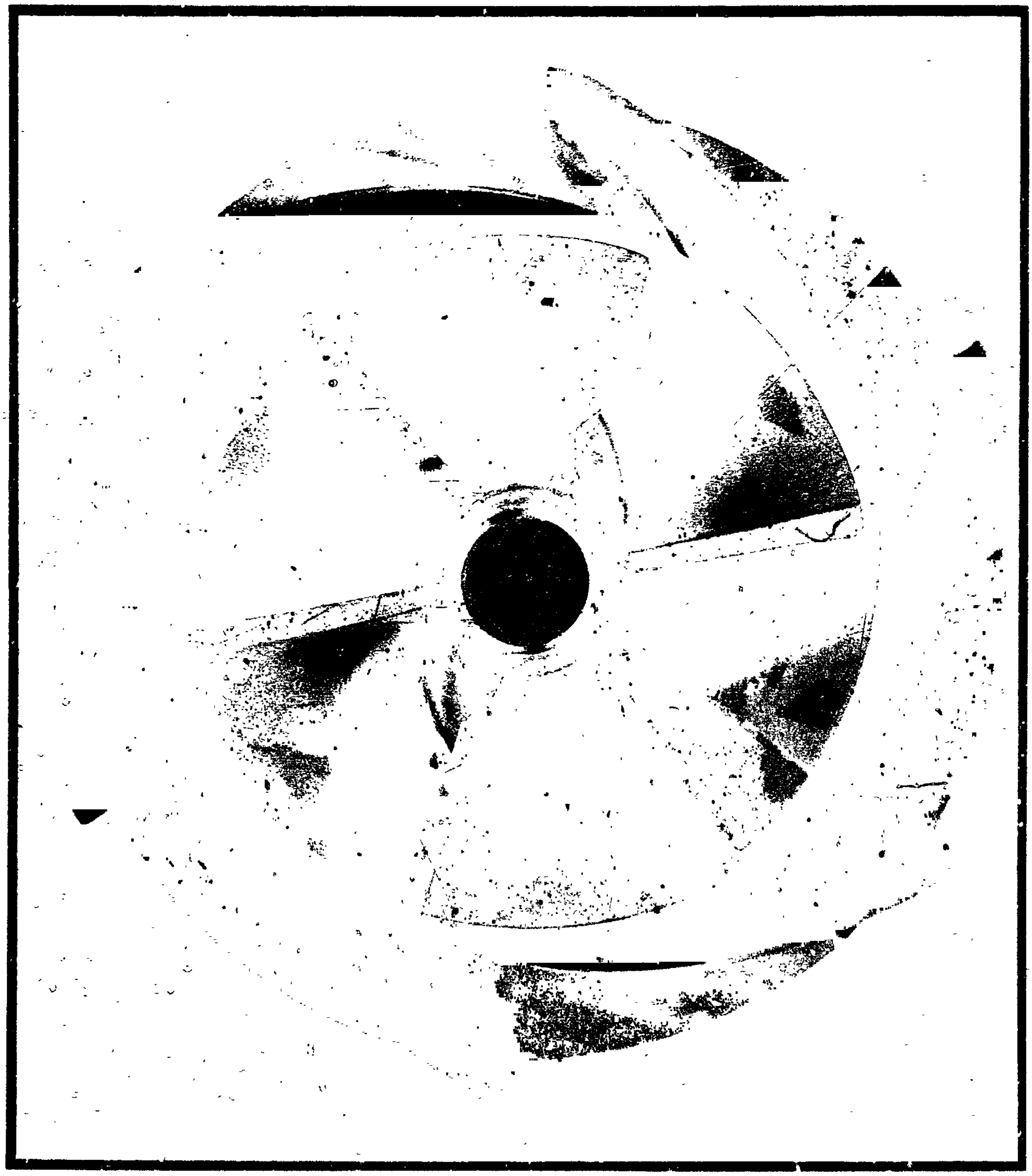
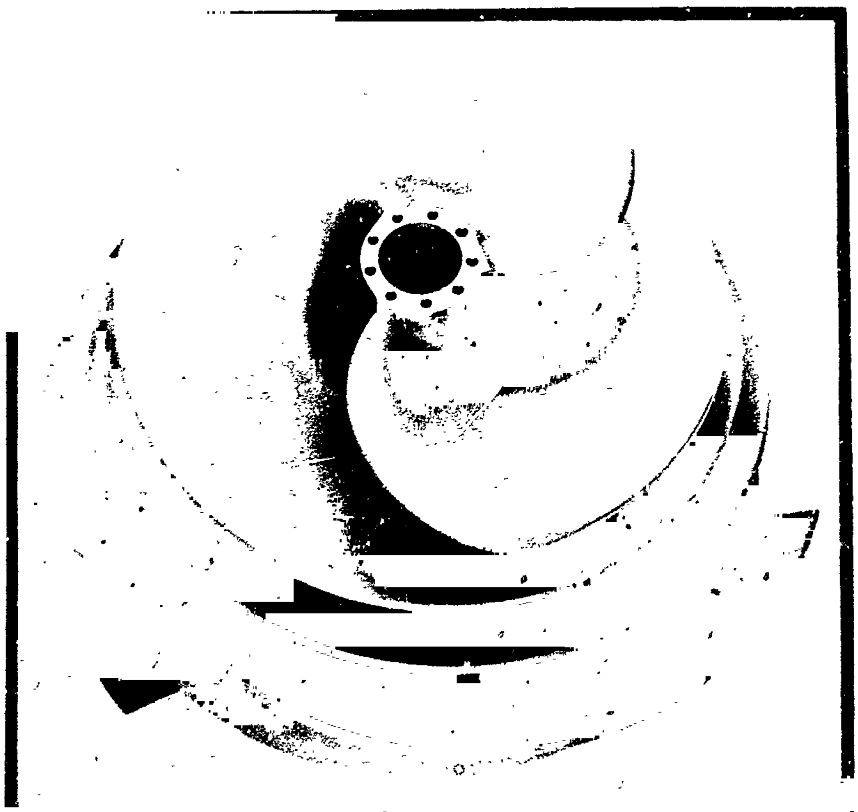


FIG 5

RI -7 RESEARCH IMPELLER



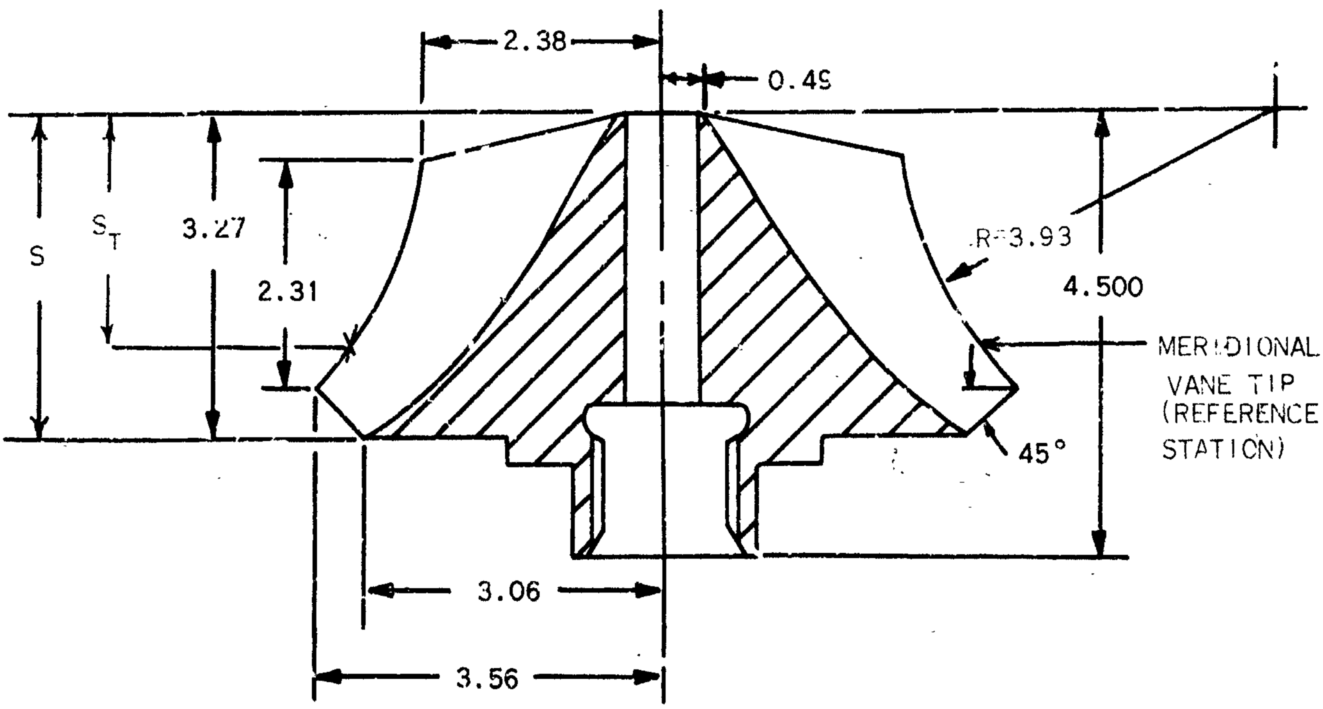
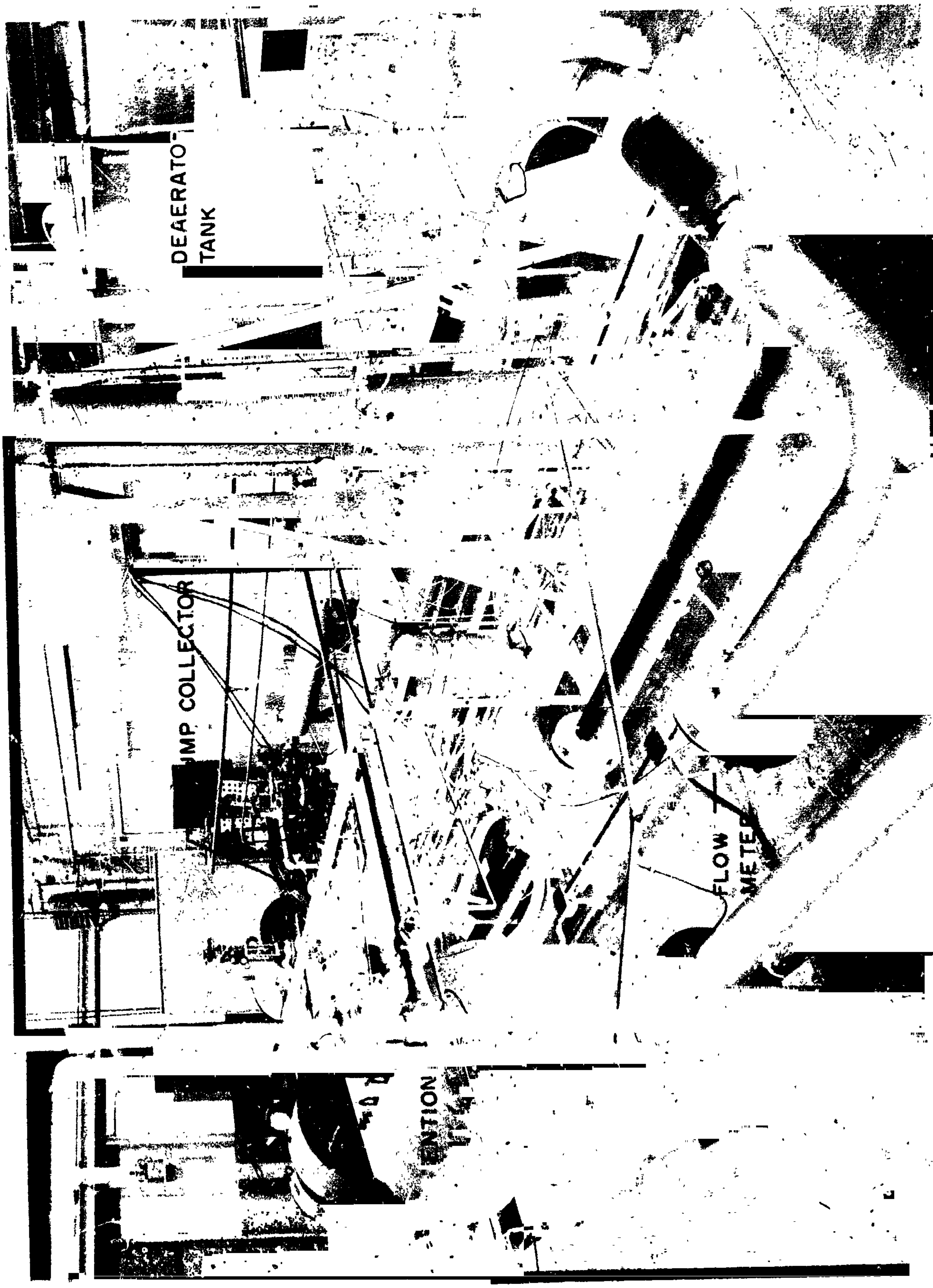


