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GULF GENERAL ATOMIC

Gulf-GA-A12714

UC-77, Gas Cooled
Reactor Technology

PSC PRE-NUCLEAR PELTON WHEEL CAVITATION REPORT

By

Technical Staff

Prepared under
Contract AT(04-3)-633
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

Date Published: August 2, 1973

GULF GENERAL ATOMIC COMPANY
P.O. BOX 81608, SAN DIEGO, CALIFORNIA 92138

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INTRODUCTION

During the Hot Flow Test, the motive power for the circulator is supplied by pressurized water from the emergency feedwater system, which drives each circulator through a Pelton wheel trubine. These Pelton wheels are larger and capable of delivering much more power than the ones used in regular plant operation (2500 Hp vs. 560 Hp). They are also made of a different material (17-4 PH vs. Inconel 718). After a few hundred hours of operation, circulators 1A and 1D showed higher than specification wobble readings. Circulator 1C would not self-turbine after planned shutdown and 1B could not be brought up to full speed because of the inability to achieve full flow of the turbine water. After instrumentation integrity was established, the circulators were removed for inspection.

The wobble of 1A and 1D circulators was caused by an out of balance condition due to the loss of buckets (weakened by cavitation damage) from the Pelton wheel. The rotation of the 1C circulator was prevented by the ingestion and wedging of foreign metal particles in one of the water seals. The restriction in water flow to the Pelton wheel of circulator 1B was due to a piece of a tool file in one nozzle, and a portion of a valve trim in another nozzle.

The chronological sequence of events that led to the shutdown of the four circulators is described in the report, and the causes of wheel degradation and bucket failure are discussed. A comparison of the cavitation damage pattern with the kinematics of jet impingement provided guidance in formulating a cavitation suppression test program. This program, performed in the Circulator Test Facility, and its results are discussed in the report. A description is given of the nitrogen pressurization system designed to create sufficient backpressure in the turbine cavity to prevent cavitation. In addition, results of 300 hours of running with the corrective system are presented.

DESCRIPTION OF EVENTS LEADING TO
SHUTDOWN AND REMOVAL OF CIRCULATORS

"D" CIRCULATOR

On 7/31/72 excess wobble was noted on the "D" circulator while running at 7000 RPM. The circulator was shutdown to self-turbining. The wobble magnitude decreased with speed, but did not disappear at self-turbining speed, as would be expected if unbalance were its only cause.

Several quick checks were run at self-turbining speed in an effort to establish instrumentation integrity. One speed signal from "D" was routed through a "C" circulator speed module. No apparent change in wobble was noted; however actual values were not recorded. The speed simulator (a test rig with a rotating shaft and speed/wobble probes) was then used as a signal substitute from the circulator end of one of the speed probe cables. The indication was read on the wobble scope through a "D" circulator speed module. The signal received (a peak to peak wobble indication of approximately 200 millivolts) represented a normal speed simulator signal. The speed pulses from the simulator did not coincide with the peaks and valleys of the wobble sine wave as was the case when the "D" circulator speed probes were supplying the signal. No record of these initial checks were made inasmuch as they were immediate checks made to search out possible instrumentation malfunction. No instrumentation problem could be found. Direction was subsequently given to GGA Operations to limit "D" circulator operation to self-turbining speed until a test could be outlined which would better define the problem.

On 8/2/72 through 8/4/72 wobble magnitude measurements were obtained from all 12 speed probes from the "D" circulator at self-turbining speed. In addition, measurements from four of the 12 probes were obtained through

a "C" circulator speed module. Measurements obtained through the "C" module agreed reasonably well with those obtained through the "D" module on three of the four probes. On the fourth probe the measurement through the "C" module was approximately 50% that obtained through the "D" module. The data indicated shaft wobble with the greatest magnitude at the lower journal bearing.

On 8/7/72 Engineering requested further tests in order to define the problem more clearly. These tests (described in detail by GGA Test Request #045) obtained wobble measurements plus pictures of the wobble display at several shaft speeds above self-turbining. Their results clearly indicated shaft unbalance in the steam turbine/Pelton wheel area of the circulator, probably concurrent with shaft and/or lower bearing damage. It was thus determined that the "D" circulator was unavailable for the remainder of the Hot Flow Test. The immediate plans were to continue the Hot Flow Test with the three remaining operable circulators, even though "B" circulator was incapable of maximum available speed because of partially plugged Pelton wheel nozzles. This decision was reached on 8/11/72.

Subsequent problems on the "A" circulator (see next section) led to discontinuance of the Hot Flow Test. The "D" circulator pre-nuclear piping was removed and the Pelton wheel examined. It was found to be severely damaged: two complete buckets plus half of two more were missing. After removal of the damaged wheel and installation of a spare pre-nuclear wheel, self-turbining testing showed that shaft wobble was still present. This indicated that there was shaft (and possibly bearing) damage. The machine therefore was removed.

"A" CIRCULATOR

On 8/12/72 the wobble of the "A" circulator was noted as being somewhat larger than on prior operations. Speed was approximately 7000 RPM. The wobble indications were approximately 0.3 mill and 0.5 mill; higher than on previous operation but well below the 2 mill shutdown value. Pertinent circulator parameters were noted as being normal. Verbal direction was

given to continue operation and to observe wobble indications more frequently than had been practiced. The "A" and "B" circulators had been brought to speed in an effort to continue the Hot Flow Test. Approximately 5 hours later the "A" circulator tripped off on an indicated overspeed. Speed at the time of the trip was 7500 RPM. Wobble magnitude had not changed during that 5 hour period. About 45 seconds after the "A" circulator overspeed trip, the "B" circulator tripped on low bearing water flow, completely shutting down both "A" and "B". A logical explanation of this is that when "A" tripped the rapid speed change joggled the related bearing supply to drain ΔP sufficiently to call for an accumulator firing. The accumulator firing trips one bearing water pump and consequently "B" circulator tripped on low bearing water flow. Following this incident "A" would not self-turbine. The "A" circulator was subsequently broken free by bumping with Pelton water at 430 psi nozzle pressure. The circulator continued to self-turbine after it was bumped, although the wobble indication now was approximately 1 mill at the lower journal. Because of this excessive wobble indication at self-turbining speed "A" circulator was restricted to self-turbining speed.

On 8/13/72 a test was run on the "A" circulator to obtain and record wobble magnitudes and pictures. The test included a check of the wobble instrumentation, performed by substituting the input from the "A" circulator first with the input from the speed simulator, and then with the input from the "B" circulator speed probes. The test verified that the instrumentation was operating satisfactorily. Following the test the "A" circulator tripped during a blowdown of buffer sense lines. It would not self-turbine again. Subsequent removal of the pre-nuclear Pelton wheel piping and inspection of the wheel showed four buckets plus a part of the wheel hub were missing. The section of the hub with two buckets attached was recovered from the turbine water drain tank. The machine was subsequently removed.

"C" CIRCULATOR

On 8/10/72 the "C" circulator would not self-turbine. There had been no reports of excessive wobble on this circulator. It had been operated at

self-turbining speed and at 5300 RPM on 8/8/72. "C" was shutdown from the 5300 RPM run above because of relief valve problems on the emergency feedwater header. On 8/10/72 following repair of the relief valve, an unsuccessful attempt at self-turbining by bumping with Pelton water was made. A 15% open speed valve position was used.

On 8/11/72 another attempt at self-turbining by bumping was made. Five hundred psi at the Pelton nozzles was used. The circulator would not break free.

Attempts to manually break the circulator free so that it would self-turbine failed. The machine was therefore removed.

"B" CIRCULATOR

No problems other than partially plugged Pelton supply nozzles were noted on the "B" circulator. Because of the plugged nozzles the "B" circulator had been operated sparingly since 7/18/72 even though there were no operational restrictions imposed. The "B" circulator still self-turbined freely with no indicated wobble on 8/15/72.

Subsequent visual inspection of the pre-nuclear Pelton wheel showed no missing buckets, although some damage was evident. As predicted, the piping nozzles were found to be plugged with construction debris plus parts of the speed control valves which suffered cavitation damage.

The "B" circulator was to be left in the PCRV penetration pending examination of the other machines. This examination indicated that the bearing system of all machines required cleaning from debris and checking for possible debris damage. Therefore, the "B" circulator was removed from the penetration. At this time it was discovered that damage to the compressor rotor blades and inlet assembly support struts had occurred. This was later determined to be due to ingestion of a washer which reportedly fell from a temporary fixture above the circulator in the circulator outlet plenum.

METALLURGICAL FAILURE ANALYSIS

Upon removal of the Pelton wheels and closer examination of their buckets, it was determined that the failures were caused by severe cavitation damage. This led to undue stress concentration allowing cracks to develop. By repeated load application the failure of the bucket hub followed because of fatigue.

All the wheels exhibited cavitation damage, both on the tip of the splitter edge of the bucket face (see Figure 1) and on the back side of the bucket at the junction with the hub (see Figure 2). The C wheel was the most severely cavitated, followed by the D, A, and B wheels. The damage correlates with the actual operating times (see Table I). In addition to the cavitation damage, wheels A and D were missing several buckets and the C wheel was badly cracked. The B wheel bore no cracks and was intact (Figures 3 through 8).

Cavitation damage is caused by forces developed when vapor bubbles collapse against a solid surface. Pressures resulting from the collapsing bubbles may reach 225,000 psi with a damaging effect that looks like pits which may be reentrant and honeycombed. The cavities in the Pelton wheel buckets were rough, reentrant, honeycombed and penetrated deeply into the center of the bucket. The cavitation damage obliterated the tip of the splitter edge of the buckets. On the back side of the bucket, cavitation penetrated well into the hub. This damage appears to have occurred at the time of initial bucket contact with the water, when the jet impinges on the tip of the splitter, and leaves the bucket at its bottom, flowing along the junction between the hub and the back of the preceding bucket. Later on, the jet impinges on the inner portion of the splitter, and leaves the side of the bucket rather than the bottom.

TABLE I

CIRCULATOR OPERATING TIME, HOURS

RPM	A	B	C	D
1000	42	30	65	33
2000	42	72	24	24
3000	19	11	46	47
4000	28	35	54	54
5000	20	17	42	55
6000	20	48	10	11
7000	122	30	242	141
8000	43	14	23	16
	336	257	506	381
Self-turbining Time, hours	1465	1465	1180	1326
Operating Time Above 6000 RPM	185	92	275	168
Operating Time Above 7000 RPM	165	44	265	157

The A wheel lost two individual buckets and a large piece consisting of two adjacent buckets and an adjoining portion of the hub (Figure 3). The D wheel lost two individual buckets, plus portions of two more (Figures 4 and 5). The C wheel was cracked badly and on the verge of losing a pair of buckets (Figure 6). In the B wheel cavitation damage had progressed to a smaller extent (Figure 7). Dye-penetrant inspection of the wheels disclosed the presence of secondary cracks at the roots of several of the buckets on the A, D, and C wheels, but none were found on the B wheel.

Fatigue loading caused by the jet of water impinging on the buckets was the fracture mechanism that resulted in the bucket failures. Two points of fracture initiation were noted. One is located in the root of the bucket at the back side, in an area of severe cavitation damage (see for instance Figure 6 and top of Figure 3). The other is at the intersection between the front face of the bucket and the feather edge of the hub, as indicated by the arrow in Figure 8; a similar fracture is shown in Figure 5. The severity of the notch created by the cavitation damage or by the feather edge determined the origin of the fatigue crack. As shown by Figure 6, a crack of the first type was initiated in the C wheel by the cavitation damage at the back side of bucket No. 1 and was propagated in the direction of rotation by the stress created when the water jet impinged on the following bucket. A similar crack in the A wheel resulted in the loss of two buckets (see Figure 3). There was no doubt that the mechanism of crack propagation was fatigue, for when the C wheel crack was opened to show the fracture face, striations indicative of fatigue loading were clearly evident. The cracks originating in the root of the front face of the buckets had fracture features which less clearly indicated that fatigue was the mode of failure (Figure 8). The fracture propagated diagonally across the bucket under the stresses produced by the impinging water jet. As the crack continued to open, the force of the jet became more unbalanced, until finally the blade was torn away. Fatigue was the suspected mode of failure, but the characteristic striations were not clearly visible on the fracture. There were some indications of striations in the electron fractographs. To confirm that fatigue was responsible, a piece of the bucket fracture was sent

to Mr. William Wiebe of the Structures and Materials Laboratory for the National Research Council of Canada and Mr. J. A. Isasi of Westinghouse Steam Turbine Division. Mr. Wiebe's electron fractographs confirmed that the crack had propagated under fatigue loads.

Mr. Isasi's conclusions were that the failure is a typical high-cycle, low stress fatigue failure. No evidence could be found of cavitational damage associated with the origin of the fracture. However, it was determined that only 250,000 stress cycles were required to propagate the fracture from the origin to its maximum depth. At 7000 RPM, this corresponds to 35.7 minutes, a very short period compared with the several hundred hours of Pelton wheel operation. On the other hand examination of the fractured buckets (see for instance Figures 5 and 8), indicate that cavitation had progressed considerably at the time of fracture. These circumstances are explained by the fact that the stress in the affected area is comparatively low (3350 psi centrifugal, 20,000 psi bending). Therefore, considerable cavitation damage had to occur before the stress level could be raised enough to initiate a fatigue failure. This is further confirmed by the fact that wheel B, which has experienced limited cavitation damage, does not show fractures of any sort.

To determine whether the fracture might have been affected by material properties, the mechanical properties of the metal in the damaged areas were also tested. Three tensile test coupons were cut circumferentially from the hub immediately below the buckets on wheels A and D. The coupons were then machined to make 0.250 in. diameter by 1.0 in. gauge length tensile specimens, in accordance with ASTM E8, "Tensile Testing of Metallic Materials". The following results were obtained:

TABLE II

MECHANICAL PROPERTIES OF TENSILE TEST COUPONS TAKEN FROM WHEELS A AND B

Wheel	Coupon	YS (ksi)	UTS (ksi)	% C	% RA
A	1	114	144	12	34
	2	115	144	14	47
	3	114	144	14	47
B	1	111	142	11	36
	2	113	143	13	48
	3	114	145	15	52

The yield strength, elongation, and reduction in area were slightly below the nominal values reported by the Alloy Digest for ESCO Alloy 36PH in the H1050 heat-treat condition, namely, UTS 135 ksi, YS 120 ksi, elongation 18%, and RA 48%. The material callout on GGA Drawing No. C9901-111D is AMS 5355, which is 17-4PH stainless steel. It further requires the H1050 heat treatment, which includes:

1. Homogenizing at 2100°F for 1-1/2 hr in an inert atmosphere, followed by air cooling,

2. Solution heat-treating at 1950°F for 1 hr, followed by oil quenching, and

3. Aging at 1050° $\pm$ 25°F for 4 hr, followed by air cooling.

It should be pointed out that AMS 5355 B recognizes only the H925 heat-treat condition and its tensile properties; however, the H1050 condition is recognized by the industry as an acceptable treatment.

As a conclusion of the failure analysis the following decisions were taken: (1) the new Pelton wheels were cast in 17-4PH stainless steel and heat-treated with homogenization to the H1050 condition; (2) the feather edge between bucket roots was blended out to form a smooth contour both radially and circumferentially; (3) the necessity was recognized to suppress cavitation, by changing the ambient pressure in the Pelton wheel cavity.

A DISCUSSION OF THE CAVITATION MECHANISM

Despite the difficulty of making field measurements some conclusions concerning observed cavitation damage on Pelton wheels may be drawn.

Firstly, damage was observed in the center region of the bucket where the pressure coefficient must be positive. There is no way for bubbles to be generated here on a smooth surface, and even if impingement of solids caused eventual roughening the cavitation damage should appear downstream of this in the bubble collapse region. The bubbles must therefore have been generated somewhere upstream in the nozzle. There are many possible sources of bubble generation:

(a) The flow straightening vanes causing local secondary flow vortices near (1)* their bases, i.e., at the periphery of the jet.

(b) A negative value of the pressure coefficient over some portion of the vane profile or tips.

(c) Pressure minima due to secondary flows in the elbow preceding the nozzle.

(d) Effective angles of attack for the straightening vanes due to the elbow causing a curved velocity profile.

A study of the kinematics of jet impingement on a given bucket is of valuable assistance in the interpretation of the cavitation damage pattern. The study is illustrated in Figures 9 through 12. Based on the relative

*Numbers in parenthesis designate references at end of paper.

jet velocity V_r and the bucket curvature, the general flow pattern in the bucket can be established. By comparing the flow pattern with the cavitation damage pattern (shown by Figures 1, 2 and 5) it appears that the damage was done essentially during the initial period of jet-bucket interaction, that is by the water in the periphery of the jet. Therefore, of the possible problem sources considered above, the most likely is (a), probably compounded by (d).

Regardless of the source, the bubbles generated may be collapsed before reaching the Pelton buckets if sufficiently high chamber pressure is used. Whether or not this occurs depends upon the collapse time which is given (2) by:

$$t = 0.915\ R_o \left(\frac{\rho}{P_\infty - P_v}\right)^{1/2}$$

The distance traveled in the jet from approximately the beginning of the nozzle straight section is accordingly:

$$S = Vt = 0.915\ V\ R_o \left(\frac{\rho}{P_\infty - P_v}\right)^{1/2}$$

Let us consider, for instance, a 1 millimeter initial radius, with one atmosphere above vapor pressure in a 600 ft/sec jet; in this case the distance before collapse would be approximately 1.8 centimeters, sufficiently short to avoid collapse on and hence damage to the bucket. It can be seen that the distance traveled is proportional to initial bubble size and jet velocity, whereas it is inversely proportional only to the square root of the overpressure.

The initial size of the bubble is very difficult to calculate since it depends on the history of local pressures in the flow field as well as

the existence of undissolved gas. It seems that the effect of dissolved gases would be slight due to the high flow velocities involved. This has some experimental verification (3) and the physical reason is that there is not enough time for gas to come out of solution at the bubble wall when the bubbles are of the transient type and do not spend long periods in a thick boundary layer. (5) The critical size (radius of the bubble above which it will start to grow) does however increase with gas content and with (6) temperature, according to the formula: $R^* = \left(\frac{3}{2}\frac{NT}{\sigma}\right)^{1/2}$. Thus higher temperature or gas content could lead to greater distances of travel in the jet before collapse.

As indicated by the above formulae, if the cavity pressure P_∞ does not exceed the saturation pressure P_v the bubbles do not collapse before reaching the buckets and cavitation occurs. Unfortunately, in the initial period of the Hot Flow Test no measure was taken to control the pressure in the closed cavity where the Pelton wheels are located. Thus, an equilibrium saturation pressure was established corresponding to the ambient temperature and any bubbles present in the jet could not collapse before reaching the buckets.

If the bubble has not collapsed by the time it reaches the bucket, then the high pressures due to the stagnation region will cause it to collapse unless it is extremely close to or on the jet outer boundary where the pressure must just be chamber pressure. Bubbles in the outer boundary may be skimmed off without collapsing until this thin spray sheet containing them hits some other boundary (such as the rear of a bucket) where it does come into a high stagnation pressure region and can collapse, causing damage.

It appears that the mechanisms discussed above are sufficient to explain most of the observations. Fortunately the indicated remedies are the same for most of these mechanisms. They are, in order of importance:

(a) Raising the chamber pressure to as high a value as possible and/or reduce the water temperature to as low a value as possible. (Although the pressure required has been calculated here, it does not apply if the upstream separation induced vorticity is of sufficient intensity to cause low pressure vortex cores to persist in the free jet. However, the latter circumstance is not very likely.)

(b) Remove the straightening vanes. (Cavitation inception parameters as high as 0.8 have been observed even without an attack angle (1) and the situation is worse if there is one).

(c) If possible, avoid elbows near the nozzle, and if this is impossible keep them where the pipe diameter is large and the velocities smaller.

Of these three solutions of course, only the first two are possible due to geometry restrictions in the PCRV. These two solutions were tested at the Circulator Test Facility and are described in detail in the next chapter.

CAVITATION SUPPRESSION TEST

Test Hardware

As discussed in the previous section, suppression of cavitation can be achieved by controlling the ambient pressure at some level above the saturation pressure. To test this concept, and determine the amount of overpressure required, a rig was designed. This rig (illustrated by GGA Drawing 90-SK-5198, and outlined by Figure 13) contains a nozzle mounting flange, a fixture to hold specimens reproducing the geometry of the bucket, a large reservoir to collect the water and provisions to vary the pressure. In addition, four windows allow visual and photographic flow observation, as well as lighting. To prevent condensation from forming on the inside of the glass, double windows were provided with hot (280°F) water flowing between them. One of the side windows was used for a strobe light source with a 1 μsec pulse and the other three for placement of photographic equipment.

The inlet of the Pelton wheel nozzle was connected to the discharge of two water accumulators. Boiler feedpump water from the Valmont Power Plant was admitted to these accumulators and then pressurized with nitrogen with sufficient pressure to be able to simulate the nozzle water discharge velocity. Nitrogen was also used as the cavitation suppressant gas in the test chamber.

Three different specimens were selected for use in the test chamber. All of them were made with almost pure aluminum which is highly susceptible to cavitation and therefore minimizes test duration requirements. The first, specimen A, (Figure 14) approximates the bucket's curvature in its sections normal to the radius, but it has no curvature in the sections perpendicular

to the axis of rotation. By arranging specimen A at an angle to the jet equal to the bucket's angle in Figure 9, and letting it intercept the periphery of the jet, the flow at the start of impingement can be approximately simulated.

Specimen B was designed to approximate the bucket's profile along the section of maximum cavitation line, which is very close to the streamline corresponding to initial impingement. With reference to Figure 15, let AA be the cross section along the direction of maximum observed cavitation damage. Specimen B approximates this cross section by a combination of a straight line and a circular arc. In the test rig, it is arranged with its straight section parallel to the jet.

Specimen C is identical to specimen B in shape, but it is arranged with a positive incidence angle with respect to the jet.

Three separate nozzles were used in an attempt to determine an optimum nozzle configuration. These configurations were:

(1) Pre-nuclear nozzle. (Stearns-Roger Drawing No. 90/99-M-1-12). This is the nozzle used throughout the initial Hot Flow Test running.

(2) "Modified nuclear nozzle" (By modified it is meant that the nozzle had the same area ratio and area ratio schedule as the nuclear nozzle but the diameters increased to be fitted to the pre-nuclear piping). (GGA Drawing No. 90-SK-5194-1)

(3) Short "modified nuclear nozzle" (this nozzle had the same shape as (2) except it had no straight section at the discharge). (GGA Drawing No. 90-SK-5194-2)

In addition, each nozzle was run both with and without the flow straightening vanes installed. For vaneless runs, a spacer sleeve was added to maintain a smooth flow surface.

Test Description

With the test rig assembled and a specimen mounted in such a way as to capture only the first 10% of the jet, ∿260°F water was run through the nozzle into the rig to equalize the temperature. The chamber was vented several times to drive out any air trapped inside. When the equilibrium pressure in the vessel equaled the saturation pressure of the ∿260°F water, it was assured that all air was removed from the chamber. The accumulator was then filled with this same temperature water and the volume above the piston inside the accumulator pressurized to 1600 psig. This pressure was required to drive the water through the jet at the same relative velocity as in the actual operating Pelton wheel. Then, depending on the test condition, nitrogen could be added to the test chamber to supply the overpressure needed to suppress cavitation.

Then, all valves would be reset stopping the normal low pressure water flow to the vessel and the bottom valve of the accumulator opened. A fast opening valve was then actuated to allow the high pressure flow from the accumulator into the nozzle. During the firing, pictures of the jet were taken. Unfortunately, due to the high flow rate of water, the upper part of the vessel would fill with water and splash on the viewing windows within one second after the firing. This limited the amount of pictures taken but did include the initial high velocity jet. Due to the adiabatic expansion of the gas in the accumulator, after one second, the supply pressure decayed by ∿175 psi thereby making photographs of this lower velocity phase less important.

Test Results

During the course of testing all three specimens were fired upon at different suppression pressures. It was very difficult to obtain cavitation damage on specimens A and C. In fact, on C, possibly only one or two cavities were observed. The damage on A was more appreciable, but it came only after several firings. Since severe damage was detected on specimen B after only one firing, to expedite the testing time, B was chosen as the reference specimen. However, it was found that in specimen B the damage

occurred at the base of the cusp unlike the Pelton wheel buckets that had damage at the tip. Probably, the tolerances in the parts and the assembly of specimens in the holder could have developed a slight negative angle of attack. Besides moving the damage downstream, this may generate more bubbles than were originally present in the jet, thus explaining why specimen B was damaged when A and C were not. If this were the case, the test cavitation mechanism would be more severe than the mechanism which occurred during the Hot Flow Test. In view of such possible increased severity, the test was continued under the consideration that the results would be very conservative.

A total of 85 conditions were run in a first series of tests and the results are shown in Table III.

TABLE III

TEST SUMMARY OF THE FIRST 85 CONDITIONS
(SPECIMEN B)

Nozzle	Pre-Nuclear		Modified Nuclear		Short Modified Nuclear	
Straightening vanes	Yes	No	Yes	No	Yes	No
N_2 pressure (psi above sat.) needed to suppress cavitation	No cavitation suppression up to 22 psid	Very slight damage @ 22 psid	5-10 psid	Very slight damage @ 22 psid	15 psig	Not tested

A second series of tests was run to confirm the above data, but it did not duplicate them. Further investigation into this matter indicated that nitrogen was getting into solution in the accumulator water due to insufficient sealing by the O-rings on the piston separating the water from the nitrogen. Therefore, a sampling system was set up by extracting a small quantity of water while the accumulator was firing, and measuring its nitrogen content.

The original testing consistently indicated that the damage occurring at saturation was less severe with the modified nuclear nozzle and therefore, only it was used for all subsequent tests. These tests are summarized in Table IV; runs with specimens A and C in which no cavitation damage was observed are omitted from the table.

The results of this second series of tests showed many inconsistencies, and no correlation could be observed between cavitation damage and amount of dissolved nitrogen. For instance, cavitation was suppressed in condition #104 with 27-34.5 psi of suppression pressure and a partial pressure of dissolved N_2 in the water as high as 28.5 psi. On a later run, #105, very slight cavitation damage was observed with nearly as much dissolved gas and substantially more suppression pressure. In subsequent runs, #113-132, cavitation could not be suppressed even with 30 psi suppression pressure and no dissolved N_2 in the water. In no instance were we able to repeat the earlier tests described in Table I.

All these inconsistencies are probably due to differences in the specimen angle of attack and the amount of jet intercepted. The tests proved that the location and amount of cavitation damage in specimen B was, when all other conditions were equal, a function of the quantity of jet captured (runs 120, 121, and 125).

The encouraging note was the ability to repeat the suppression of damage with 24-32.5 psi with the vaneless modified nuclear nozzle. Very slight damage was noted in the original runs and no damage in the second series. In the light of this information it appears as previously stated that the flow straighteners should be eliminated, modified nuclear nozzles should be used and a head of 30 psi represents a conservative margin for cavitation suppression.

Attempting to photograph the jet proved both interesting and frustrating. Samples of the pictures taken are shown in Figures 17-24 for various N_2 back pressures and with and without straightening vanes. As can be seen, some flaring of the jet does occur, but for the most part, the jet holds its shape

TABLE IV

SUMMARY OF SECOND SET OF TEST RESULTS
OMITTED CONDITIONS WERE RUN WITH SPECIMEN A OR C AND RESULTED IN NO DAMAGE

Cond.	Straightening Vanes	Percent of Jet Captured (Approximate)	Vessel Temp. °F	Damage[a]	Ambient N_2 Backpressure[b] (psid above saturation)	N_2 Partial Pressure in Water
101	Yes	10	250	C	13 - 16	37.5
102	"	"	250	S	24 - 25.6	7.7
103	"	"	267	N	47.5 - 54	16.6
104	"	"	258	N	27 - 34.5	28.5
105	"	"	260	N[d]	38.5 - 46	27.3
106	No	"	262	C	0	0
107	"	"	268	C	5 - 7.4	0
108	"	"	265	S	10 - 16	0
109	"	"	264	S	15 - 20	0
112	"	"	262	N	24 - 32.5	0
113	Yes	"	260	C	5.2 - 8.4	0
120	"	100	264	S	0	61
121	"	40	260	C	0	28.5
125	"	10	277	C	0	0
126	"	"	255	C	5.3 - 10	0
127	"	"	266	S	18.9 - 27.4	0
128	"	20	249	S	30.0 - 38.5	0
129[c]	"	25	255	C	0	0
130	"	50	260	C	0	1.7
131	"	100	269	N	0	8.6
132	Yes	10	254	C	20 - 26.5	9.8

[a] N, S, C indicate, respectively, unappreciable, slight and heavy cavitation damage.

[b] The two pressures indicate the range of N_2 backpressure during the first four seconds of the run.

[c] This run was much shorter than other runs (~2 sec).

[d] About a dozen holes observed under a magnifying glass.

throughout the distance it would be expected to interact with the buckets. From the multitude of photos, it was concluded that the light did not travel through the jet. Instead, the jet photographed was a result of reflected light from the interior of the test chamber. The fogging, or blackout of the jet as seen in the photos could be a result of bubbles on the surface preventing the light from reflecting back into the camera.

LOW SPEED CAVITATION SUPPRESSION TEST

Following the experimental investigation described in the previous section, another series of experiments were performed at the University of California at San Diego facilities under the supervision of Dr. A.T. Ellis. The main areas of investigation were:

a) The formation, growth and collapse of water vapor bubbles along a target (similar to those used in the previous experiments) over a range of negative angles of attack. This was being done to try and explain some of the results of previous testing at Valmont.

b) The behavior of gas bubbles coming from upstream along the target surface over a range of positive angles of attacks and static pressure fields.

The equipment used was a blow down water tunnel consisting of two 210 gallon tanks, upper and lower, connected by a vertical 8 inch pipe. At the middle of the vertical pipe is a 2-3/4 inch square lucite test section where flows can be photographed. Water is transferred from the lower to the upper tank and held there by pneumatic pressure. To make test runs, pressure is both released from the lower tank and compressed air from an accumulator is applied to the upper tank, through electrically operated and sequenced valves. Flow velocities of up to 90 ft/sec are possible. The system can also be run under partial vacuum to give low static pressures in the test section.