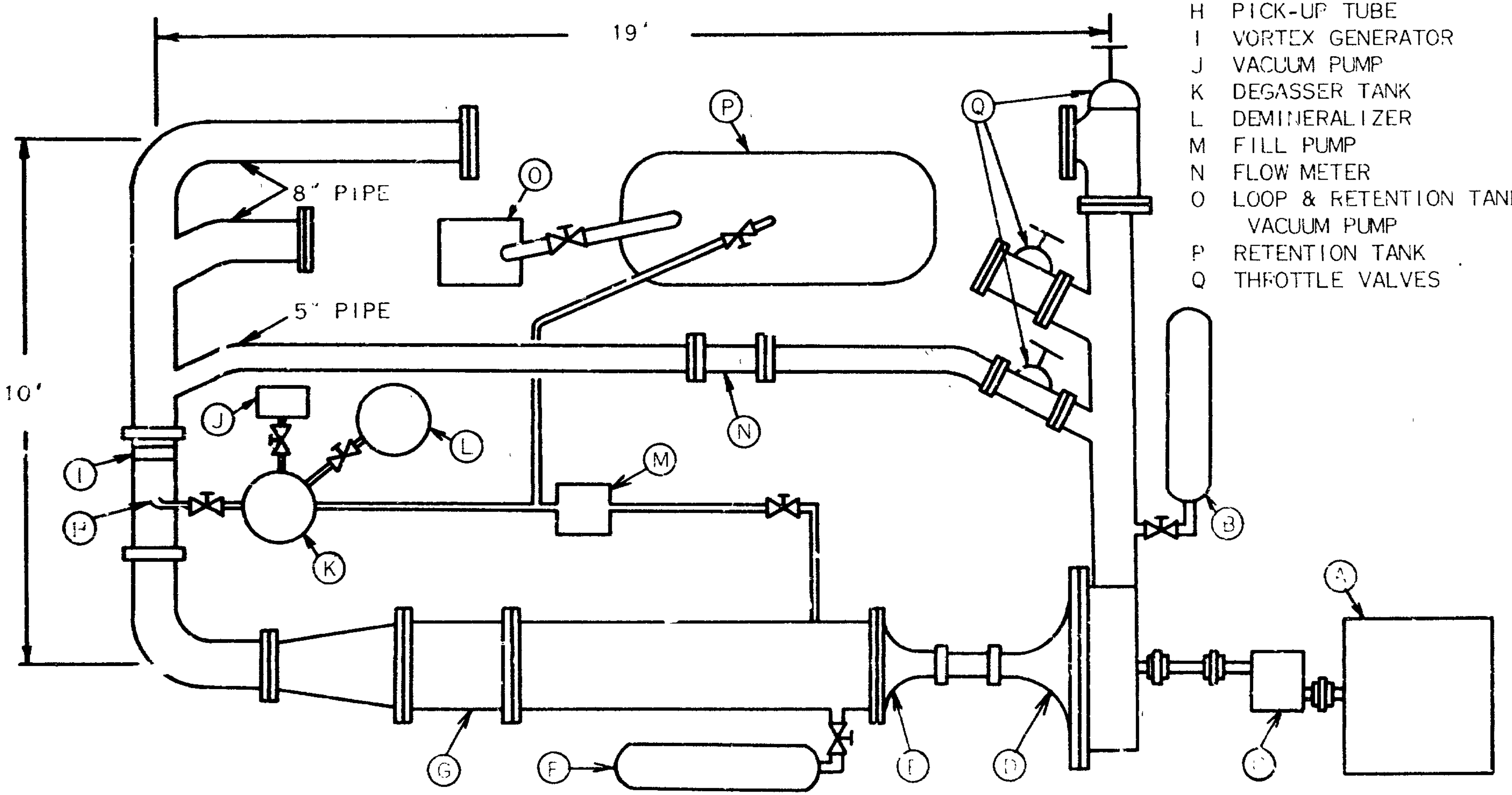
FIG 6



OVER-ALL VIEW OF IMPELLER WATER TEST STAND

FIG 7

SCHEMATIC OF IMPELLER WATER TEST STAND



LEGEND

A DC DRIVE MOTOR
B DISCHARGE PRESSURE ACCUMULATOR
C GEAR BOX
D IMPELLER HOUSING (CLEAR PLASTIC)
E INLET FLOW NOZZLE
F INLET PRESSURE ACCUMULATOR
G HEAT EXCHANGER
H PICK-UP TUBE
I VORTEX GENERATOR
J VACUUM PUMP
K DEGASSER TANK
L DEMINERALIZER
M FILL PUMP
N FLOW METER
O LOOP & RETENTION TANK VACUUM PUMP
P RETENTION TANK
Q THROTTLE VALVES