For the present work a two dimensional target was made with the same flow profile as specimens B and C of the cavitation suppression test run at Valmont. The target spanned the 2-3/4 inch test section and was installed so that it could be pivoted through various attach angles.

Photographs were made on Polaroid 10,000 speed type 410 film in a Graphic View II camera positioned normal to the two-dimensional cross section of the target. The velocity field was obtained by visualizing the flow with light scattered 90° by small (about 20 micron) polystyrene latex spheres in suspension in the water. The illumination was from a pulsed short arc strobe lamp of 1-2 microsecond flash duration. The light was focused and collimated into a thin sheet normal to the axis of the camera lens. During a run of the tunnel the lamp was flashed 24 times at a frequency of 8000 Hz which was precisely measured by a quartz crystal frequency counter. The camera shutter was open to a single sheet of polaroid film for the 24 flash sequence. A single polystyrene sphere in the flow then appears in the photograph as a string of 24 dots against a dark field. The string defines a path line (streamline since these are steady flows) while the displacement between dots is proportional to velocity. These displacements can be accurately measured on a David W. Mann measuring microscope which reads out to one micron on both absicissa and ordinate. The velocities in these tests ranged from about 25 to 70 ft/sec.

In order to investigate the first area a series of pictures were taken with negative angles of attack ranging from 0° to 3°. In all the pictures a large turbulence field was noticed along the target inner surface and it was impossible to calculate the pressure field from the velocity distributions. No pressure taps were available at that time along the surface. Large variations in pressure in the turbulence zone will tend to localize growth and collapse the bubbles.

Another series of tests was run with positive angles of attack ranging from 0° to 30° and with a gas bubble forming device located upstream of the target. This consisted of a .050" stainless steel tube cantilevered in the plane of photography. The tube could be slid in and out to position its tip with respect to the target. Bubbles were injected into the stream through this tube. At high velocities cavitation vapor bubbles could be made to break from the tube.

At the velocity range at which the experiments were run, it was impossible to direct the bubbles along the target surface. Probably the adverse pressure field generated by the stagnation region around the tip of the target did not allow such penetration. Undoubtedly higher velocities are necessary.

Several interesting phenomena were detected however. By looking at Figure 25 one can see for a negative 3° incidence angle a stagnation point is formed in the cusp of the specimen. This is in the region where most of the cavitation damage occurred during the high speed tests. This point was not noticed for various positive angles of attack.

NITROGEN PRESSURIZATION SYSTEM

It appears from the foregoing that successful Pelton wheel operation for the plant lifetime requires cavitation prevention, such as can be obtained by controlling the Pelton wheel cavity ambient pressure at a level comfortably above the saturation pressure corresponding to the prevailing temperature. This saturation pressure is practically equal to the deaerator pressure. To achieve this pressure control, a pressurization system is designed, using nitrogen as the pressurizing gas. This system is illustrated by Figure 16.

The nitrogen is supplied to the turbine water drain tank, which is automatically equalized in pressure with the water turbine cavities of whichever two of the four circulators are operated at the moment via separate connective pipes. The nitrogen added to the water turbine cavity passes upward past the lower circulator labyrinth seal to the steam/water drain. From the steam/water drain, the nitrogen, together with bearing water from the main drain flows to the low pressure separator (T2111). The pressure in this separator is automatically maintained by a pressure control valve (PV-21443) which recycles gas from the discharge of the operating nitrogen compressor (C-2109/C-2109S) to the suction of the compressor. If the separator pressure drops below 14 psia, the valve opens to raise the pressure. Conversely, if the separator pressure increases above 14 psia, the valve begins to close.

The gas and water are separated and the gas (essentially nitrogen with a small amount of helium) is pumped back to the turbine water drain tank (T-2110) by one of two 100% capacity rotary compressors (C-2109/C-2109S). Each compressor is a liquid-piston type machine, using water as the liquid, and is equipped with a seal water cooler (E-2107/E-2107S) for removing the

heat of compression. A common separator (T-2120) is provided at the discharge of the operating compressor to separate the seal water from the pumped gas. Finally, the nitrogen leaving the separator is metered and filtered before it returns to the turbine water drain tank. Initially and for subsequent makeup, the nitrogen is added to this closed loop system from 24 standard ICC-approved gas cylinders with a total capacity of 5,376 SCF (T-2119). A pressure control valve (PV-21446) regulates the flow of nitrogen into the system, when and as required to maintain the turbine water drain tank at the set pressure.

Based on the test results previously discussed, the pressure in the turbine drain tank is controlled at 30 psi above the deaerator pressure. Except for an initial transient, which will be discussed later, the deaerator pressure is equal to about 18 psia (corresponding to a 220°F temperature setting) when the Pelton wheel is operated. The N_2 compressors have a maximum delivery pressure of about 70 psia; therefore, they possess ample capability to provide the required suppression pressure.

During the first 30 minutes of Pelton wheel operation, the deaerator temperature ramps down (about linearly) from an initial 320°F to the 280°F setting. Therefore, it takes about 16 minutes before the deaerator pressure is low enough for the N_2 compressor to assure the required backpressure. During these 16 minutes, excess nitrogen can be supplied by the bottles as required to maintain the desired pressure in the Pelton wheel water drain tank. It must be realized, however, that the design pressure of this tank is limited to 95 psia; therefore, at the very beginning only a 5 psia suppression pressure can be allowed; however, within 7 minutes the deaerator pressure has ramped down to 30 psid below the drain tank relief valve setting. From then on the full 30 psid suppression pressure can be maintained.

The nitrogen-saturated water discharged from the turbine water drain tank is pumped in the deaerator where it is stripped with steam from its gas content. In order to prevent the loss of nitrogen during operation

of the Pelton wheels the deaerator off-gas is rerouted to the low pressure separator for recovery. Moreover, whenever this pressurizing system is put into operation, all the gas from the low pressure separator goes to the nitrogen compressors (C-2109/C-2109S), and the line to the helium recovery compressors is closed (see Figure 16).

In case of failure, low pressure, low temperature Class I fire water will be used to run the Pelton wheels. This system has not therefore been designed to Class I standards. This is considered acceptable because if the nitrogen pressurization system is inoperable, the turbine water drain vent can be opened to atmosphere, thus providing adequate suppression head to prevent cavitation when operating with fire water. At any rate, cavitation damage is less likely to occur with low pressure and low temperature Class I fire water and experience has shown that the circulators remain operational even with significant cavitation damage. Furthermore, since only one circulator driven by fire water is needed for safe shutdown cooling the redundancy of circulators provides ample back-up in the event of circulator failure.

PELTON WHEEL OPERATION WITH PRESSURIZATION SYSTEM

New Pelton wheels were attached to the reworked circulators and the Hot Flow Test resumed in May 1973 with the pressurization system in operation. During the initial running of the Pelton wheels an apparent degradation in aerodynamic performance of the A circulator was noted. Until the instrumentation could be checked, operation of A was restricted to self-turbining speed. A test however was run on the Pelton wheel flow rates of all machines to determine if there were any leaks in the system. The results, shown in Table V, did indicate a leakage in A circulator, but its operation was still restricted pending helium instrumentation check.

TABLE V

RESULTS OF RT 173 (6/7/73)
LEAKAGE FLOW RATES FROM PELTON WHEEL PIPING

Circulator	Leakage
A	230 gpm
B	< 25 gpm
C	< 25 gpm
D	< 25 gpm

As the Hot Flow Test progressed, Pelton wheel D was kept under close surveillance with the TV camera to detect any early signs of cavitation damage. After about 400 hours, none was noted. It was noted later, however, that machine C had a loss of performance plus it was becoming increasingly more difficult to obtain feedwater header pressure high enough to drive the remainder of the circulators fast enough. An additional test was then run to determine if the Pelton wheel leakage rates had changed. The results, shown in Table VI showed a marked increase in leakage rates to all machines except B. As a result of these tests, it was decided to remove the C piping to determine the source of the leakage.

TABLE VI

RESULTS OF RT 192 (6/26/73)
LEAKAGE FLOW RATES FROM PELTON WHEEL PIPING

Circulator	Leakage
A	380 gpm
B	0 gpm
C	450 gpm
D	250 gpm

While the C piping was being removed, permission was granted to operate A and B so as to maintain the Hot Flow Test. On 6/27/73, a sharp drop in circulator A speed was noted along with a corresponding speed increase in B. A blockage of one of the nozzles was immediately suspected. As a result, B and D were then run while the piping was removed from A. Up to the time of the piping removal of C, the running times on the circulators were:

A - 160 hours
B - 332 hours
C - 363 hours
D - 440 hours

After removal of the C piping, a decision was made to remove all pipes one at a time so as to not delay the Hot Flow Test.

Examination Results

The Nitralloy nozzle showed, in the case of A, B and C machines, that there was erosion damage which started upstream of the nozzle throat and an erosion quadrant in an approximately 90° segment of the nozzle discharge (see Figure 26). In addition, erosion damage was discovered on the elbows almost in line with the nozzle discharge as seen in Figure 27. In the A machine, a skirt from the old type of speed valve was plugging one of the nozzles, as suspected. The copper gaskets forming the seal between the

pipe end and nozzle had not been secured tightly enough except in the case of the B machine. It was noted that many of the nozzles were free to turn within the restriction of the lock tabs.

The erosion damage on the elbows was most severe on the C machine followed by A. Some evidence of wear on the elbows was also observed on the B and D machines. The damage appears to have been caused by the jet from the adjacent nozzle as was verified by observing the location of cavitation damage on the flange above the nozzle and drawing a line through the two cavitation areas. This could only have resulted from a divergence of the jet since a collimated jet could not pass through the buckets uninterrupted under any possible operating conditions during the Hot Flow Test.

In the A, C and D machines, the asymmetry of the wear in the nozzle throat could have caused sufficient deflection to account for the elbow wear. The lack of correlation between the operating times and the damage observed also seems to support this assumption.

Pelton Wheel Examination

The A machine showed some discoloration along the splitter end on the back of the buckets. It, however, did not appear to have had any material loss. This machine had run less than any of the others. Subsequent running of the A machine to 600 hours was accomplished and the wheel was observed with the remote television camera at this time and appeared to be in quite good condition.

The splitters on the B machine show a very slight frosting in the center of the splitter with almost no evidence of the heavy cavitation at the entrance to the wheel observed in last year's Hot Flot Test operation. (Compare Figure 29 with Figure 1 and Figure 30) There is an erosion pattern on the back of the buckets at the vicinity where the buckets join the rim (see Figure 31). This damage is much less than that observed last year (see Figure 32 for old B wheel) even though the operating time at high speed was around 300 hours. This compares to only 44 hours of high speed operation

last year (see Table I). In addition, there is evidence of cavitation between the buckets as shown in Figure 33 and the center of the rim. The flow which could have caused this would have been a jet directed at the back of the buckets which with higher rotational speeds would have resulted in relative velocity radially inward. Since B machine was the only one in which leakage was not observed from the elbows, one might conclude that this damage resulted from either a uniform spraying of the jet yielding the radially inward component of velocity or the running of B wheel in a submerged condition which would have had vortical flow in the bucket.

On the C machine one observes erosion on the center of the splitter and on the back of the buckets (see Figures 34 and 35). The damage on the center of the splitter is greater than that of the B machine while the damage on the back of the buckets is of the same order. In both cases however, it is considerably less than that observed on the B machine from last year. Here again there is no evidence of the heavy erosion at the top of the bucket which characterized last year's cavitation.

On the D machine which operated for approximately 30% more time than either B or C, the observed damage on the wheel (Figure 36) was at the root of the back of the buckets. The damage appeared to be a little worse on the downside than on the upside of the assembly. On the downside, it was slightly worse than that observed on B and C but less than that observed on the B machine from last year. The upper side of the buckets was about the same as observed on the B and C machines. The splitters were extremely good with less frosting than observed on the B and C machines (Figure 37). In addition to that, there was on the upper side an area on the back surface of the bucket towards the tip where flow had caused some cavitation (see Figure 38). This was not uniform on all the buckets. It could be that this stream, deflected from the bucket tip, might have contributed to the damage on the backside of the buckets since they are both on the same side. The cause of this damage is confirmed by the existence of a 0.070" interference between jet and bucket, as measured at the Site.

Examination of the Nuclear Pelton Wheel Used in Prototype

The nuclear Pelton wheel used for the rotor inertia and air flow tests was reexamined and no evidence of cavitation was observed. This wheel was run much longer than any of the pre-nuclear wheels, ∿1000 hours, but at a lower velocity with atmospheric air and 120°F water, which resulted in a suppression pressure of ∿12 psi.

Operating History of the Pelton Wheels

On checking with the operating logs at the reactor site the following summary of the pressurization system was determined.

1) Up to one hour of running time existed with the Pelton wheels submerged in water.

2) During the depressurized operation of POT 21-03 (approximately 1 week total time) the N_2 supply pressure dropped to 12-15 psig. It is not known what the pressure in the drain cavity was but there is a sizable pressure drop between the supply and drain. The circulators were turning at 3000 RPM 80% of the time with 1-2 hours in excess of 8000 RPM.

3) Three to seven days of operating time during the high speed portion of the Hot Flow Test, the N_2 supply pressure dropped to 16-18 psig.

4) N_2 supply pressure dropped to 5 psig on B circulator for about 1 to 4 hours with the speed at ∿7900 RPM.

Conclusions

Preliminary conclusions can be drawn from these observations. The heavy cavitation at the tip observed in 1972 could be attributed to the straightening vanes in the nozzles which were removed from the present assembly. The other cavitation which was observed was slight and did

not bear any relationship to the actual operating time. Furthermore, since it has been observed that the pressurization supply had been allowed to drift downward below the recommended values and that there was not a direct measurement of pressure in each cavity, one could conclude that the observed damage resulted from an absence of pressurization.

Using the experience with the B wheel of last year as an index, the observed cavitation damage from the present running can be interpreted as the result of relatively few hours of operation (perhaps 10 or less) without sufficient pressurization to suppress cavitation. There is, however, observed damage in both the B and D wheels on the rim in the latter case and on the back of the buckets in the former case which had not been observed at the conclusion of last year's test or on the A and C machines. The location of this damage which is outside of the normal or design flow path is such that its cause might be attributed to misalignment of the nozzle which is certainly the case in the D machine and/or submerged rotation in the case of the B machine.

The observed damage on the nozzles and the elbows is a strong indication of spreading of the jet from the nozzle, which could have resulted in the elbow damage. It is interesting to note that there was consistency in the extent of damage observed on the nozzles indicating that the phenomena observed here was of the corrosion-erosion type and not cavitation.

Action to be Taken

Instrumentation has been added to sense the pressure in each of the Pelton wheel cavities and record it on an hourly basis during all subsequent testing.

The original A Pelton wheel was reassembled and placed in operation. The B and C wheels were replaced in one case with an Inconel 718 casting and in the other with a 17-4PH casting. All three of these machines are back in operation. The observed performance is equal to design predictions and much superior to that observed prior to removal of the piping.

The nozzles were also replaced in the machines. These are still of the original material and one should expect deterioration in approximately the same time periods as previously. The elbows in A and B were repaired by Inconel weld deposits and protected by a weld overlay of Stellite. In the C and D machines, the elbows were replaced with type 316 stainless steel which were also protected by a Stellite weld deposit.

Design changes have been made in the nozzle to assure back leakage across the threads cannot occur. In the pre-nuclear case, ethylene-propylene O-rings are added to assure proper sealing and in the nuclear case, a flexible metal ring is being added, along with a seal weld on the outer diameter. The nozzle material for the nuclear case has been changed to Inconel 718 in order to prevent corrosion.

No changes are recommended in the material of the nuclear Pelton wheel. Based on the experience of the pre-nuclear wheels, a sizable increase in life is expected for the nuclear wheels. Erosion or cavitation damage is a function of at least the 5th power of velocity (5,8). Since velocity is proportional to the square root of pressure, the nuclear wheel should last longer by at least the 2.5 power of the ratio between the supply pressure of the pre-nuclear nozzles and that of the nuclear nozzles. In addition, since there are two nozzles instead of three a life ratio of 1.5 should be expected from reduction of jet interaction frequency. Material difference is also a factor. Based on Reference 7, a life ratio of 3 is expected between Inconel 718 and 17-4PH (H1050).

Based on these factors, an estimate of the expected life of the nuclear wheels can be made. Since the nuclear wheels see a wide variety of pressures over its lifetime, the following equation can be used to estimate wheel life:

$$\bar{L} = \frac{1}{\frac{P_1}{L_1} + \frac{P_2}{L_2} + \ldots + \frac{P_N}{L_N}}$$

where $\bar{L}$ = expected overall life of nuclear Pelton wheel

P_1, P_2, etc. = portions of time (expressed as a decimal fraction of time) that a given load (or pressure) is in effect.

L_1, L_2, etc. = calculated life of the wheel at each different load.

This equation will be used to determine how many hours of running time are needed by the nuclear wheels to produce similar damage as observed in the pre-nuclear wheels after 350 hours. This later number is an approximate average running time of the wheels photographed. The expected running times of the Pelton wheels and their associated pressures are summarized in Table VII.

TABLE VII

EXPECTED OPERATING CONDITIONS
OF THE NUCLEAR PELTON WHEELS (9, 10, 11)

1) For Emergency Core Cooling - depressurized - once during plant life

1 day @ 2450 psi and 10,550 RPM	2 circ.
5 days @ 990 psi and 6690 RPM	2 circ.
23 days @ 1125 psi and 7580 RPM	1 circ.

2) For Emergency Core Cooling - pressurized - once during plant life

1 day @ 2450 psi and 3600 RPM	2 circ.
28 days @ 170 psi and 1000 RPM	1 circ.

3) For Refueling - 40 times during plant life

5 days @ 990 psi and 6690 RPM	2 circ.
23 days @ 1125 psi and 7580 RPM	1 circ.

The total length of time for Pelton wheel operation is the summation of 1), 2) and 3) or

$2(29) + 40(28) = 1178$ days = 28,272 hours

If it is assumed that the refueling times are shared equally among all circulators and the cooling requirements of the first two cases in Table VII handled by the same two circulators, the following operating history is obtained:

2 days	@ 2450 psi	
105 days	@ 990 psi	
100 days	@ 0 psi	- while others operate @ 990 psi
253 days	@ 1125 psi	
690 days	@ 0 psi	- while others operate @ 1125 psi
28 days	@ 170 psi	
1178 days		

P_1 - time @ 2450 = $\frac{2}{1178} = 1.7 \times 10^{-3}$

P_2 - time @ 990 = $\frac{105}{1178} = .089$

P_3 - time @ 1125 = $\frac{253}{1178} = .215$

P_4 - time @ 170 = $\frac{28}{1178} = .0234$

P_5 - time @ 0 = $\frac{790}{1178} = .670$

Also from the previous life assumption we have:

L_1 - life @ 2450 = $\left(\frac{3000}{2450}\right)^{2.5}$ (1.5)(3)(350) = 2613 hours

L_2 - life @ 990 = $\left(\frac{3000}{990}\right)^{2.5}$ (1.5)(3)(350) = 25,176 hours

L_3 - life @ 1125 = $\left(\frac{3000}{1125}\right)^{2.5}$ (1.5)(3)(350) = 18,289 hours

L_4 - life @ 170 = $\left(\frac{3000}{170}\right)^{2.5}$ (1.5)(3)(350) = 2.06×10^6 hours

L_5 - life @ 0 = ∞

$$\bar{L} = \frac{1}{\frac{1.7 \times 10^{-3}}{2613} + \frac{.089}{25,176} + \frac{.215}{18,289} + \frac{.0234}{2.06 \times 10^6} + \frac{.67}{\infty}}$$

$$= \underline{62,685 \text{ hours}}$$

In other words, if the life cycle shown in Table VII were maintained for 62,685 hours of running time, the nuclear wheels would have about the same damage as observed on the pre-nuclear wheels after 350 hours. Since only 1178 days or 28,272 hours are needed over the life of the plant, the damage to be expected on the nuclear Pelton wheels will be much less than seen on the pre-nuclear wheels. Of course, all of these assumptions are based on the pressurization system being maintained in the Pelton wheel cavity.

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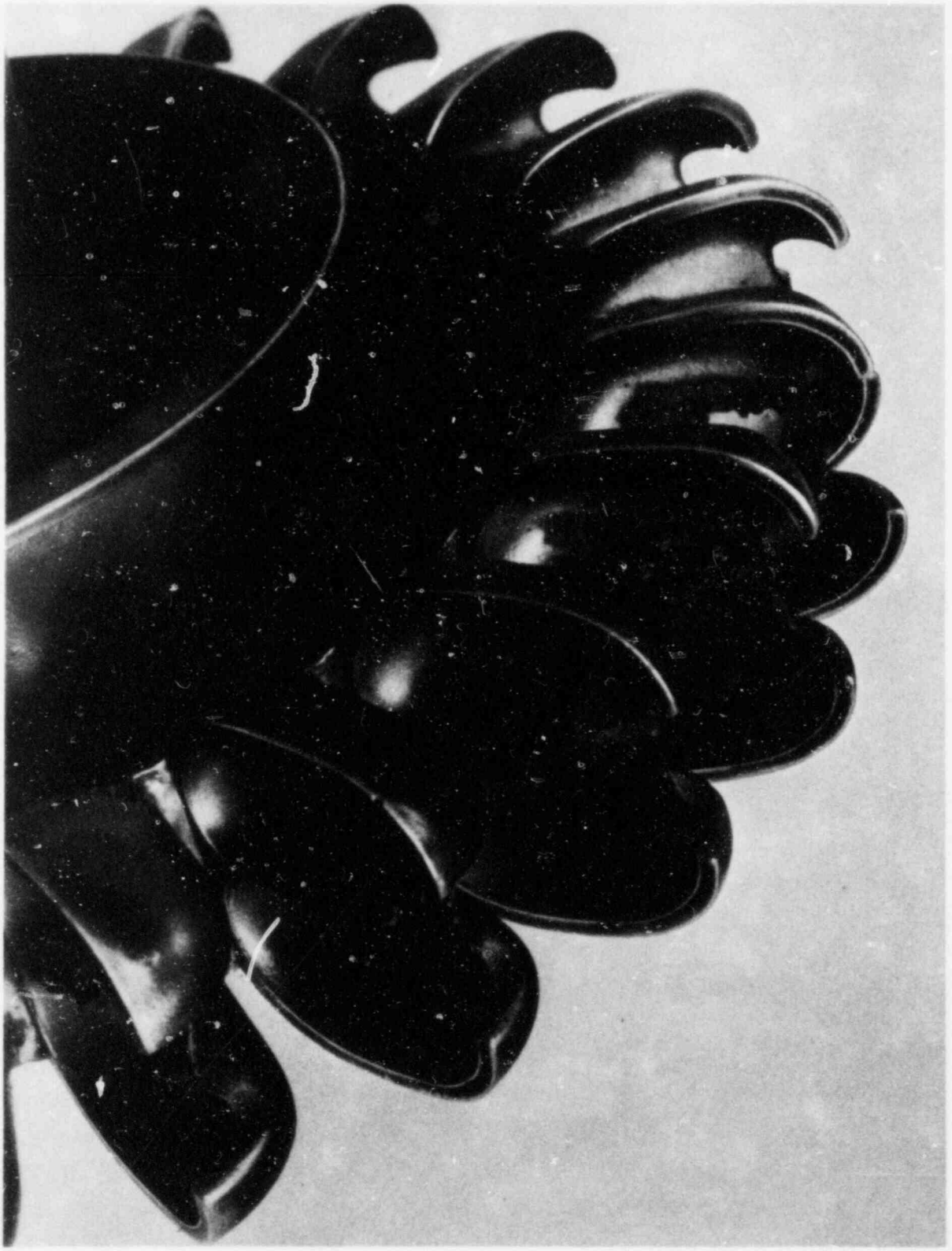