FIG 8

MODIFIED TURBOPUMP FOR LIQUID METAL TEST

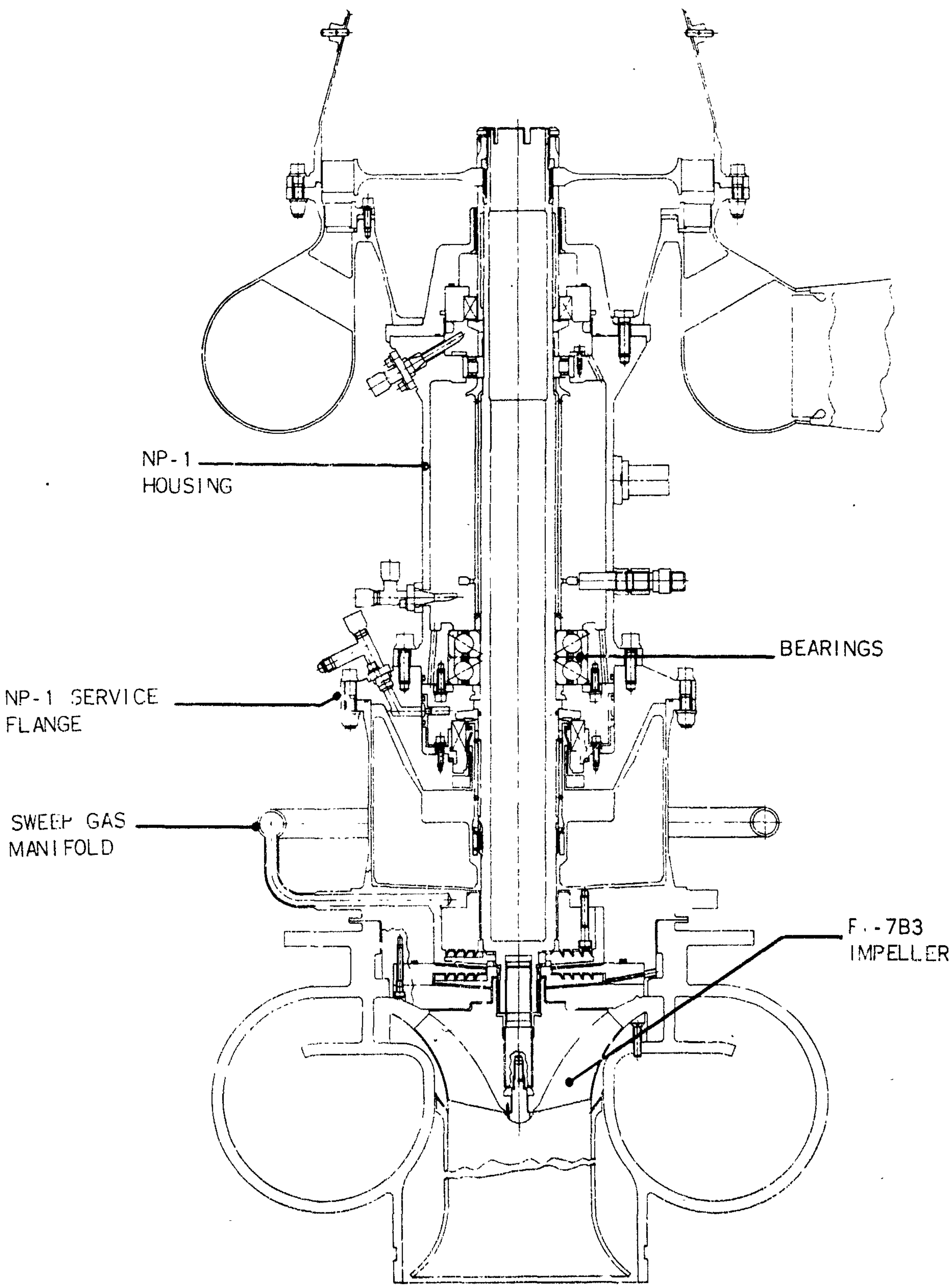


FIG 9

PHOTOGRAPHIC ARRANGEMENT

FIG 10

INSTALLATION OF IMPELLER IN WATER TEST STAND

FIG 11

HYDRAULIC PERFORMANCE OF THE RI-7A3 IMPELLER AT VARIOUS NOMINAL TIP CLEARANCES

SHAFT SPEED: 6375 RPM

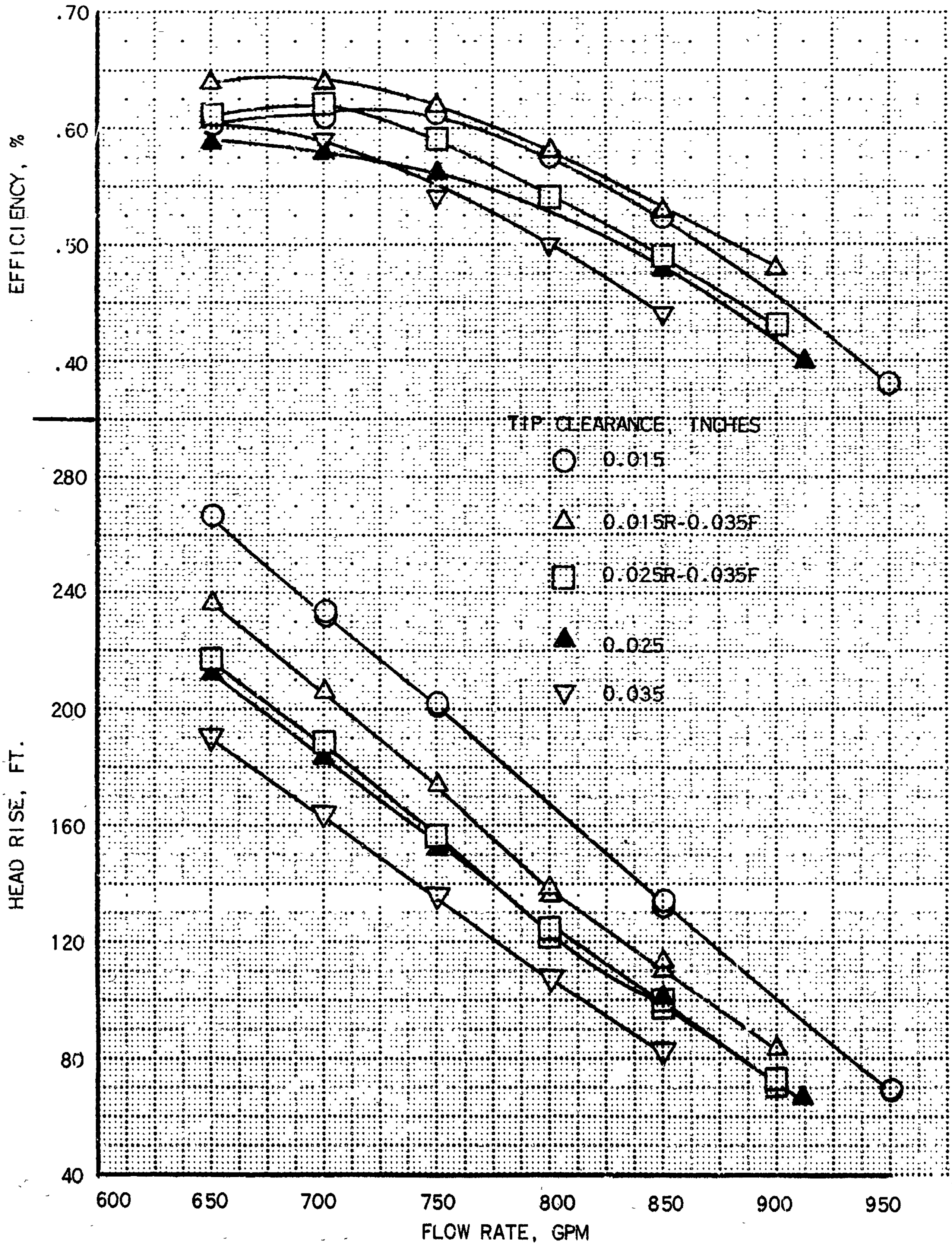


FIG 12

CAVITATION PERFORMANCE OF RI-7A3 IMPELLER AT VARIOUS NOMINAL TIP CLEARANCES

SHAFT SPEED: 6375 RPM FLOW RATE: 700 GPM

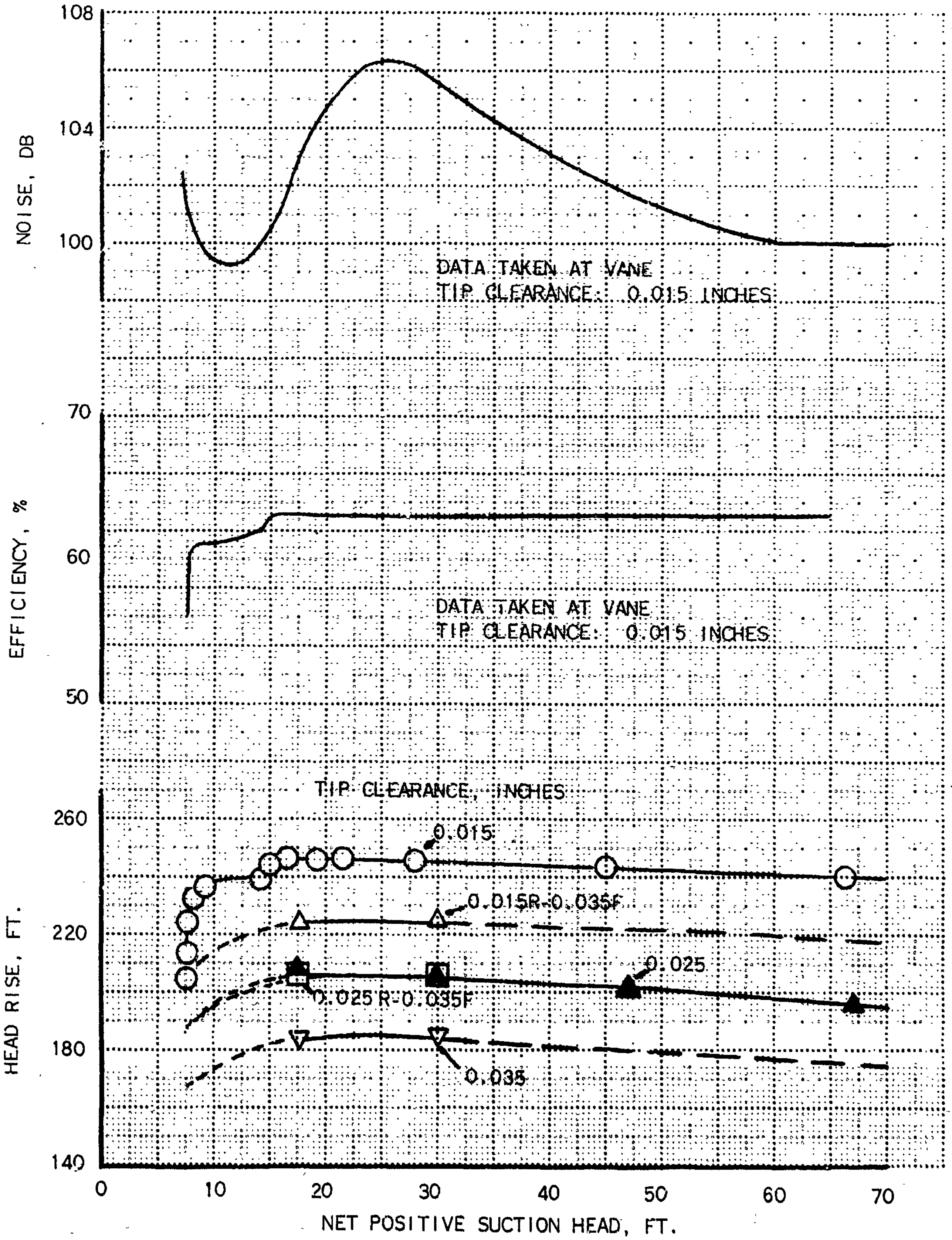


FIG 13

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 18 FEET AND 0.015 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 19,400 FLOW: 700 GPM

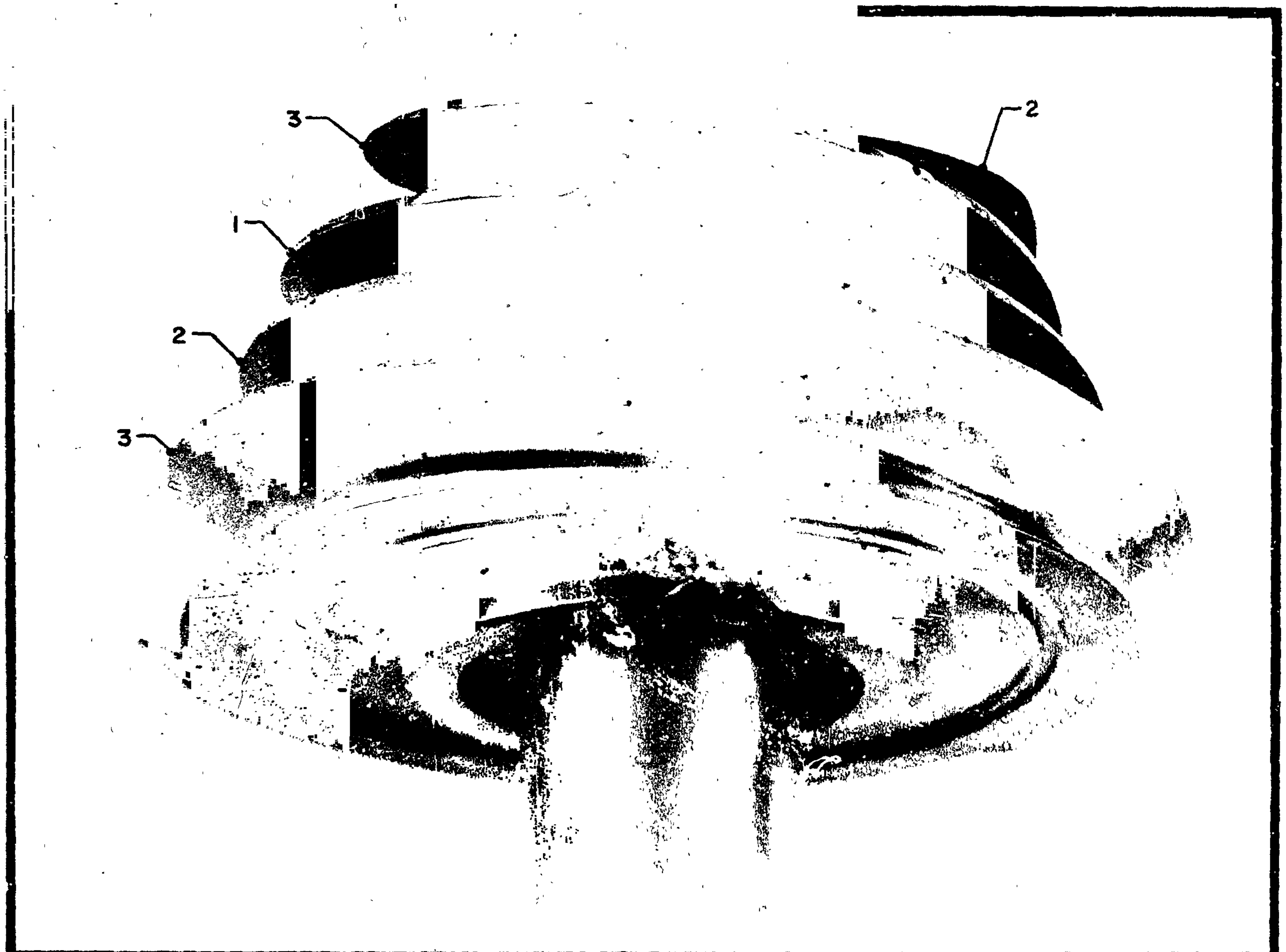
VANE 3

C-14089

FIG 14

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACE)

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.015 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)



CNLM - 6028

FIG 15

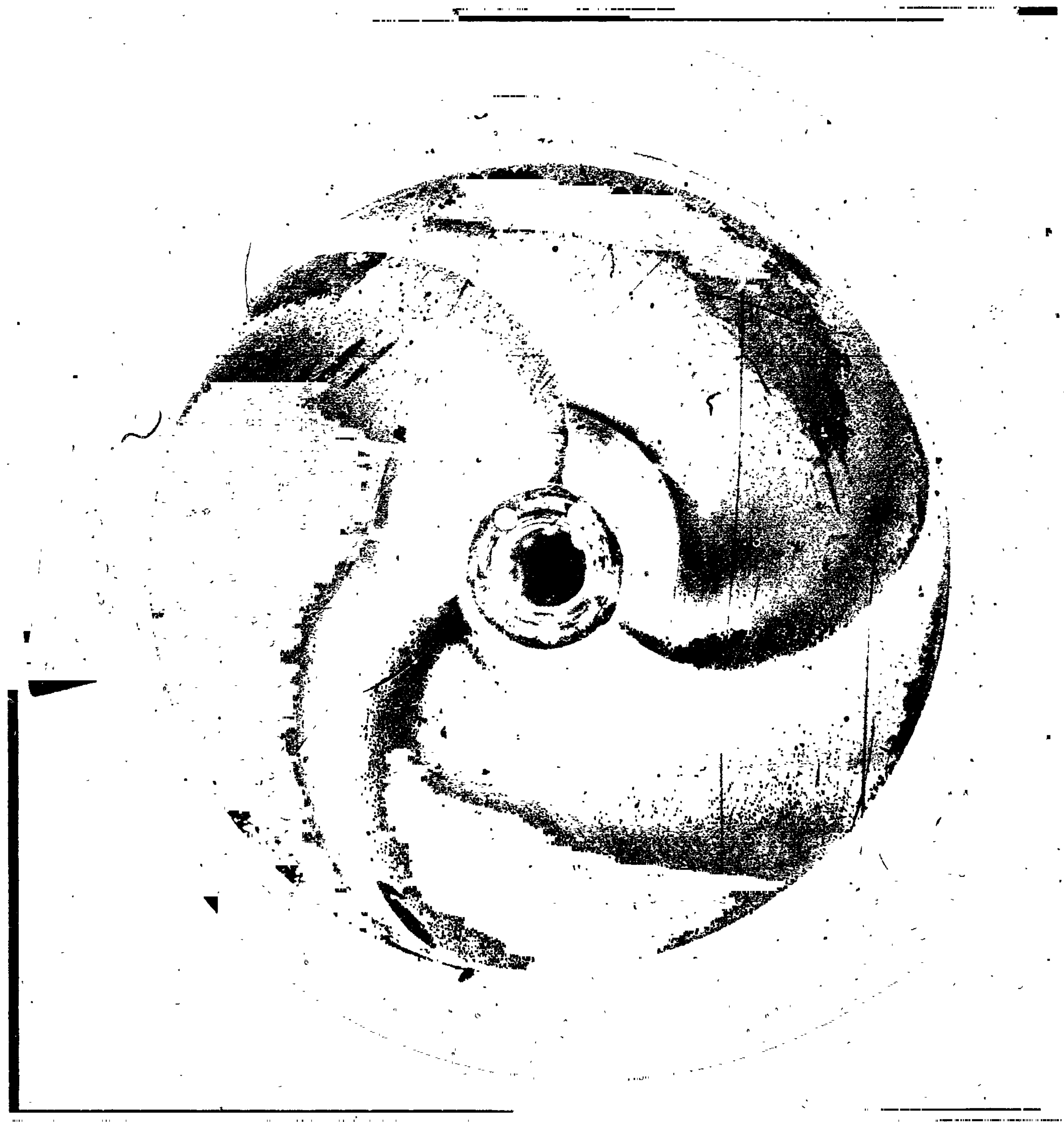
C-14087

FIG 16

C-14109

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AFTER FAIRING VANE 3 (SUCTION SURFACES)

VANE TIP CLEARANCE: 0.015 INCH



1C-570-6

FIG 17

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 30 FEET AND 0.015 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 13,100 FLOW: 700 GPM
VANE 3