Figure 1 - Cavitation Damage of the Flow Splitter - C Wheel

Figure 2 - Cavitation Damage of the Bucket Root - C Wheel

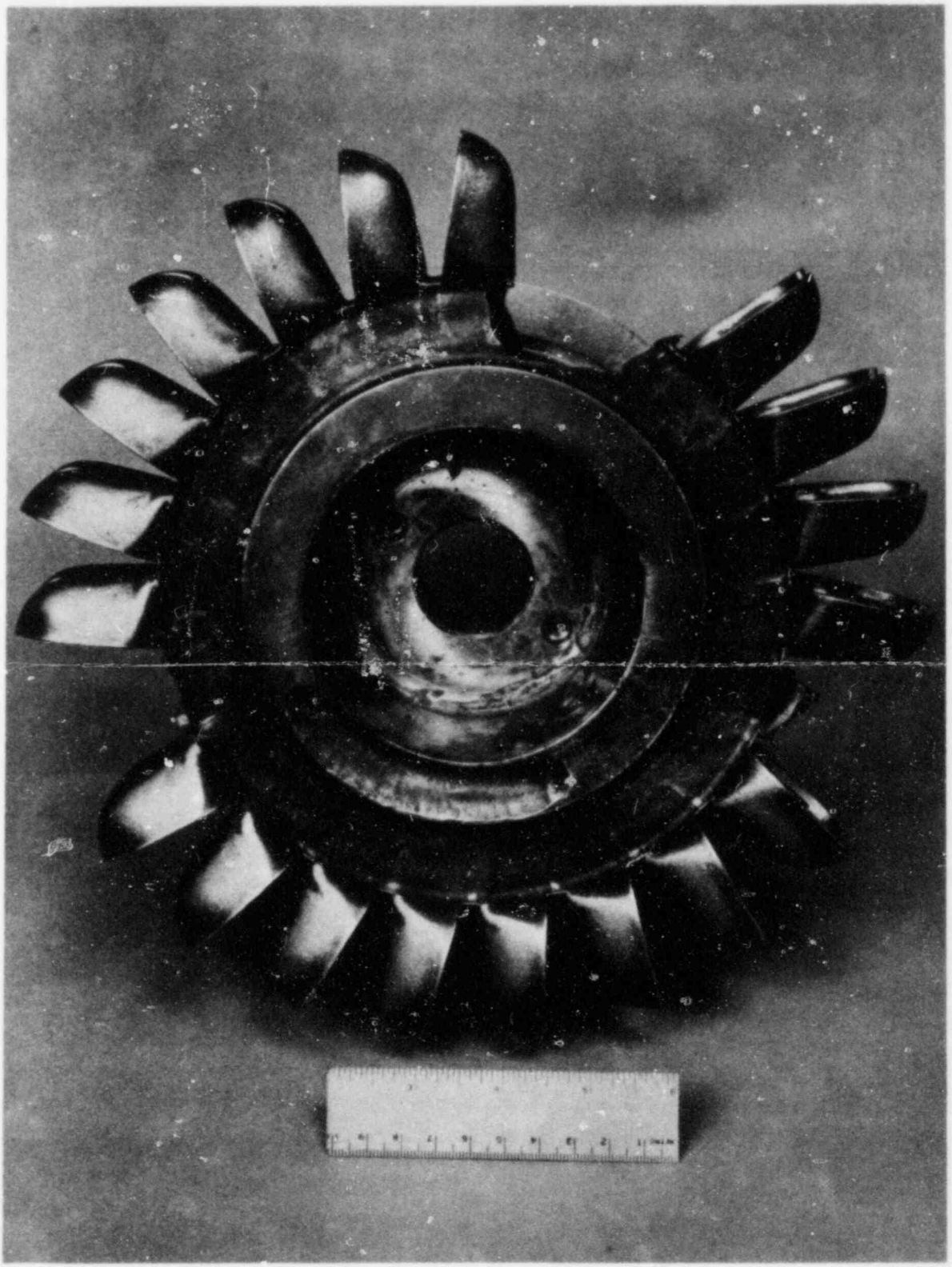


Figure 3 - End View of A Wheel Showing Missing Buckets

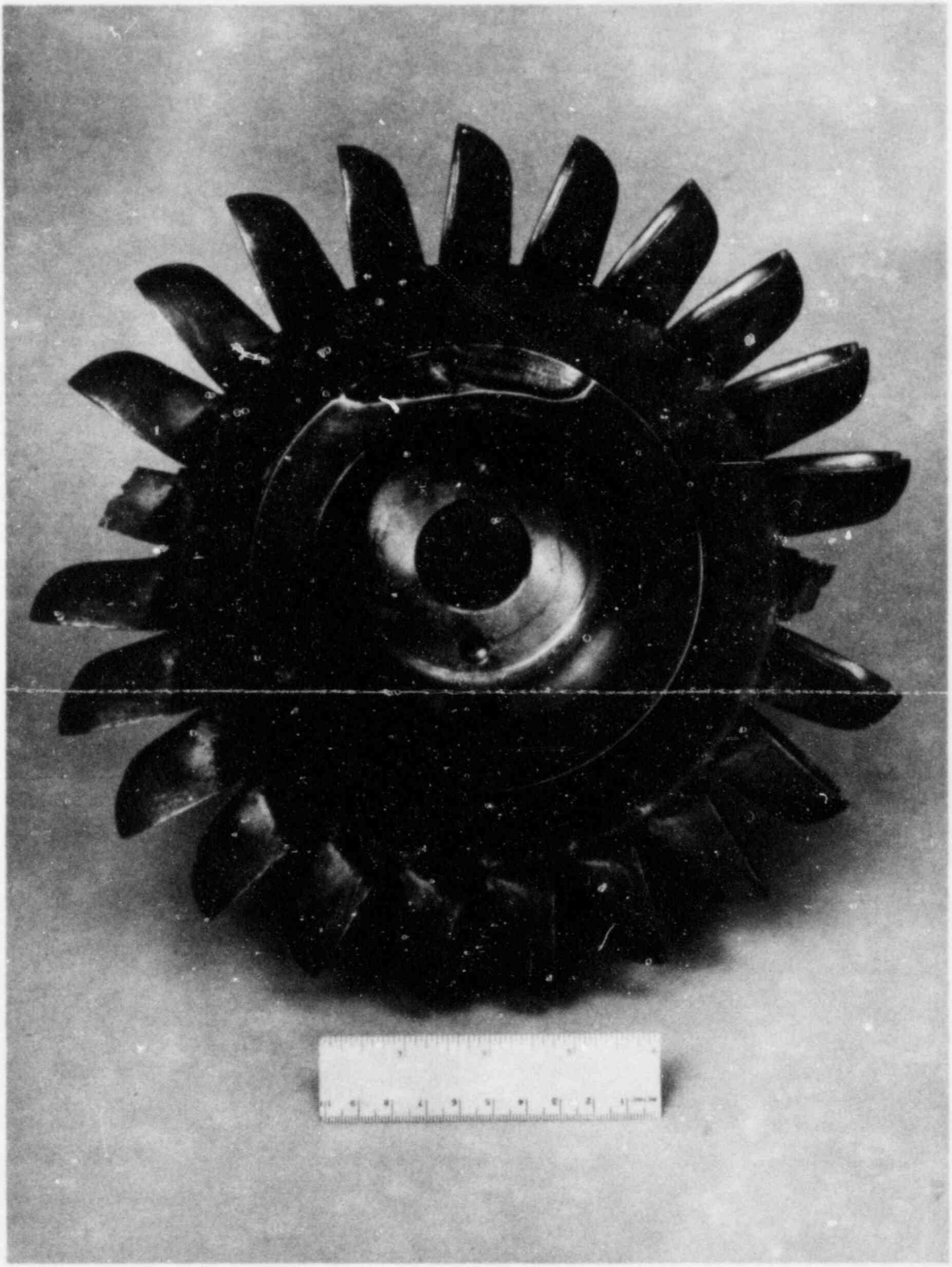


Figure 4 - End View of D Wheel Showing Missing Buckets

Figure 5 - Close Up of Partially Missing Bucket on D Wheel

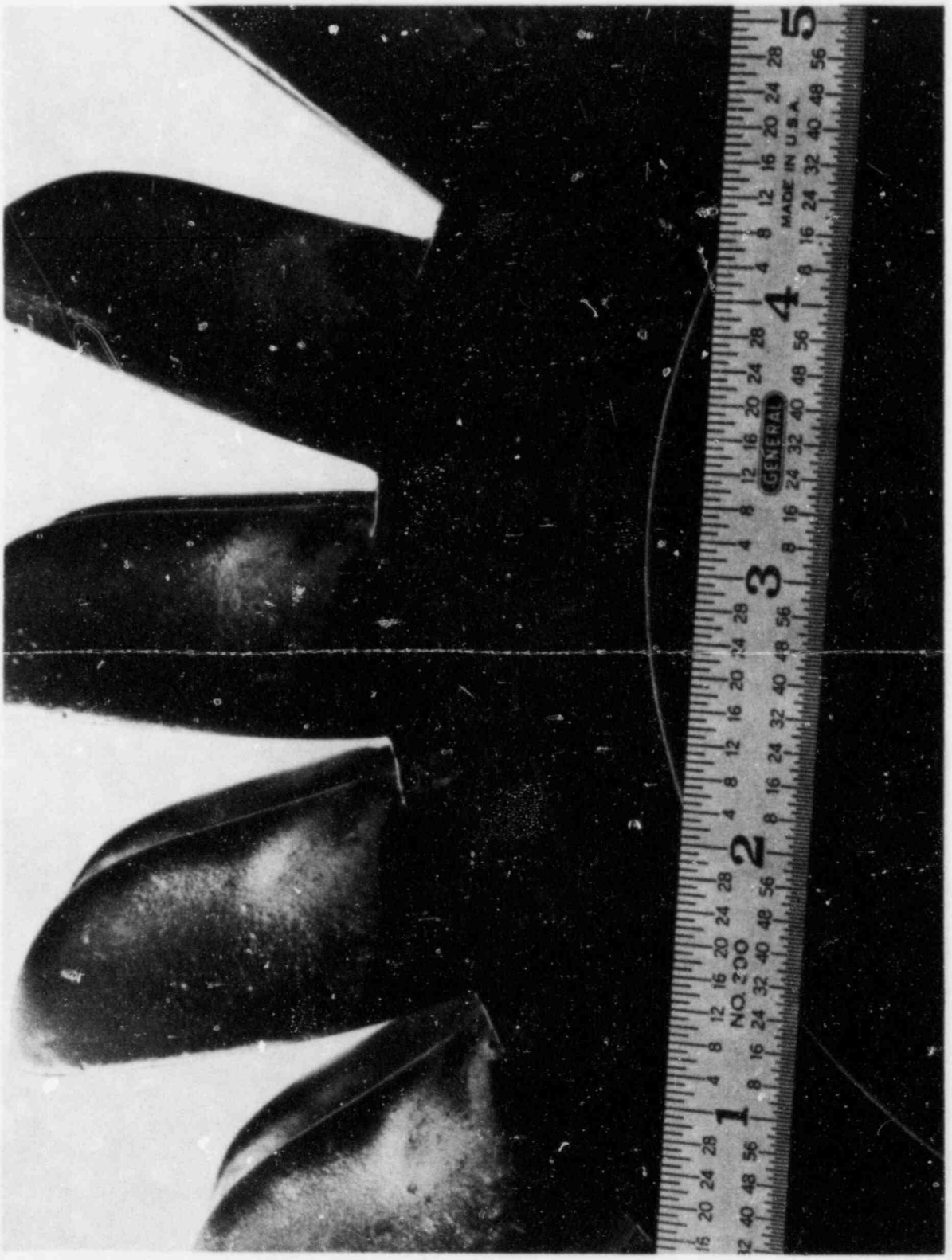
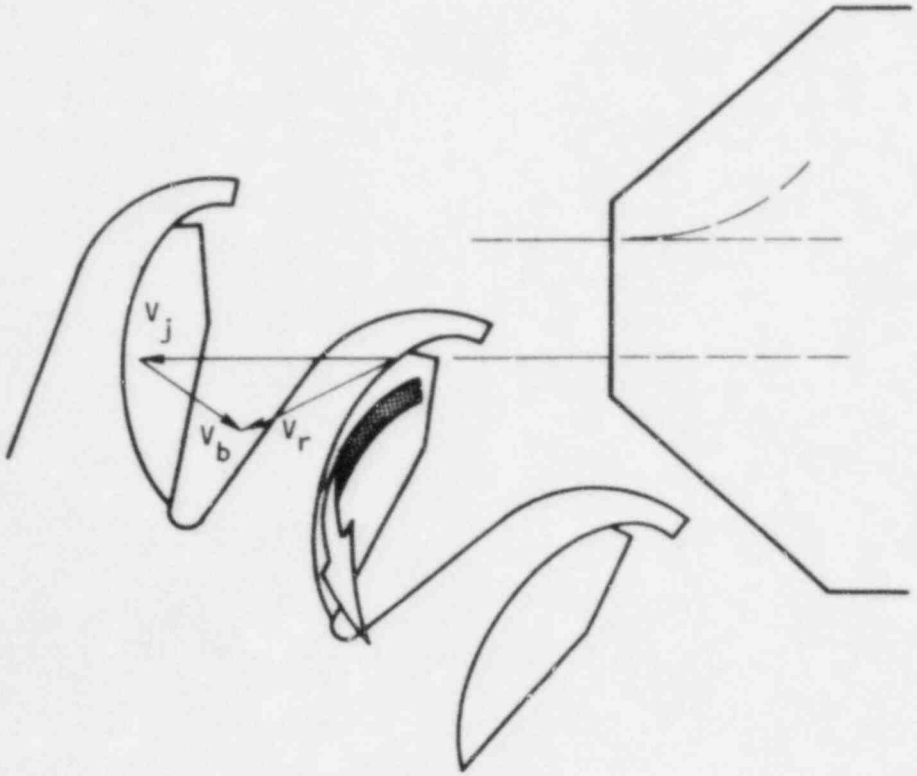


Figure 6 - Cavitation Damage and Rim Crack in C Wheel

Figure 7 - Cavitation Damage of B Wheel

Figure 8 ~ Broken Blade and Root Damage of C Wheel



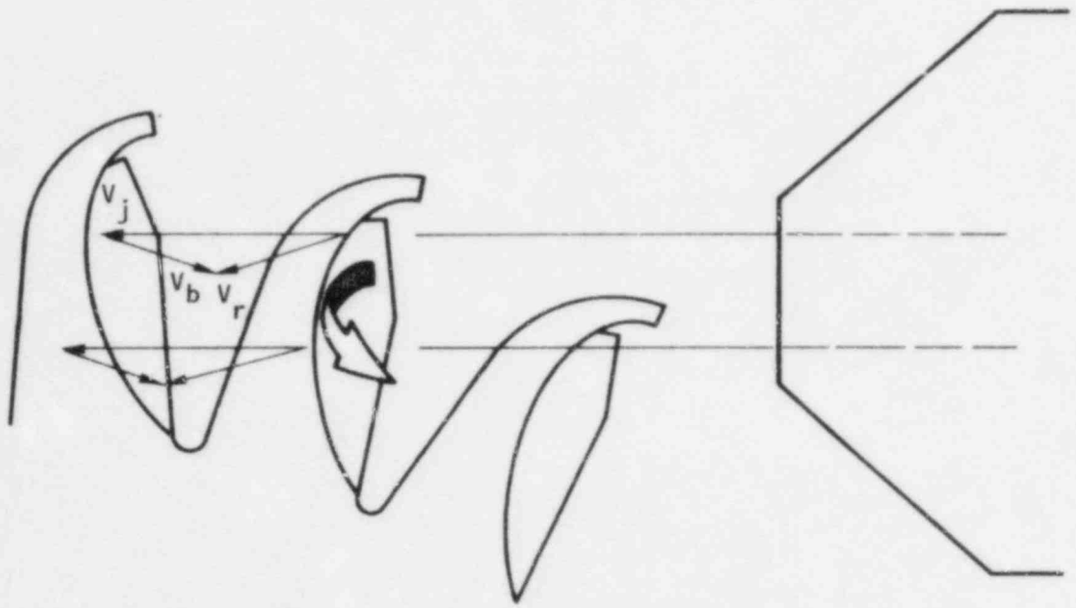
V_j: ABSOLUTE JET VELOCITY

V_b: BUCKET VELOCITY

V_r: VELOCITY OF JET RELATIVE TO BUCKET

⇨: APPROXIMATE FLOW PATTERN IN THE BUCKET

Figure 9 - Schematic of Bucket-Jet Interaction of the First Filament of Water



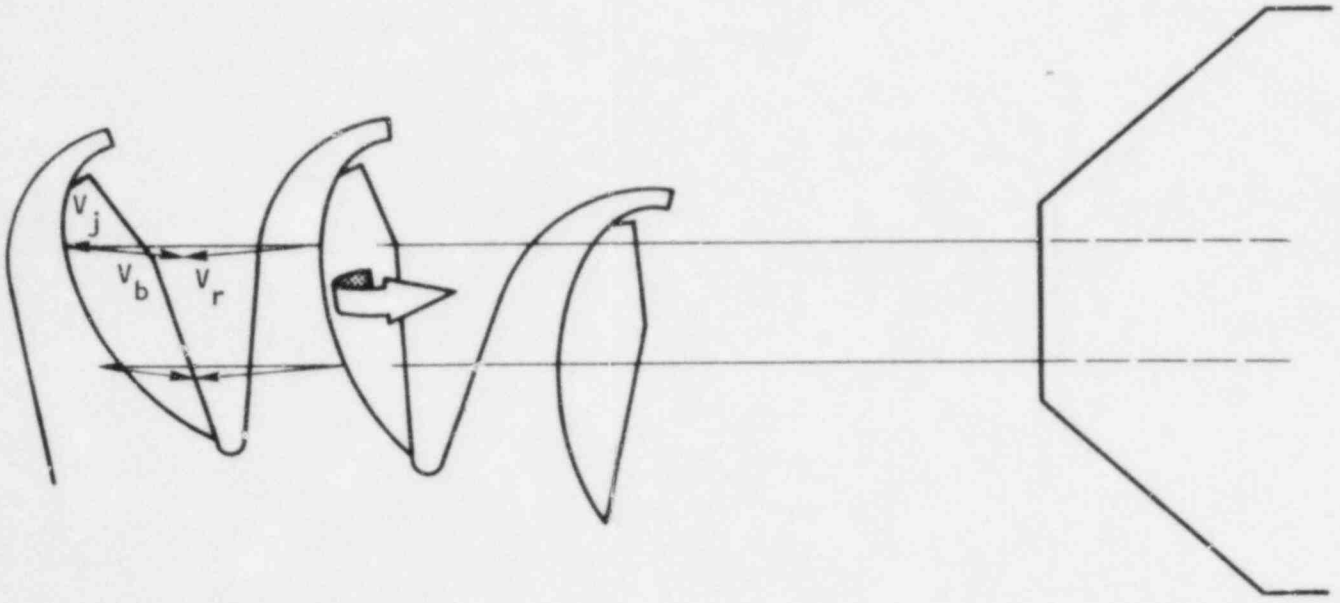
V_j: ABSOLUTE JET VELOCITY

V_b: BUCKET VELOCITY

V_r: VELOCITY OF JET RELATIVE TO BUCKET

⇨: APPROXIMATE FLOW PATTERN OVER BUCKET

Figure 10 - Schematic of Bucket-Jet Interaction - 2nd Stage



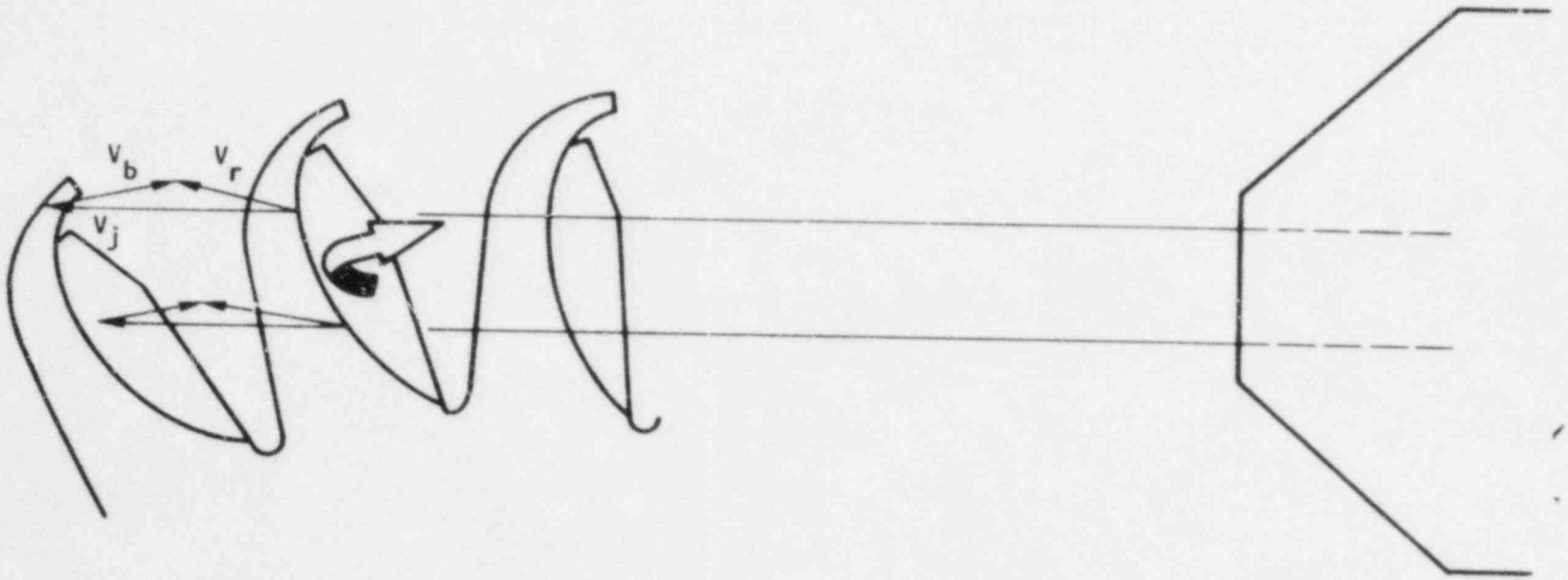
V_j: ABSOLUTE JET VELOCITY

V_b: BUCKET VELOCITY

V_r: VELOCITY OF JET RELATIVE TO BUCKET

⇨: APPROXIMATE FLOW PATTERN OVER BUCKET

Figure 11 - Schematic of Bucket-Jet Interaction - 3rd Stage



V_j: ABSOLUTE JET VELOCITY

V_b: BUCKET VELOCITY

V_r: VELOCITY OF JET RELATIVE TO BUCKET

⇨: APPROXIMATE FLOW PATTERN OVER BUCKET

Figure 12 - Schematic of Cavitation-Suppression Test Set-Up

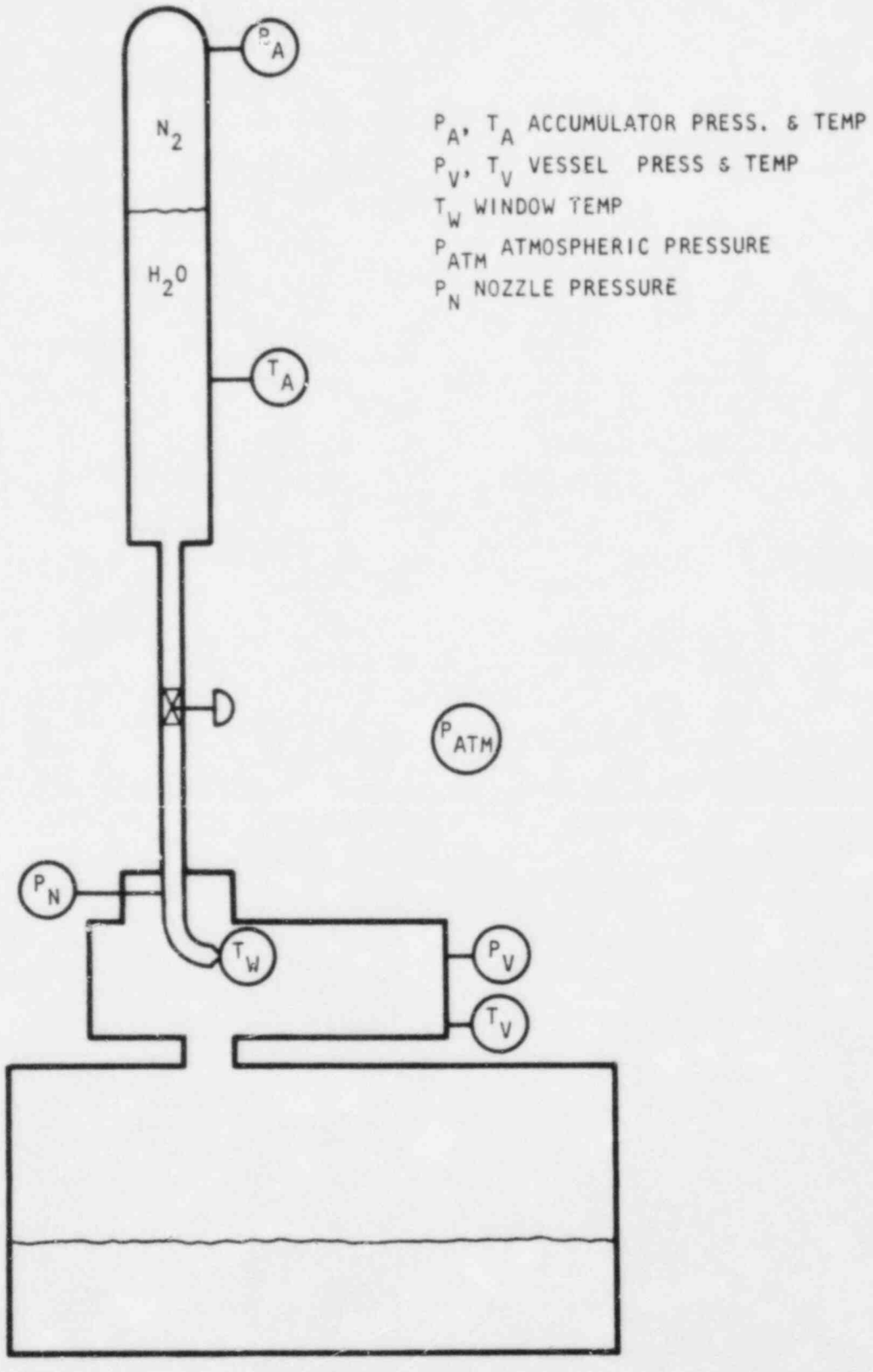


Figure 13 - Schematic of Cavitation-Suppression Test Set-Up

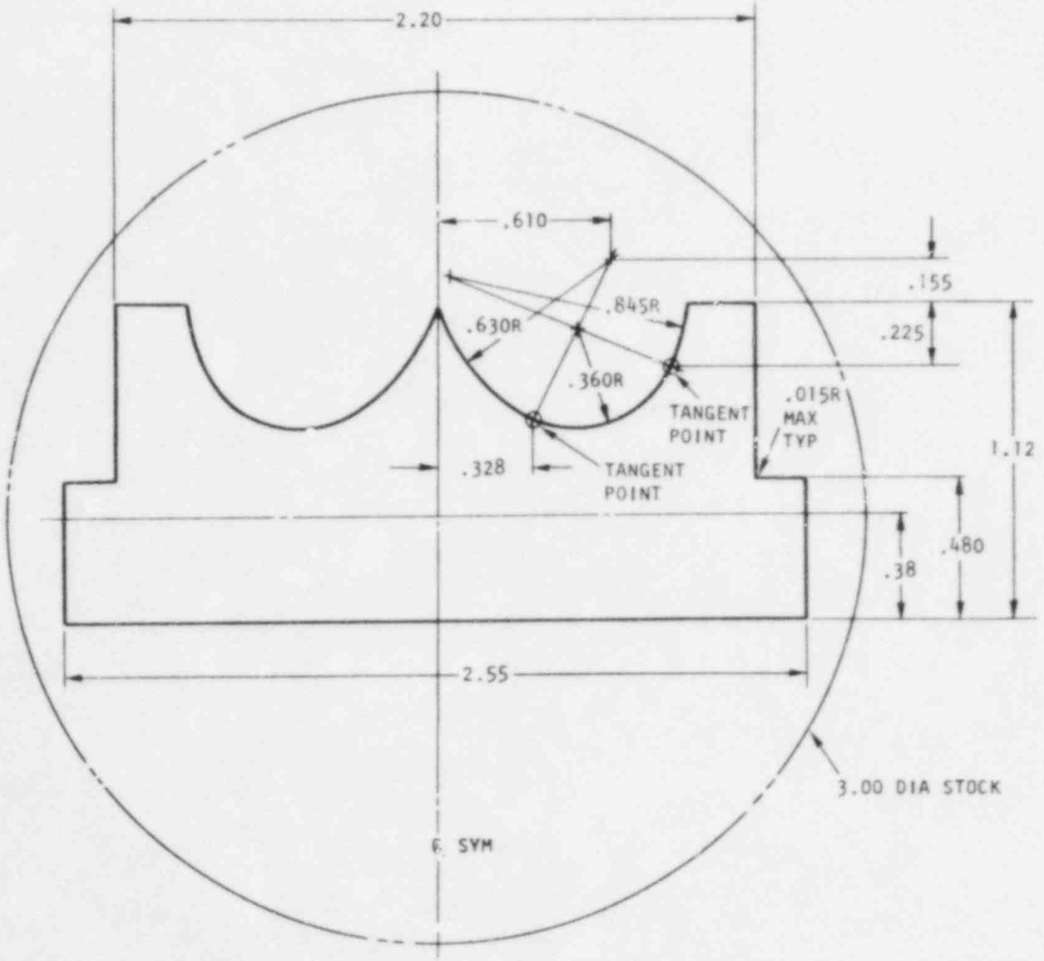


Figure 14 - End View of Specimen A

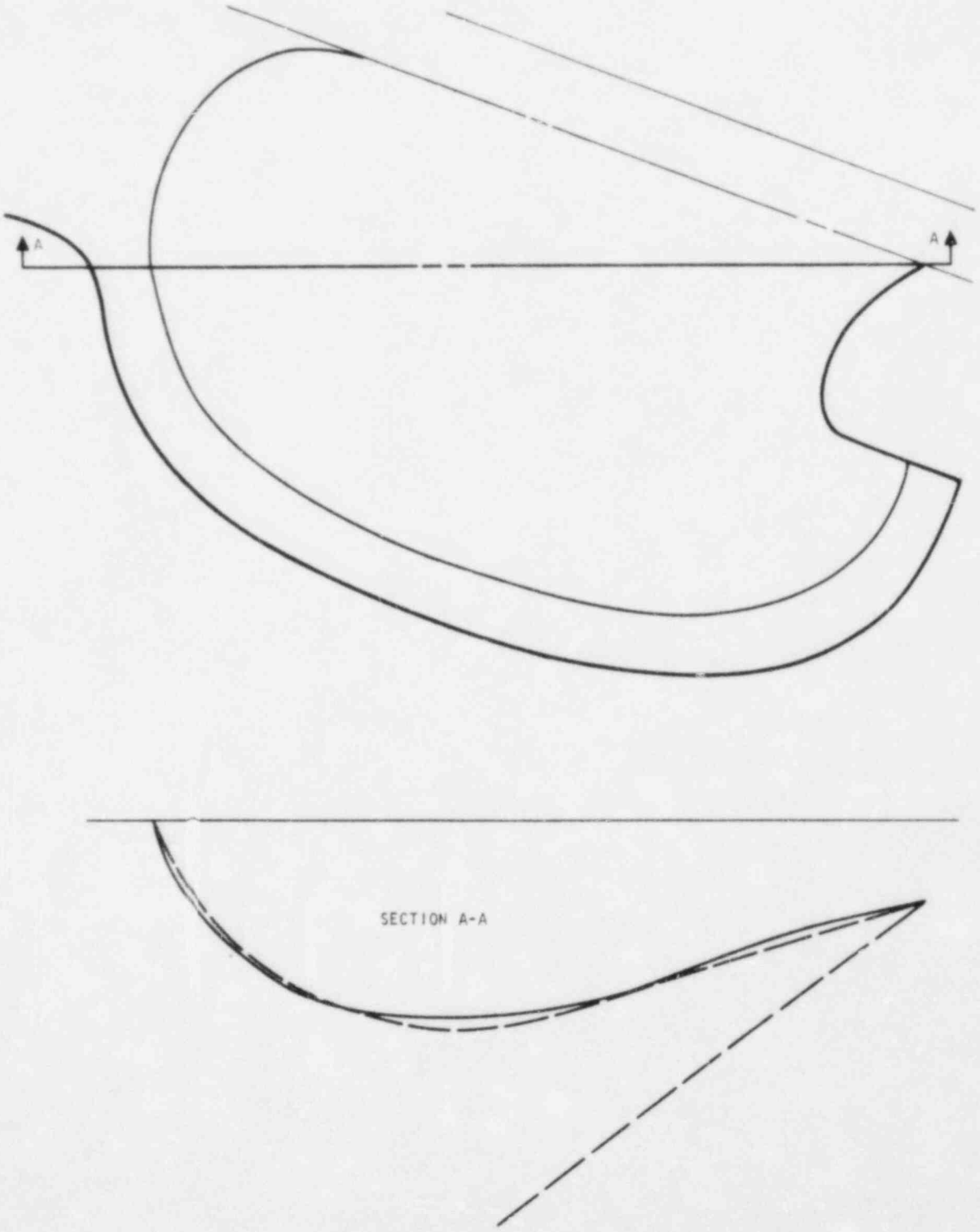


Figure 15 - Cross Section of Bucket Showing Flow Path of First Filament of Water. This section is the shape used for specimens B and C.

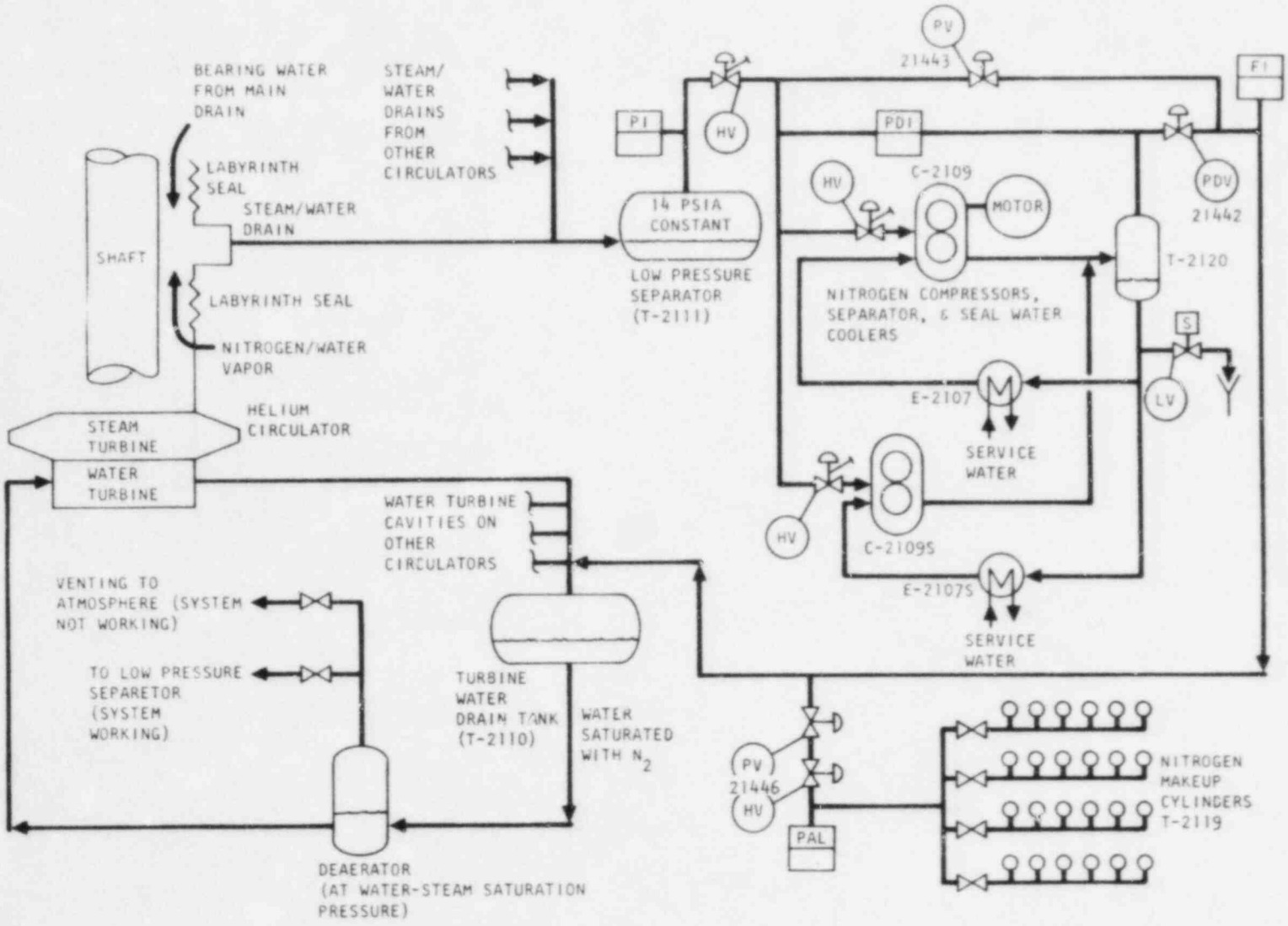


Figure 16 - Schematic of the Nitrogen Pressurization System Used to Suppress Cavitation