C-14114

FIG 18

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

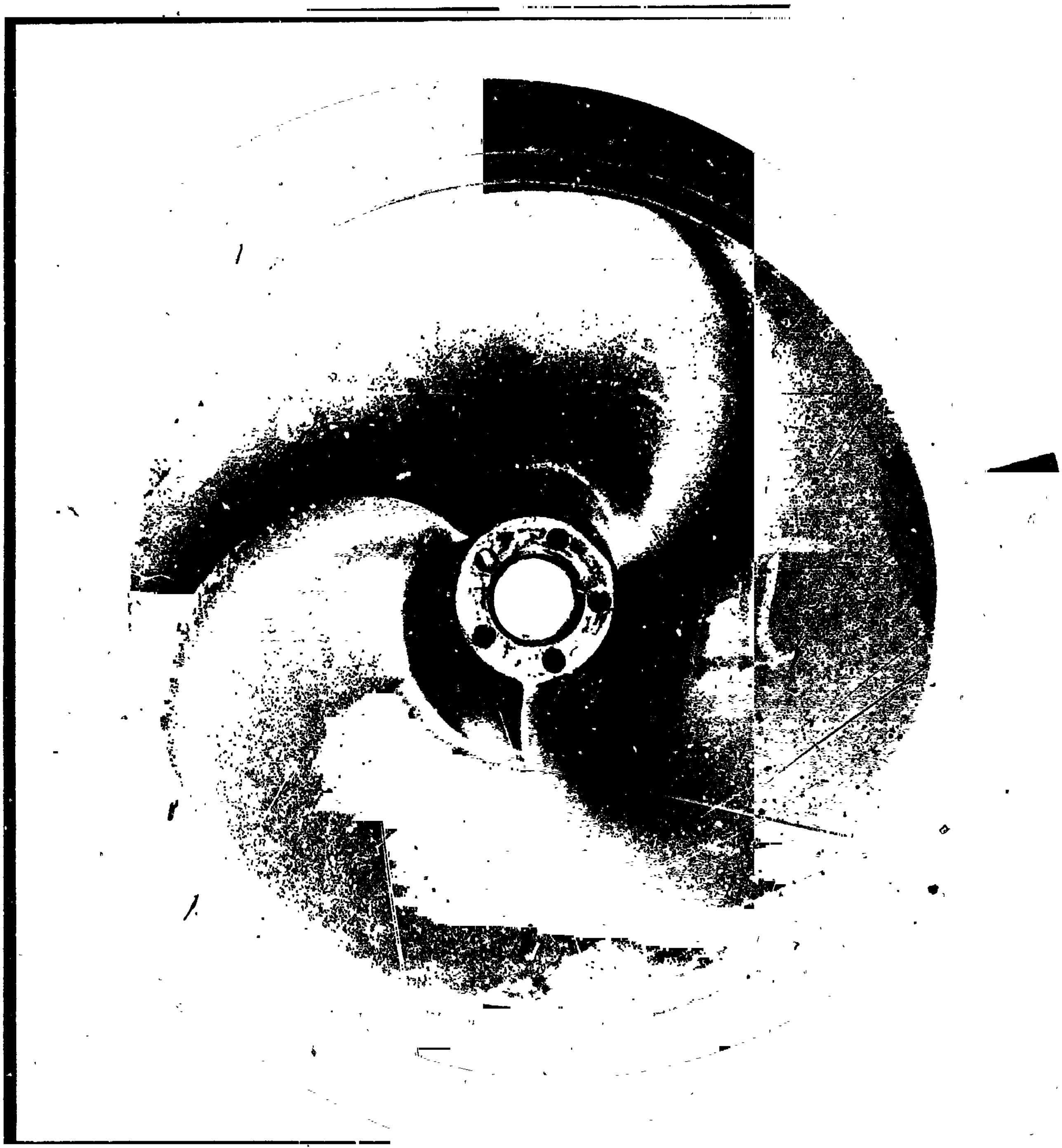


FIG 19

C-14115

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.015 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)

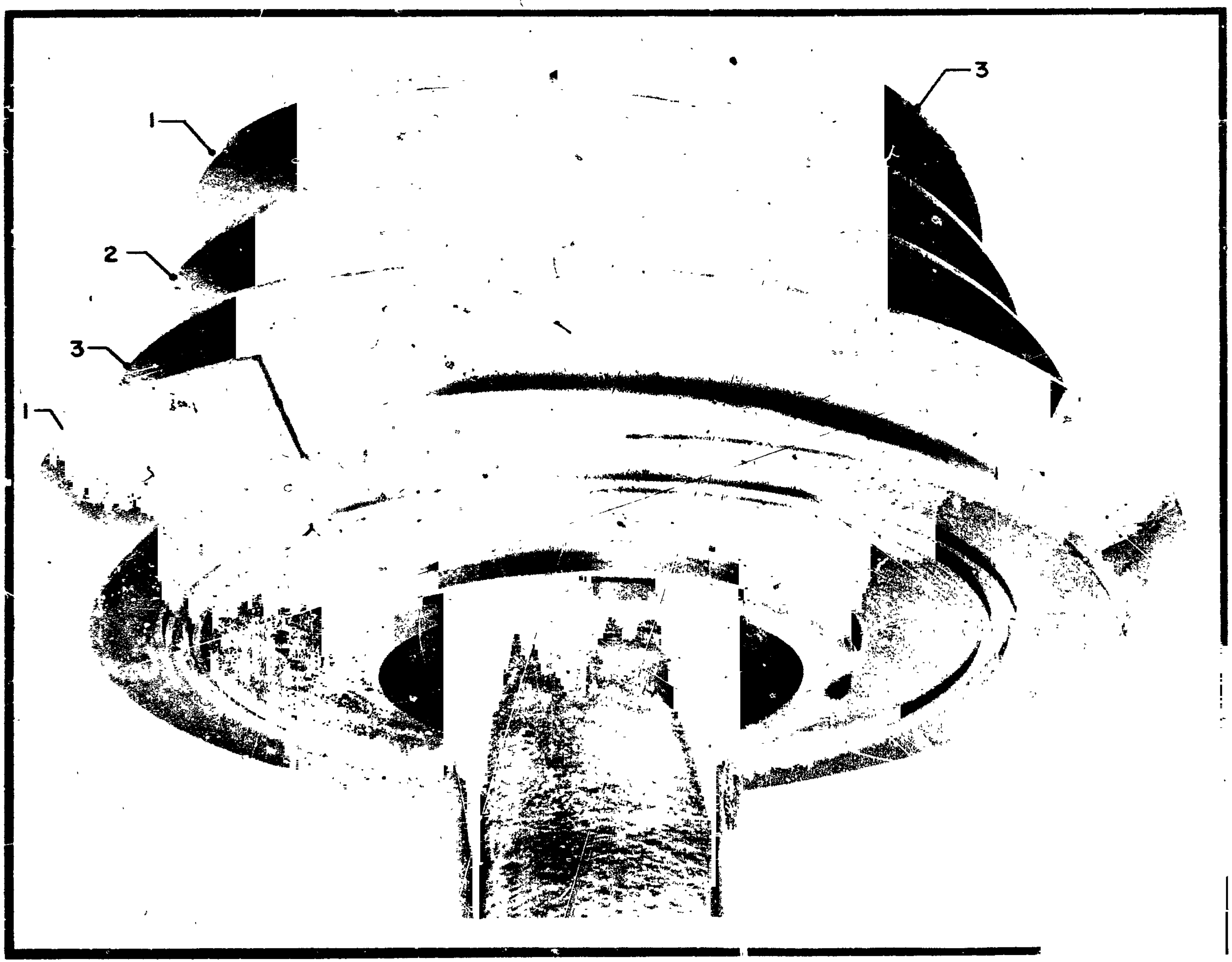


FIG 20

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 46 FEET AND 0.015 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 9500 FLOW: 700 GPM

VANE 3

FIG 21

C-14127

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 46 FEET AND 0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACE)

FIG 22

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 68 FEET AND 0 015 INCH VANE TIP CLEARANCE

SPEED: 6075 RPM N_{SV}: 7000 FLOW: 700 GPM
VANE 3

FIG 23

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 68 FEET AND 0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

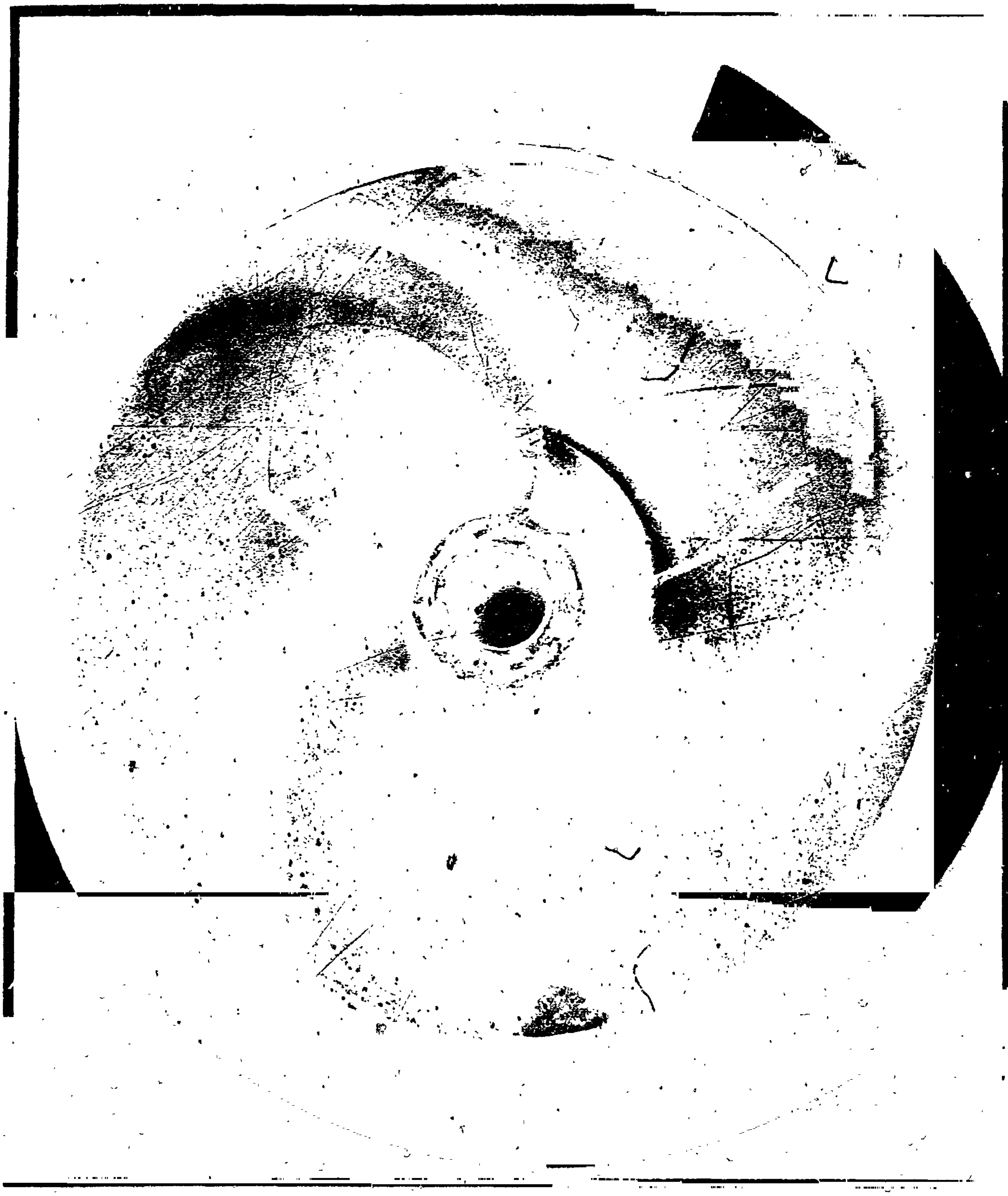


FIG 24

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 18 FEET AND 0.025 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 19,400 FLOW: 700 GPM
VANE 3

C-14230

FIG 25

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

C-14232

FIG 26

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACE CLOSEUP)

CNLM - 6028

FIG 27

C-14233

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.025 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)

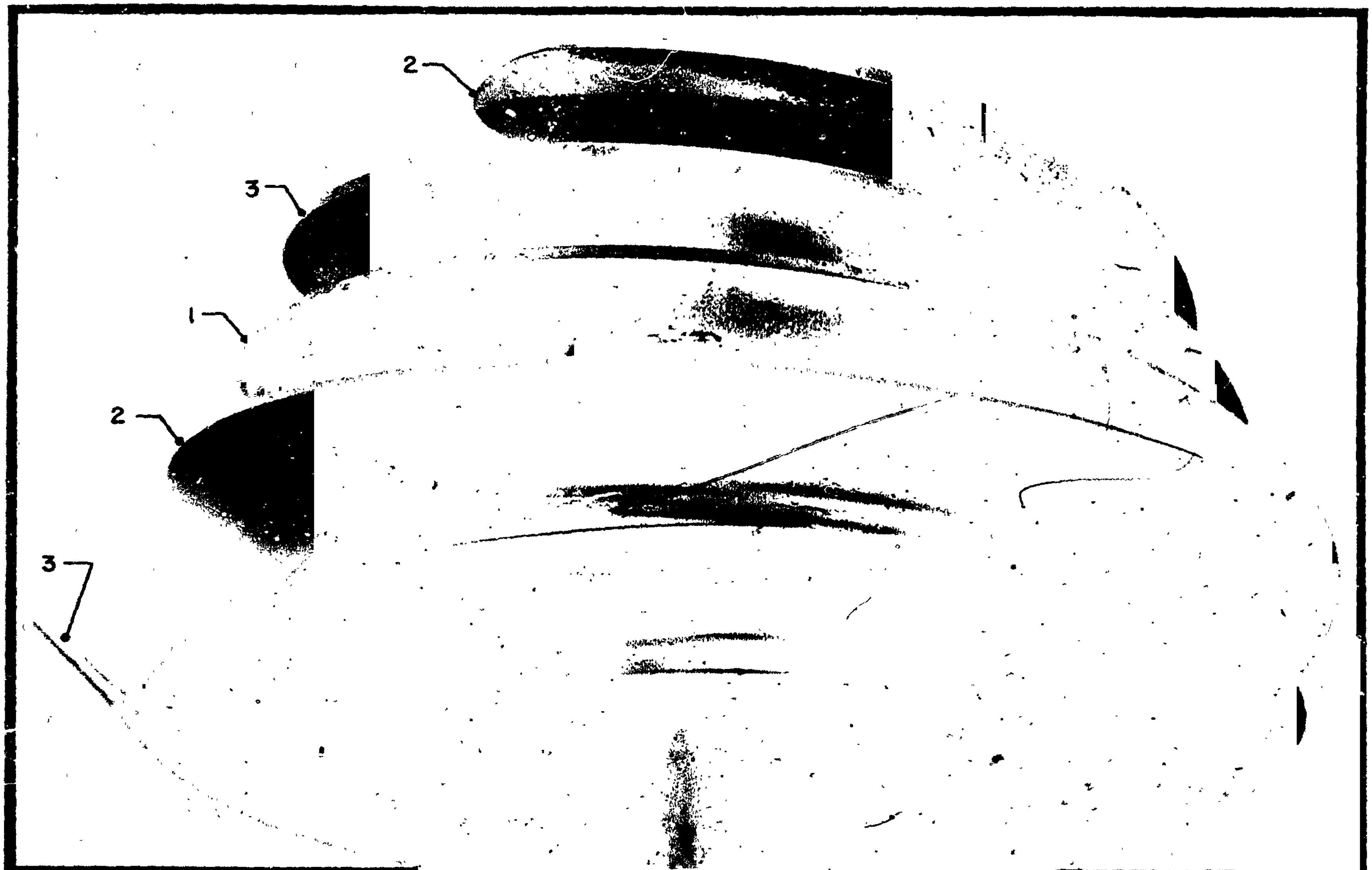


FIG 28

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 30 FEET AND 0.025 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 13,100 FLOW: 700 GPM

VANE 3

C-14236

FIG 29

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

FIG 30

C-14237

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.025 INCH VANE TIP CLEARANCE (PRESSURE SURFACE VANE 1)

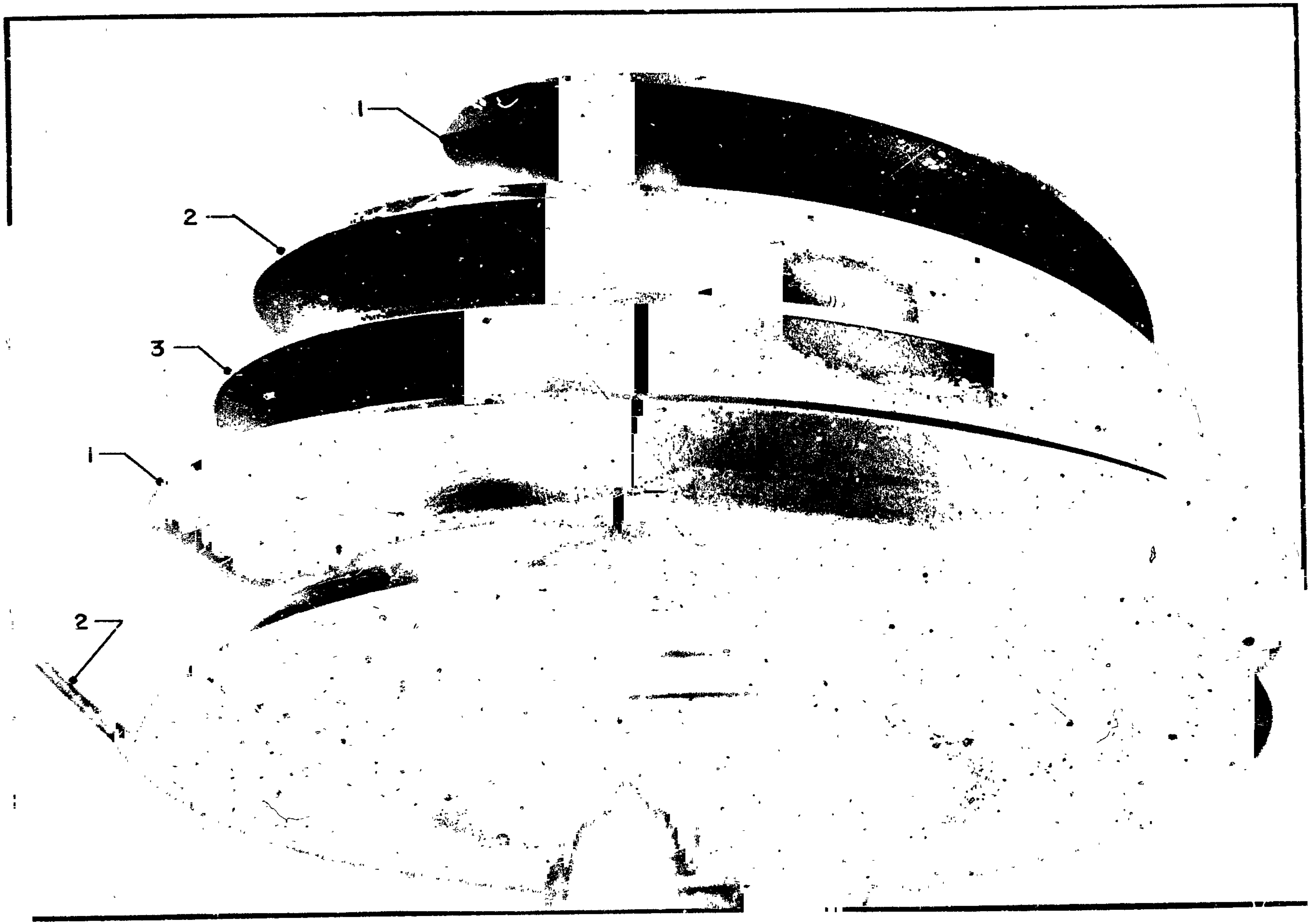


FIG 31

C-14239

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.025 INCH VANE TIP CLEARANCE (PRESSURE SURFACE VANE 2)

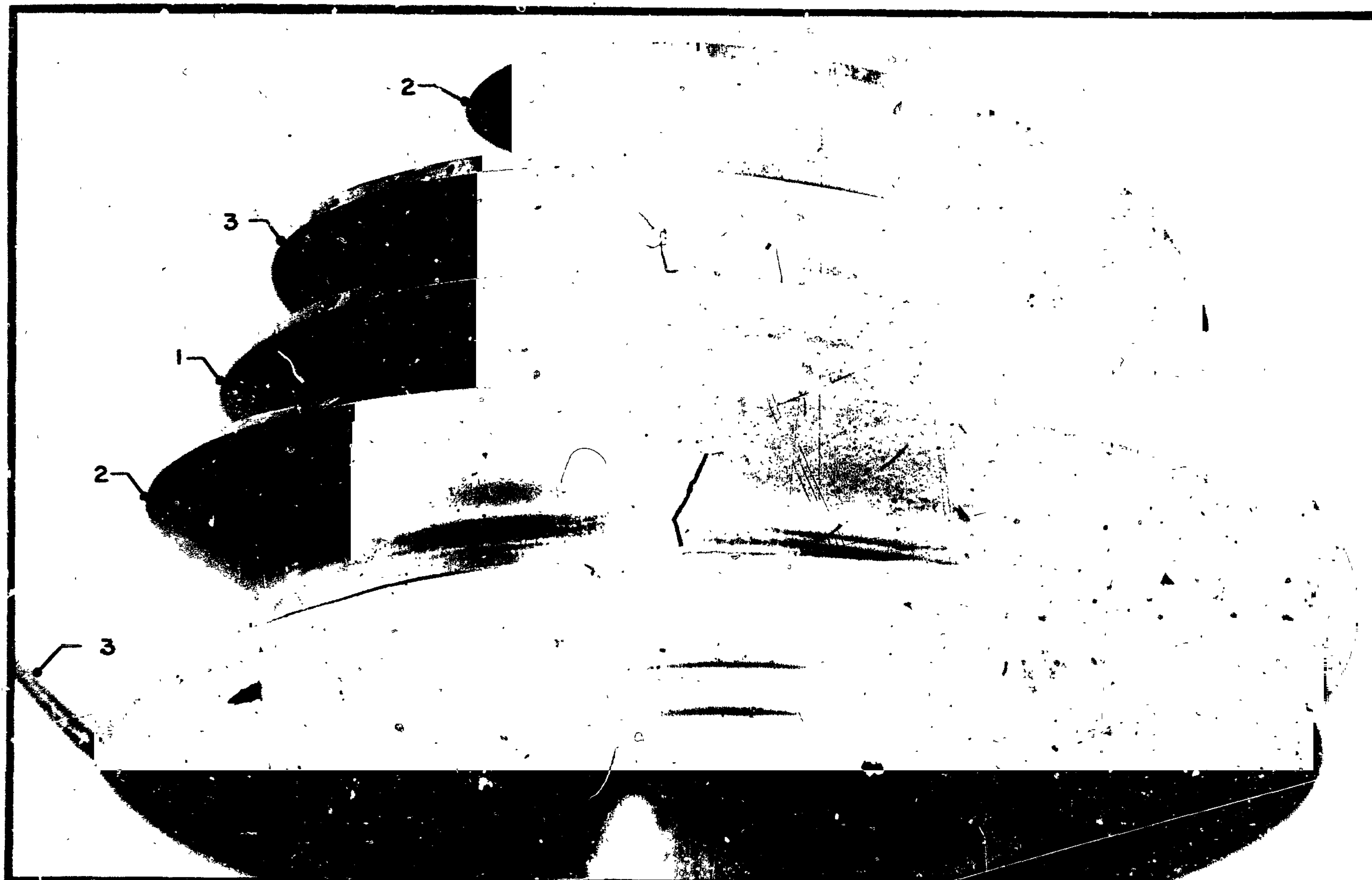


FIG 32

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 46 FEET AND 0.025 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 9500 FLOW: 700 GPM

VANE 3

C-14190

FIG 33

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 46 FEET AND 0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

FIG 34

1C-582-12

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 68 FEET AND 0.025 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM   NSS: [illegible]000   FLOW: 7[illegible] GPM

VANE 2

C-14195

FIG 35

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 68 FEET AND 0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

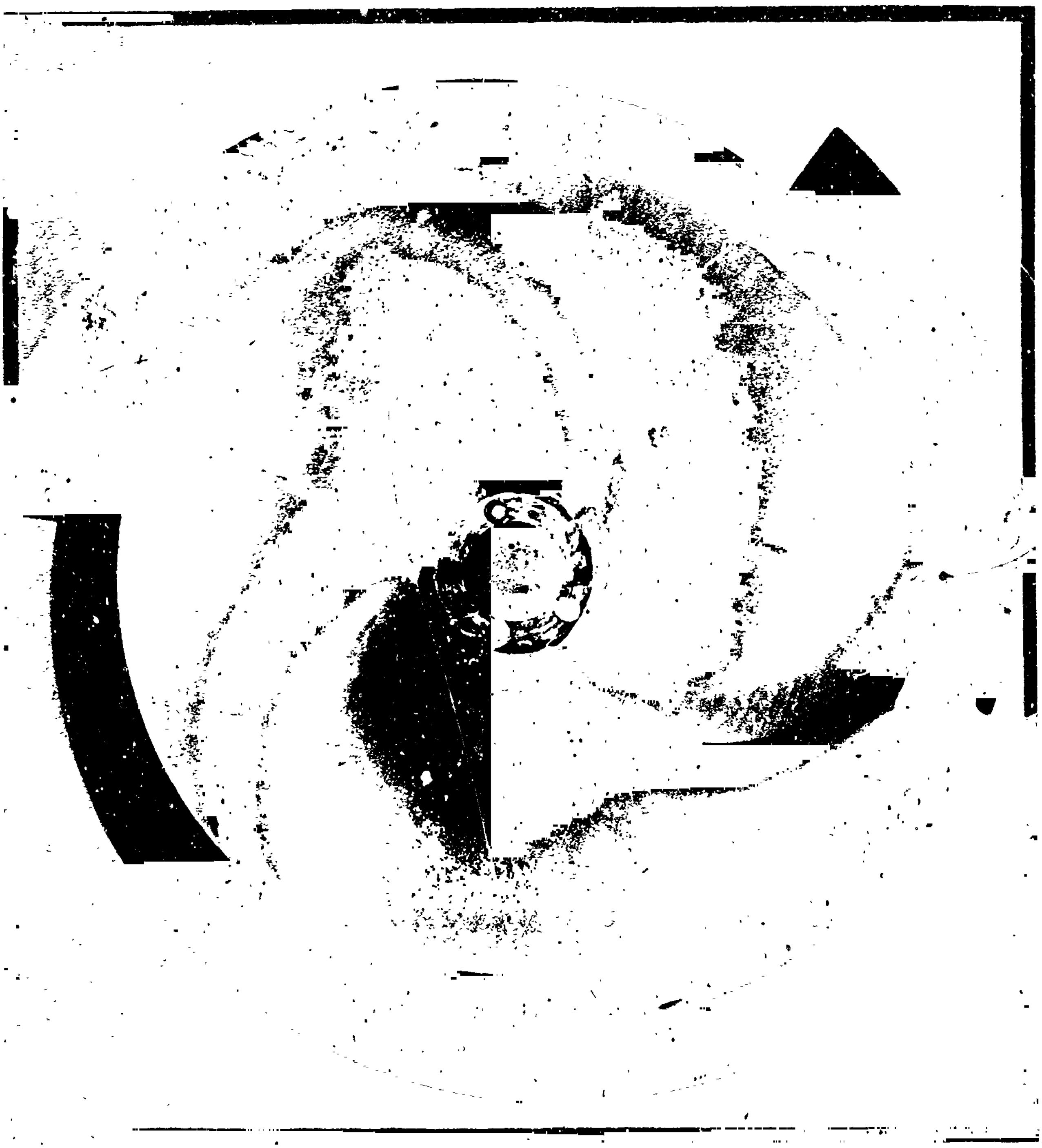


FIG 36

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 18 FEET AND 0.035 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 19,400 FLOW: 700 GPM