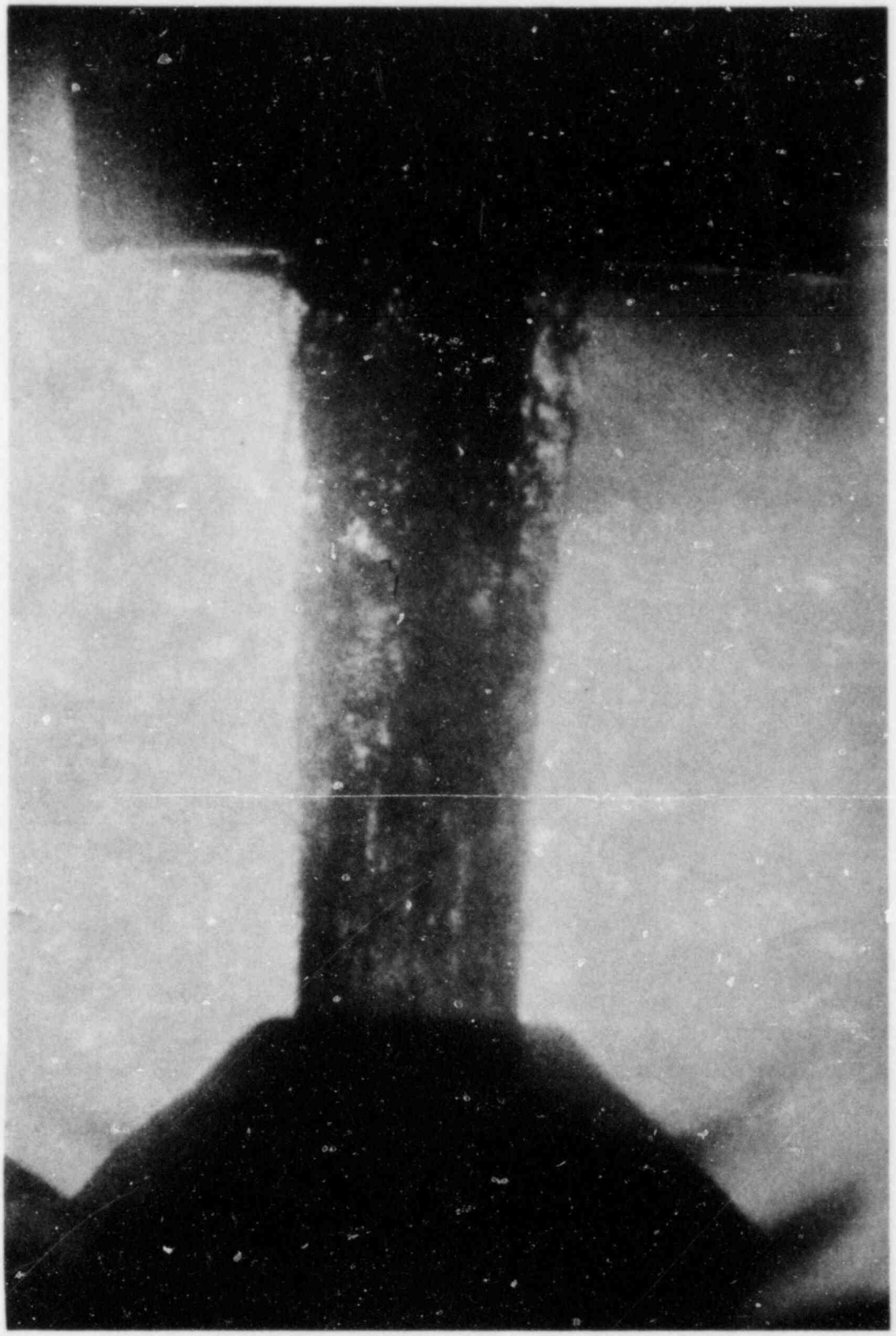


Figure 17 - Water Jet With Straightening Vanes Installed in Nozzle. No Nitrogen Pressure. Flash of 1 μsec duration

Figure 18 - Water Jet With Straightening Vanes Installed in Nozzle. No Nitrogen Pressure. Flash of 1 μsec duration taken 0.08 sec. after Figure 17.

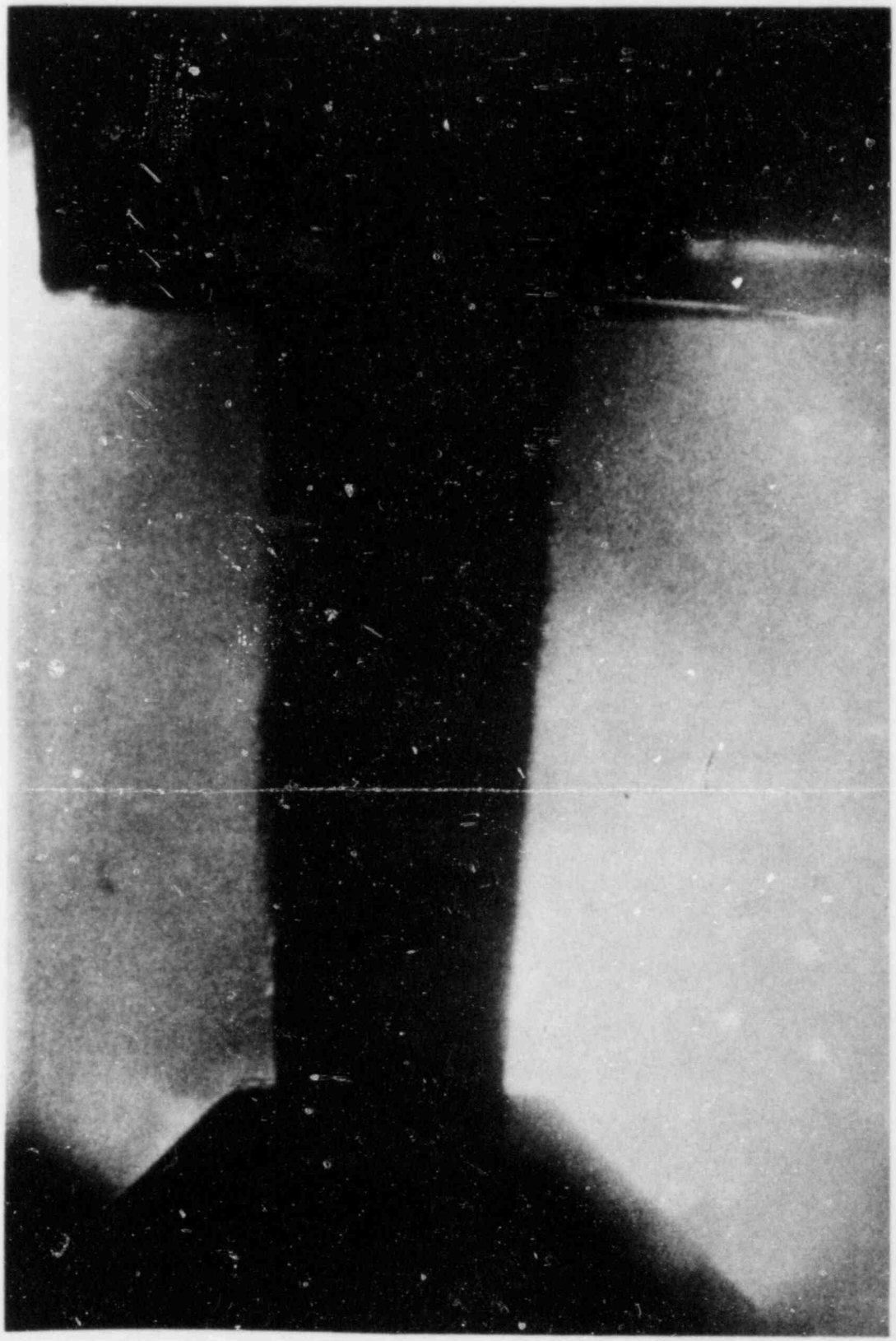


Figure 19 - Water Jet With Straightening Vanes Installed in Nozzle.
24 psi nitrogen pressure. Flash of 1 μsec duration.

Figure 20 - Water Jet With Straightening Vanes Installed in Nozzle. 24 psi nitrogen pressure. Flash of 1 μsec duration taken 0.06 sec. after Figure 19.

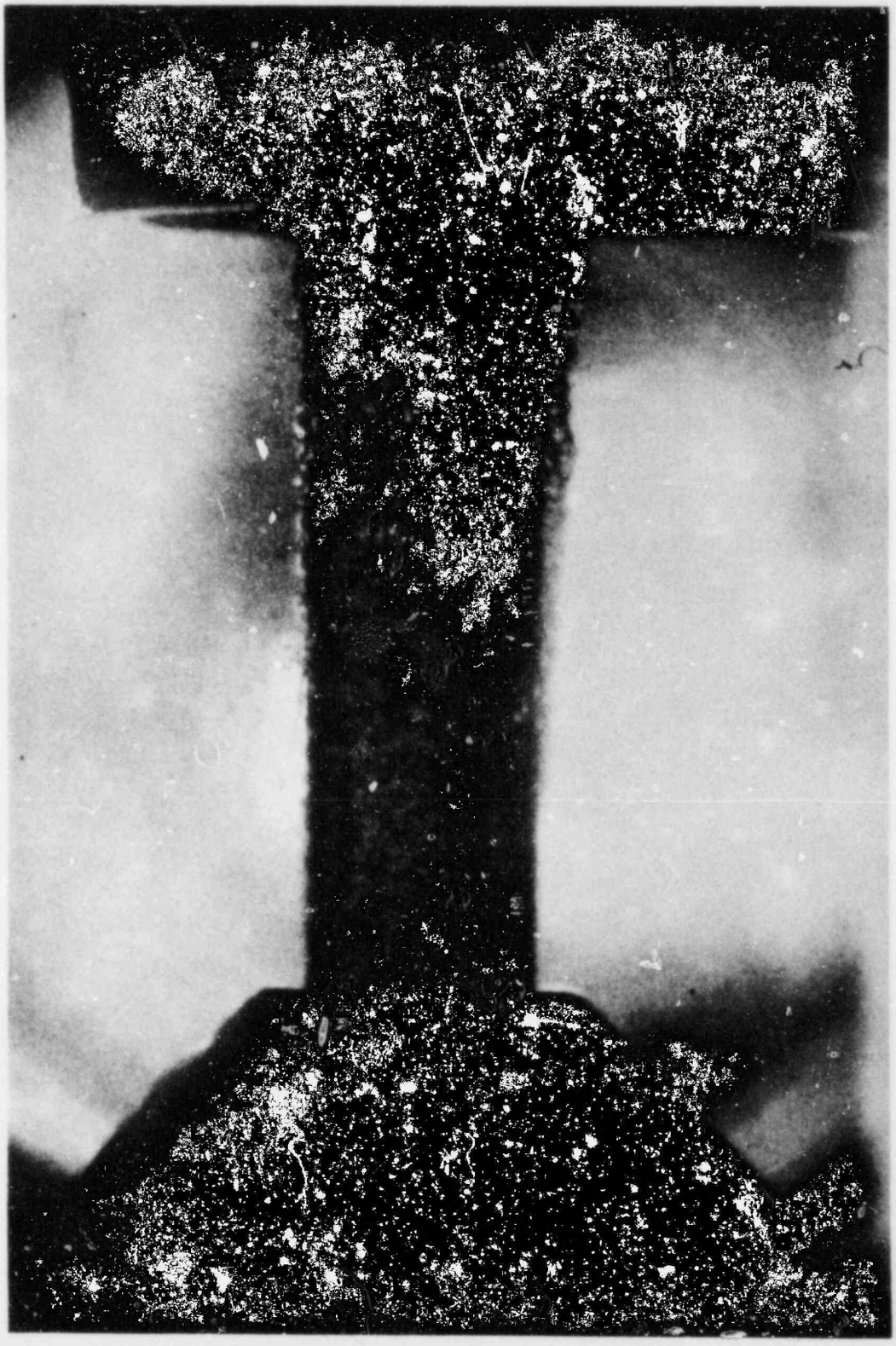


Figure 21 - Water Jet Without Straightening Vanes Installed in Nozzle. No nitrogen pressure. Flash of 1 μsec duration.