VANE 2

FIG 37

C-14352

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

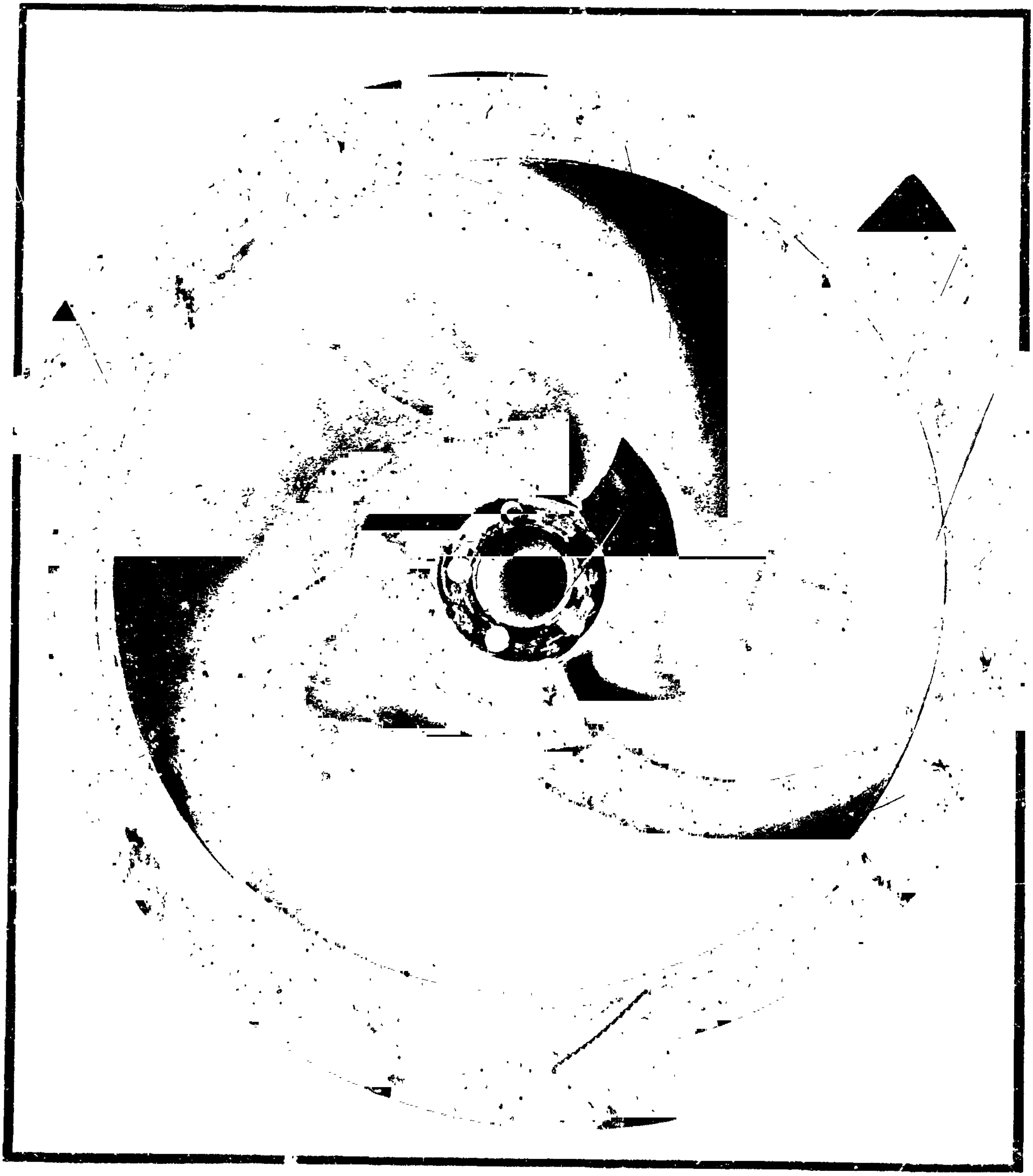


FIG 38

C-14357

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035 INCH VANE TIP CLEARANCE (PRESSURE SURFACE VANE 3)

FIG 39

CAVITATION OF THE RI-7A3 IMPELLER AT AN NPSH OF 30 FEET AND 0.035 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 13,100 FLOW: 700 GPM

VANE 3

FIG 40

C-14385

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

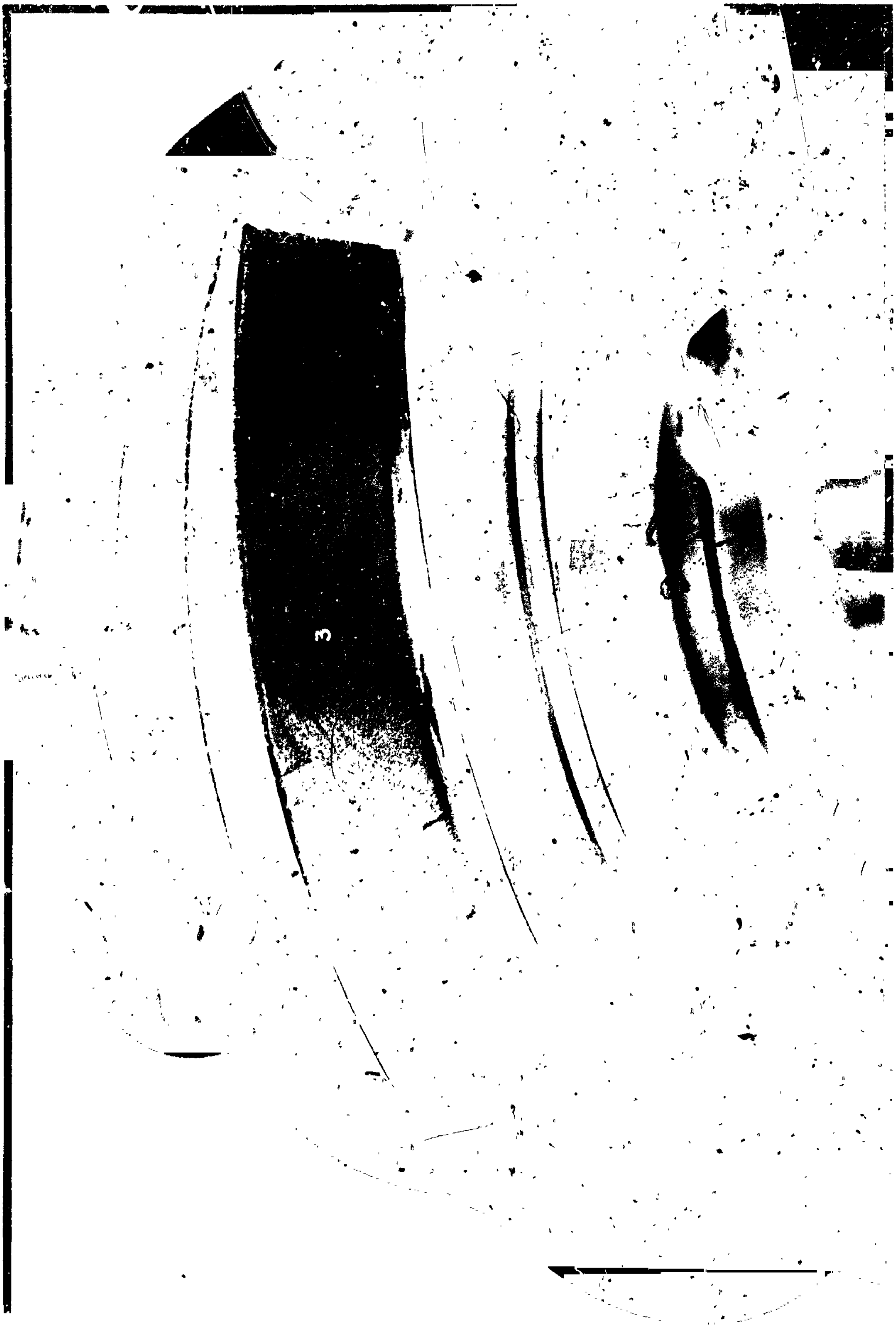
FIG 41

C-14390

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035 INCH VANE TIP CLEARANCE (PRESSURE SURFACE-INLET)

FIG 42

C-14391



COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035 INCH VANE TIP CLEARANCE (PRESSURE SURFACE-DISCHARGE)

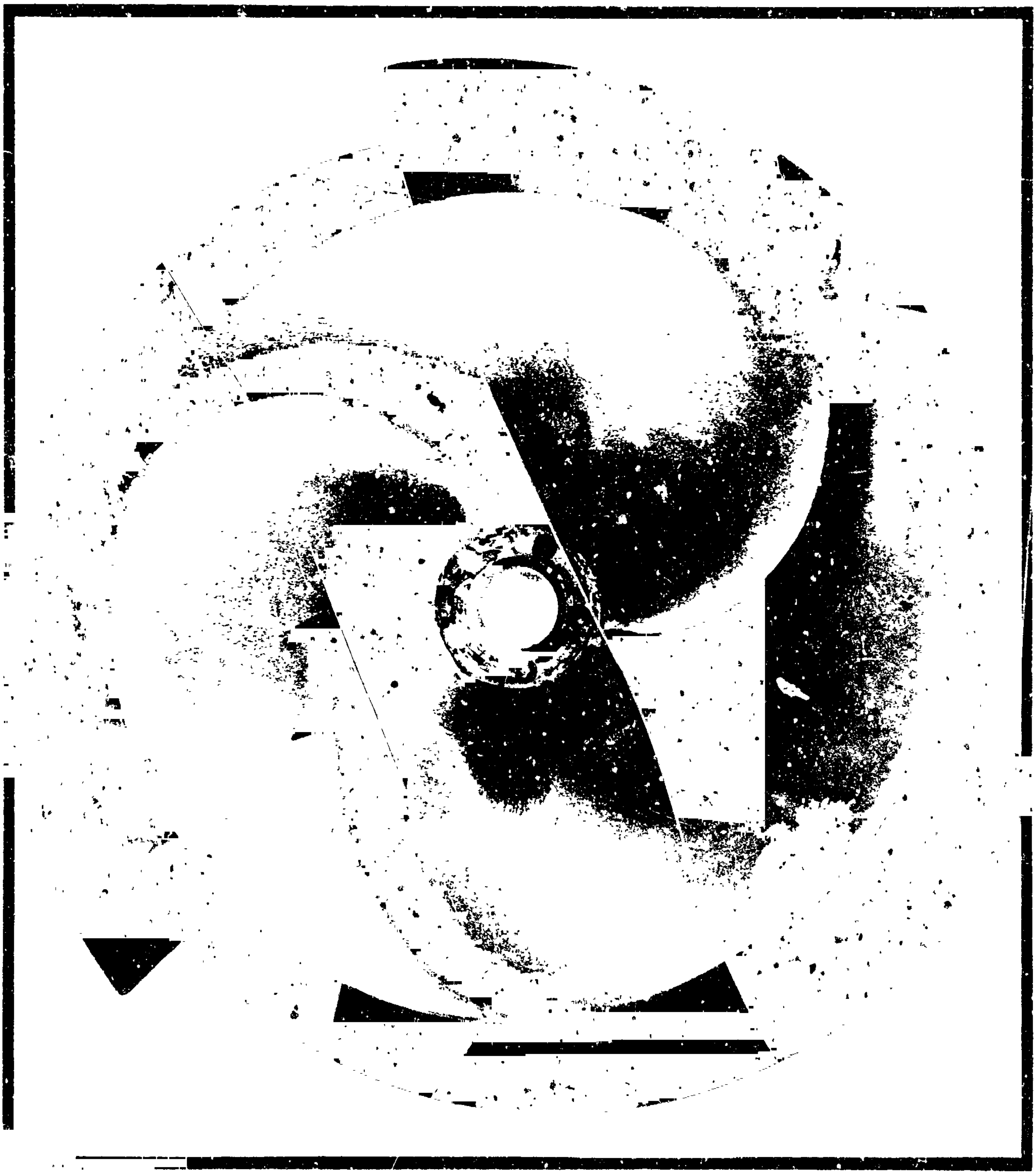
FIG 43

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 46 FEET AND 0.035 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM

FIG. ..

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 46 FEET AND 0.035 INCH VANE TIP CLEARANCE (SUCTION SURFACES)



COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 40 FEET AND 0.035 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)

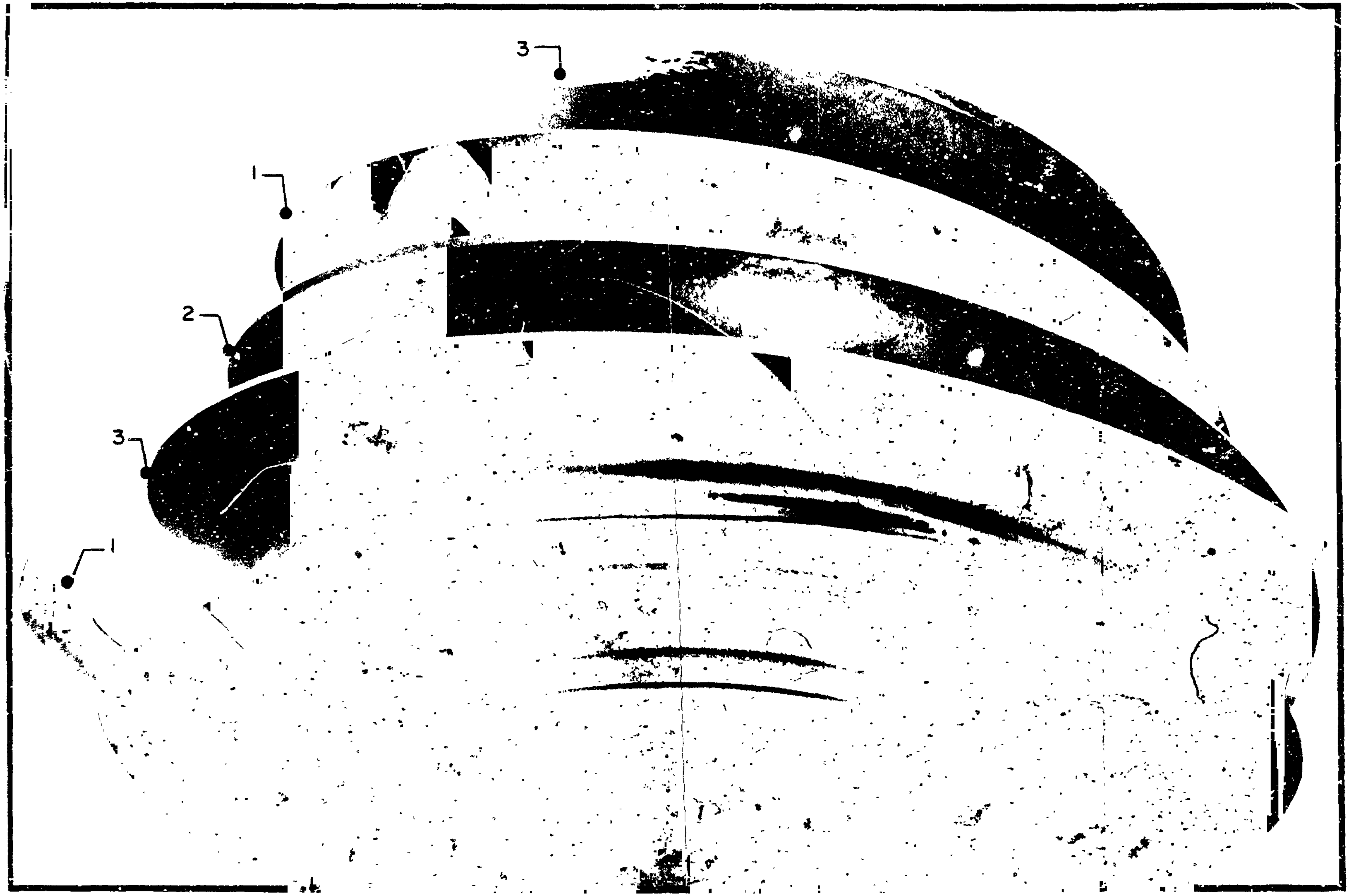


FIG :

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 18 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE

FIG :

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

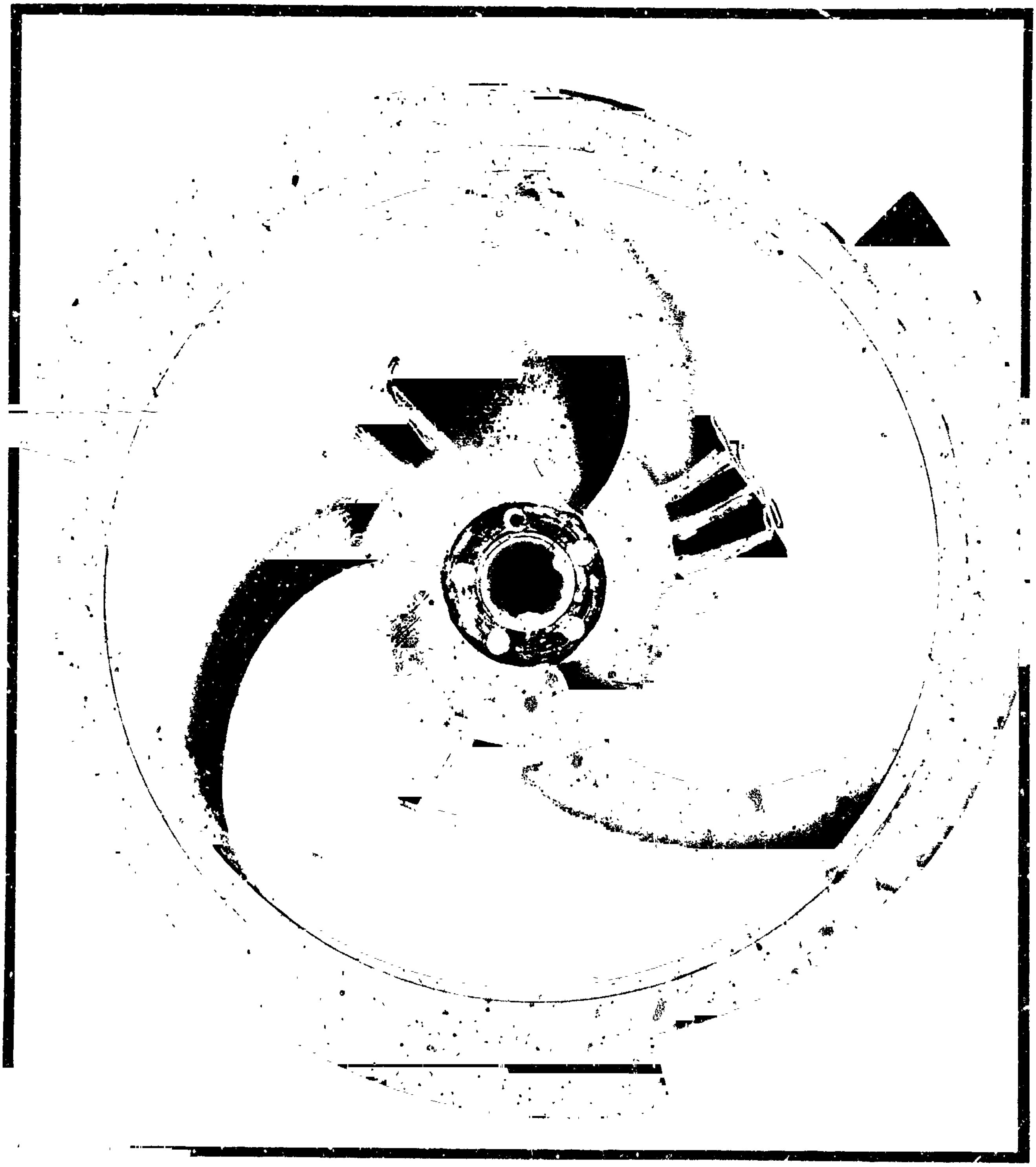


FIG 13

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE (PRESSURE SURFACE VANE 2)

FIG 49

C-14421

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE (PRESSURE SURFACE VANE 3)

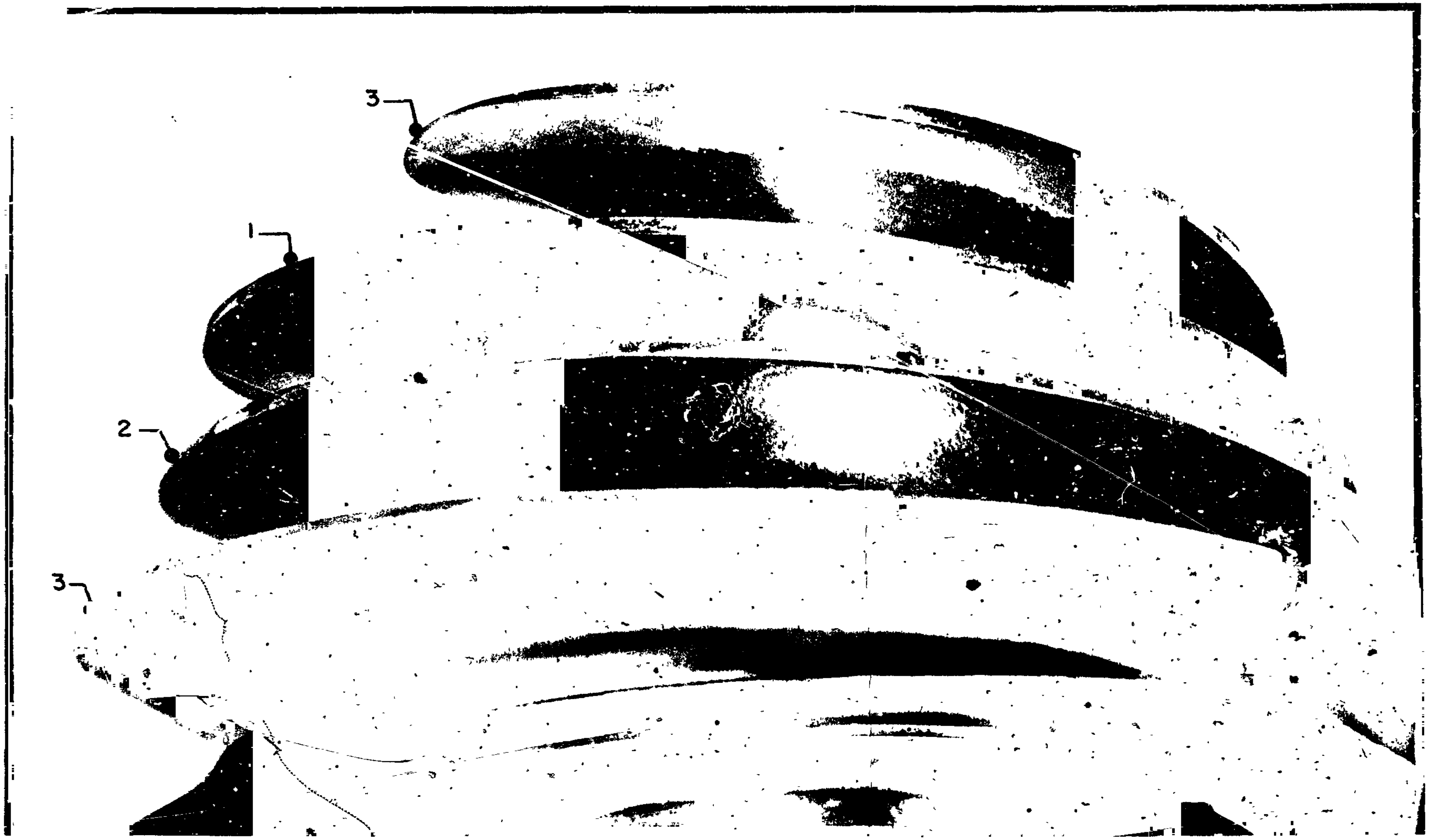


FIG [illegible]

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 30 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE

SPEED 6375 RPM [illegible] 13 [illegible] FLOW 7[illegible] GPM

VANE 3

FIG 51

C-14433

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035-0.015 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

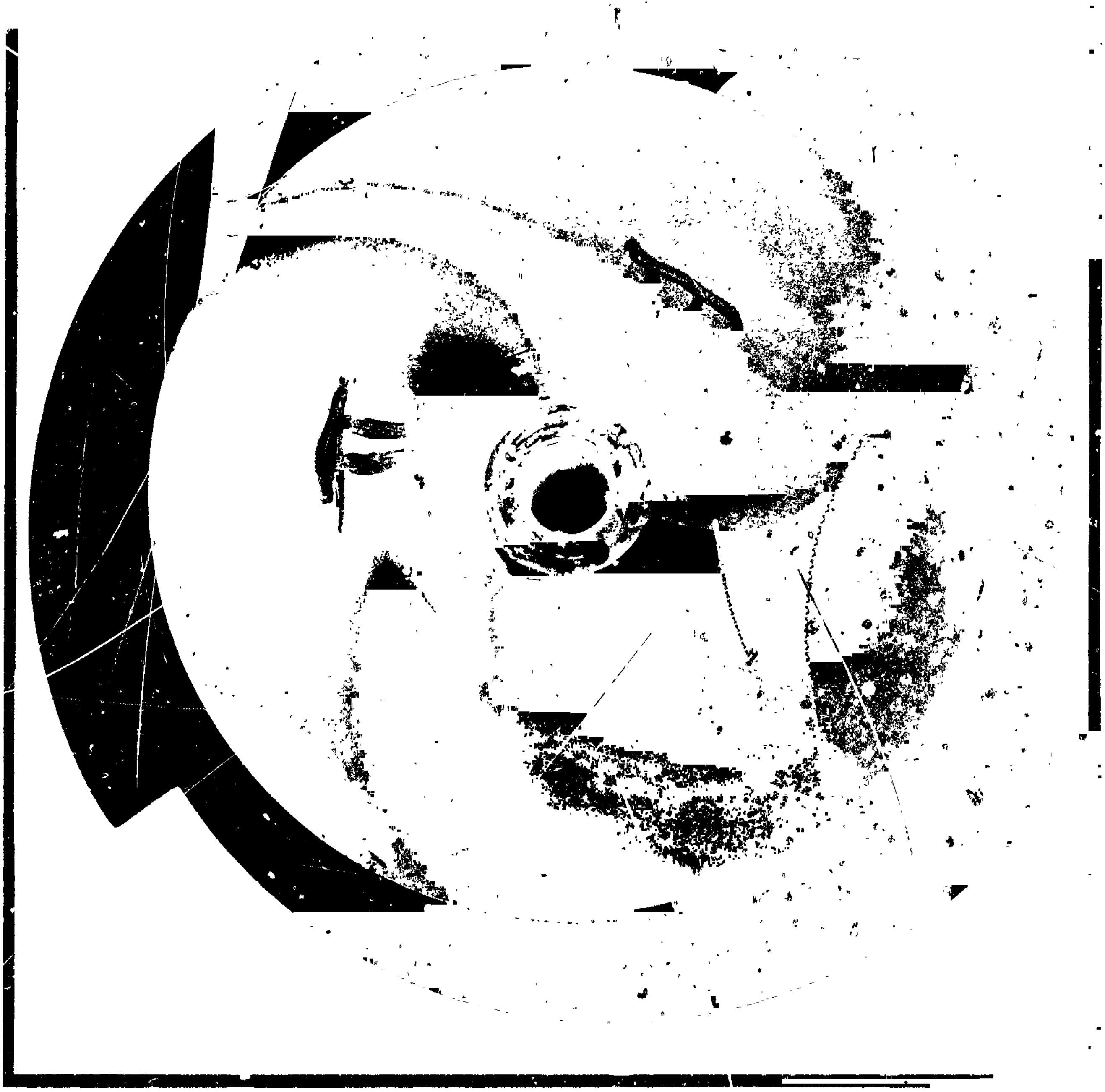


FIG 52

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND
0.035-0.015 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)

FIG 53

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 18 FEET AND 0.035-0.025 INCH VANE TIP CLEARANCE

SPEED: 6375 RPM N_{SV}: 19,400 FLOW 700 GPM

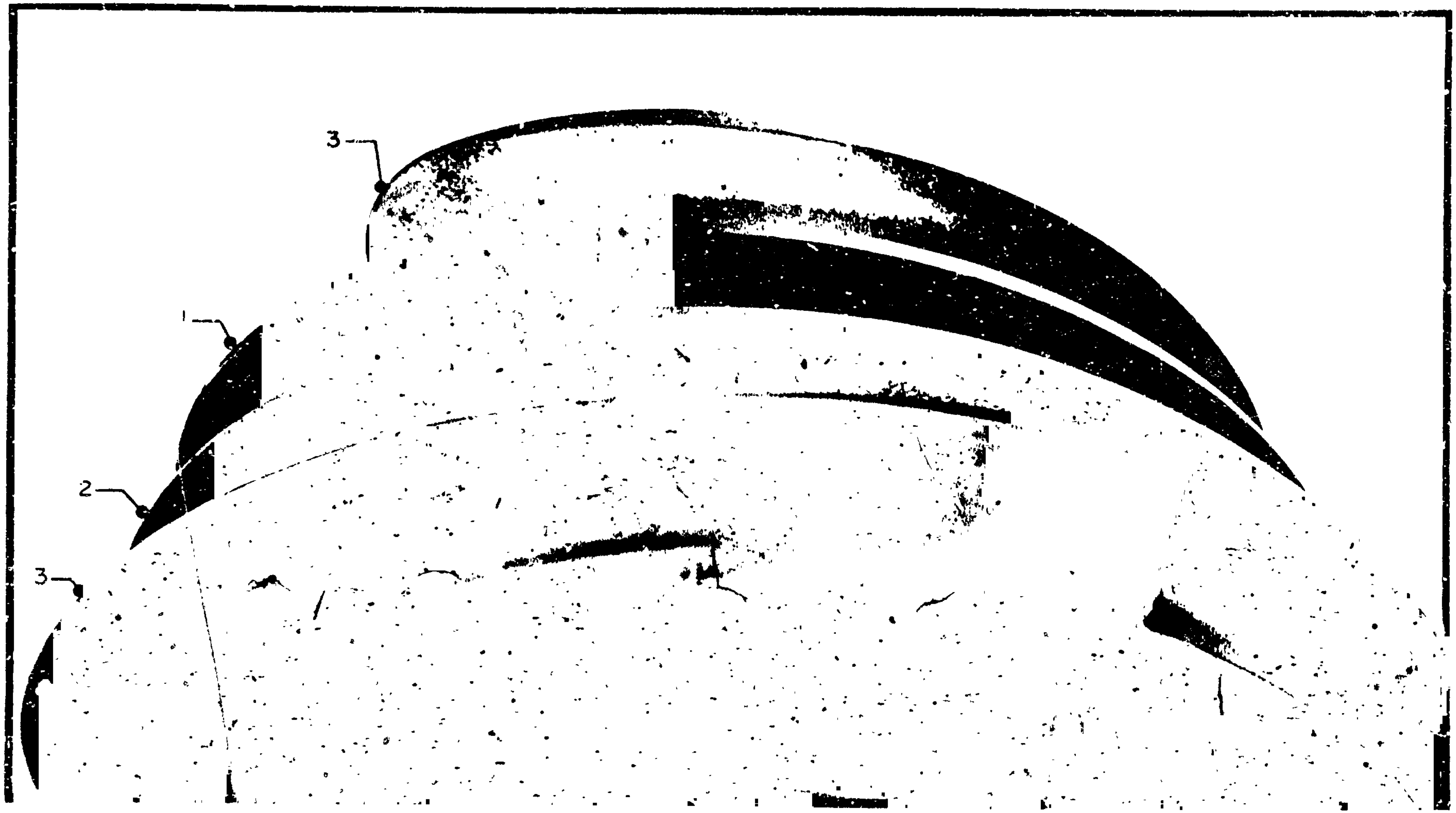
VANE 3

C-14441

FIG 54

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035-0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 18 FEET AND 0.035-0.025 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)



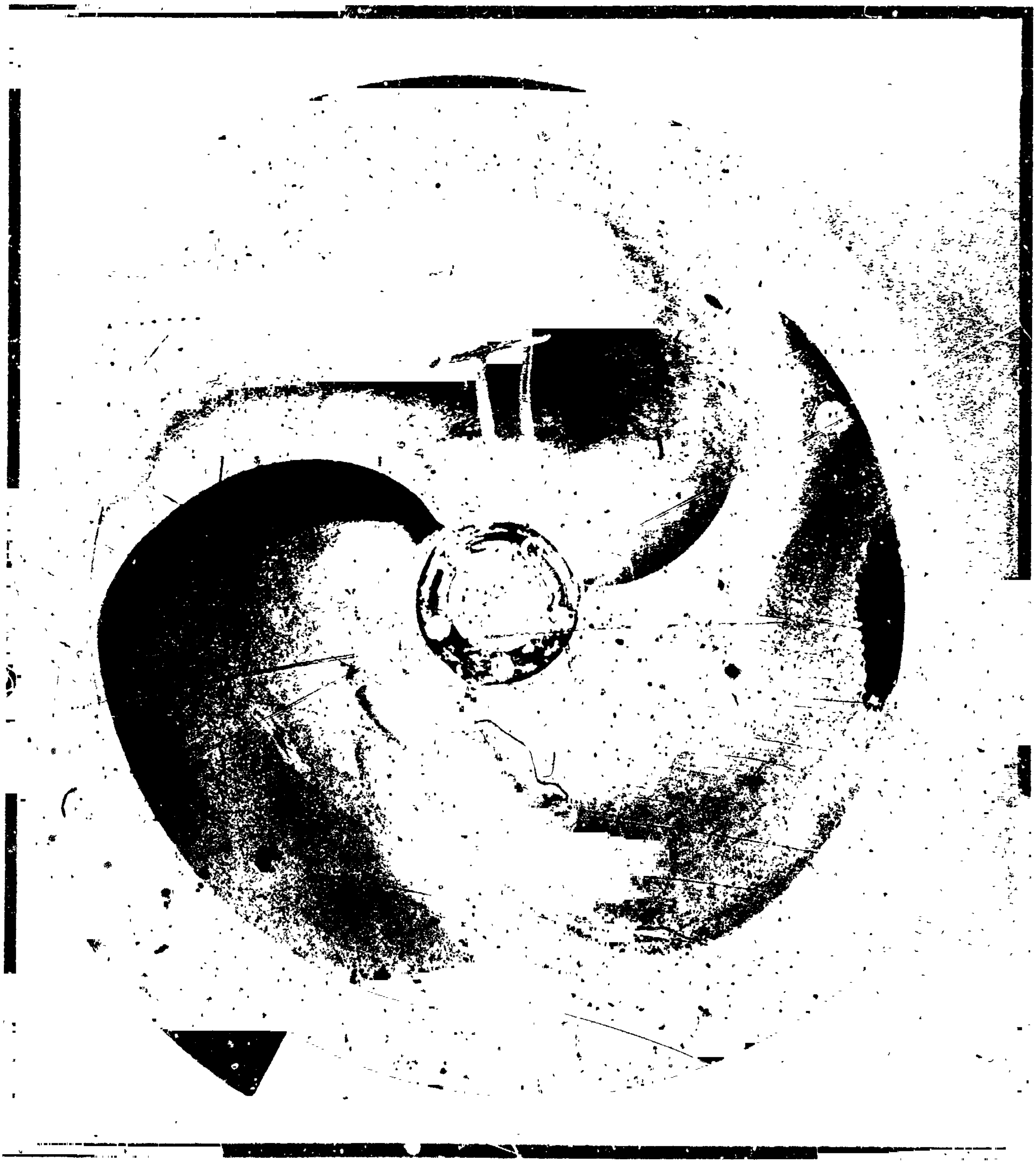
FIG

FIG

CAVITATION ON THE RI-7A3 IMPELLER AT AN NPSH OF 30 FEET AND 0.035-0 025 INCH VANE TIP CLEARANCE

FIG

COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035-0.025 INCH VANE TIP CLEARANCE (SUCTION SURFACES)



COATING DAMAGE PATTERNS AFTER 2 HOURS AT AN NPSH OF 30 FEET AND 0.035-0.025 INCH VANE TIP CLEARANCE (PRESSURE SURFACE)

FIG

IC-580-8
IC-580-1
IC-580-10

VARIATION IN DEGREE OF CAVITATION FROM VANE TO VANE

CONDITIONS

SPEED: 63[illegible]5 RPM NPSH: 30 FEET TIP CLEARANCE: 0.025 INCH CONSTANT

VANE 1 VANE 2

VANE 3

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