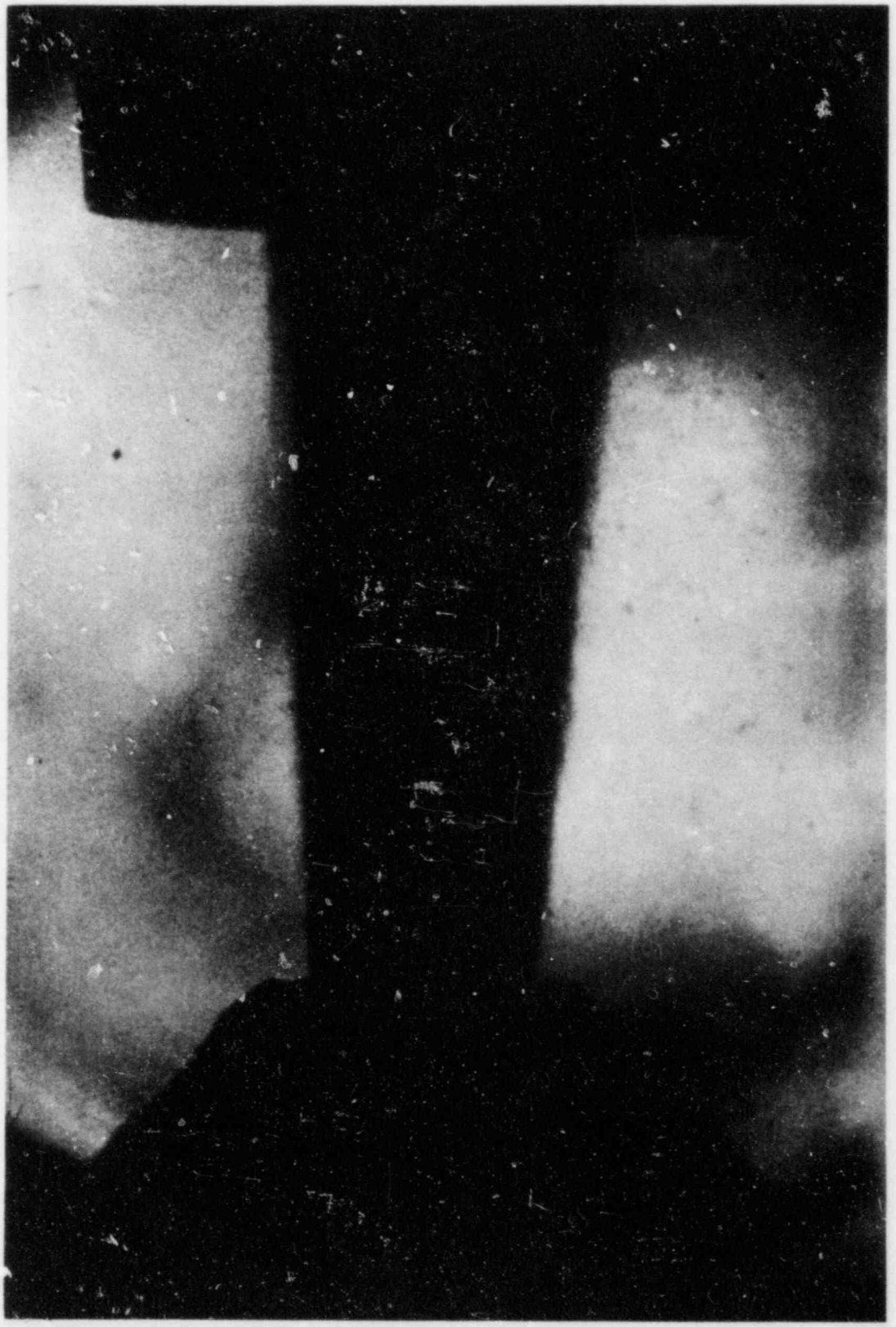


Figure 22 - Water Jet Without Straightening Vanes Installed in Nozzle. No nitrogen pressure. Flash of 1 μsec duration taken .36 sec. after Figure 21.

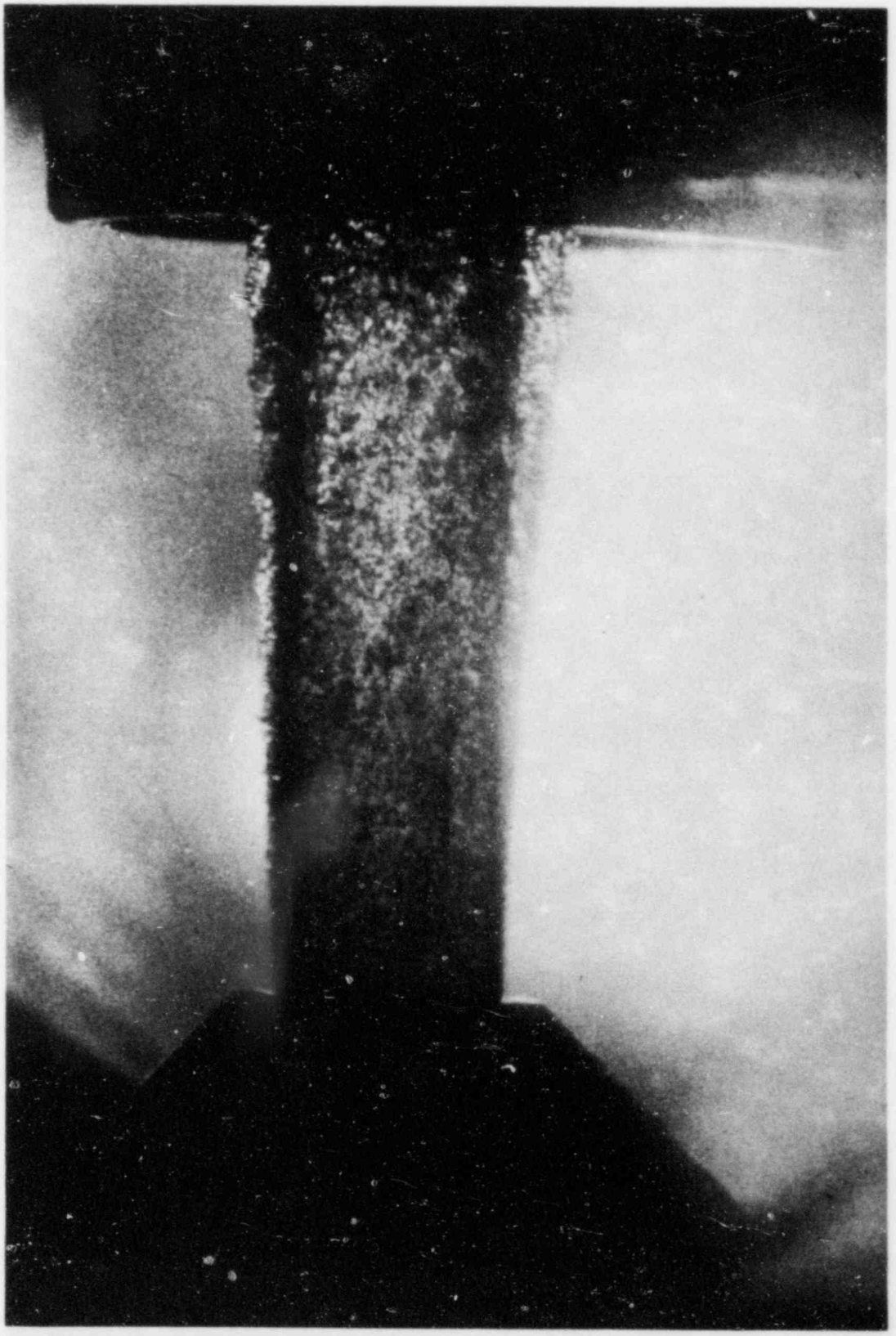


Figure 23 - Water Jet Without Straightening Vanes Installed in Nozzle. 25 psi nitrogen pressure. Flash of 1 μsec duration.

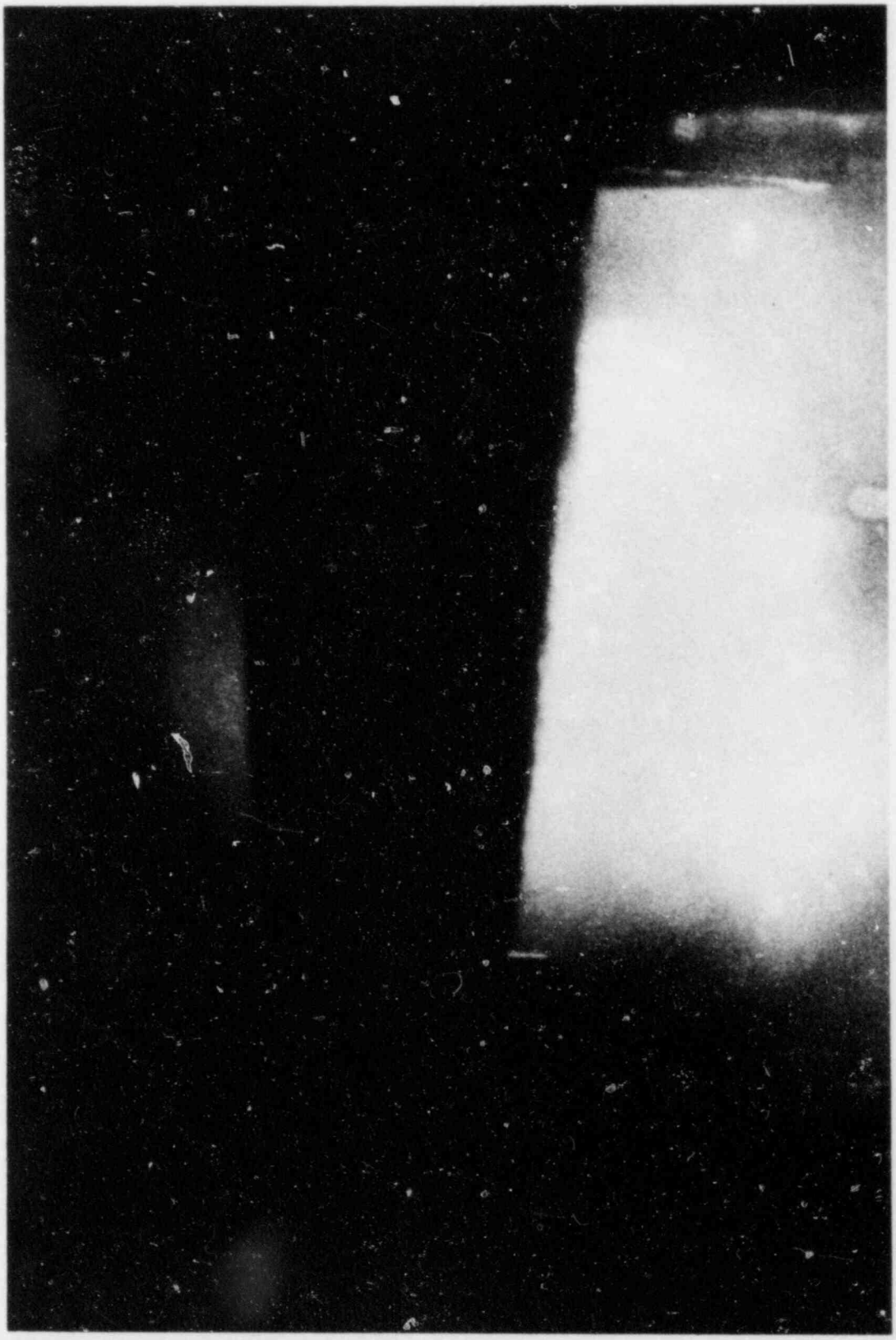


Figure 24 - Water Jet Without Straightening Vanes Installed in Nozzle. 25 psi nitrogen pressure. Flash of 1 μsec duration taken .56 sec. after Figure 23.

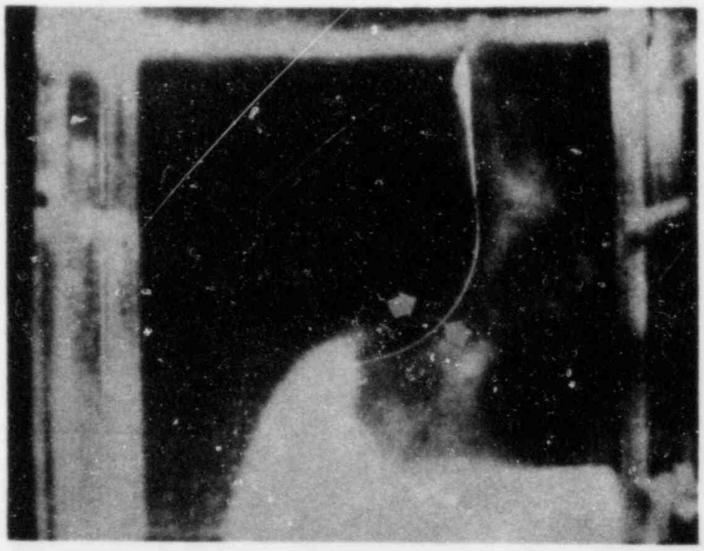


Figure 25 - Water Flowing Past Specimen B With a -3° Angle of Attack in the Low Speed Water Tunnel. Note the Stagnation Point in Cusp

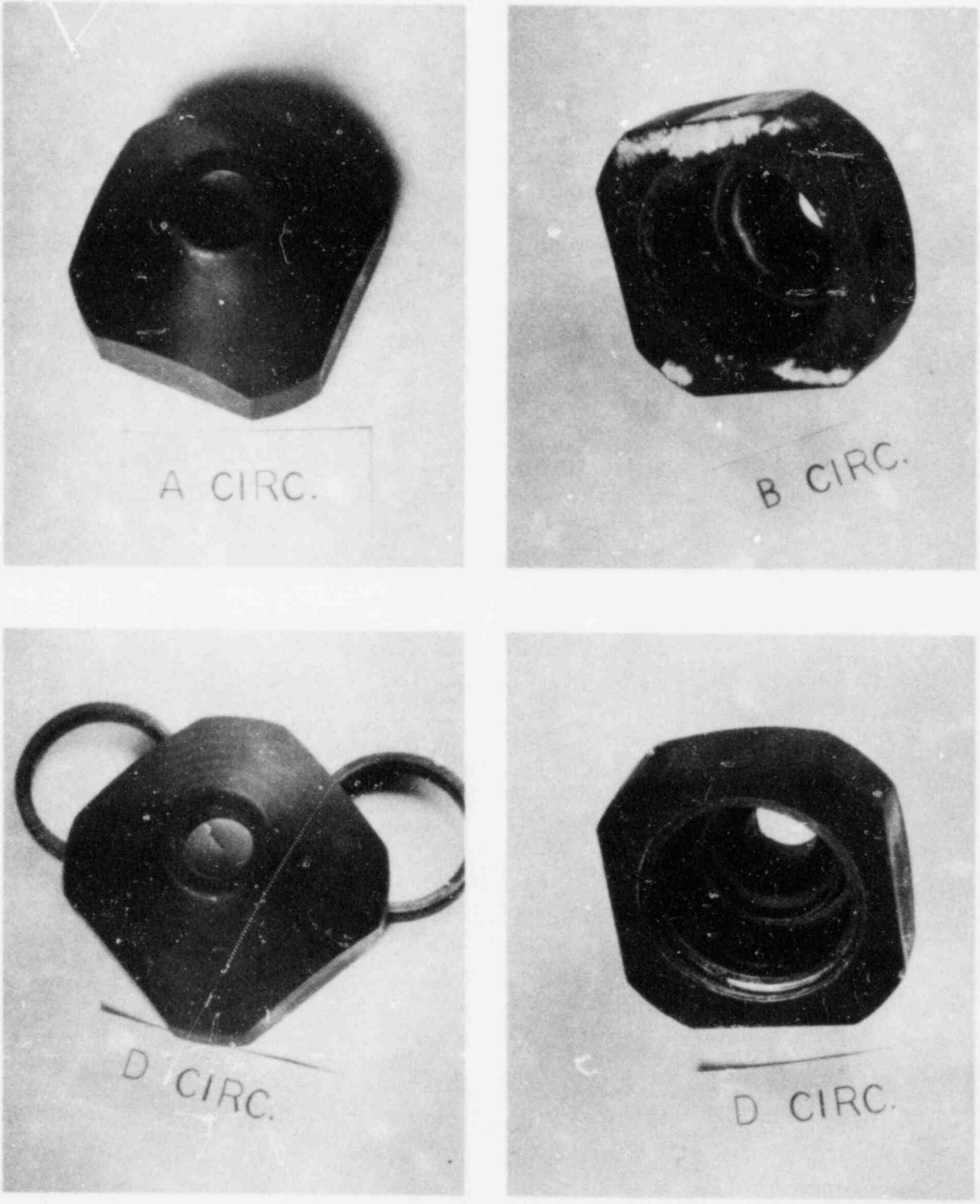


Figure 26 - Different Pictures of Nozzles A, B and D. Note the Segmented Damage in A and D and the Symmetric Damage in B

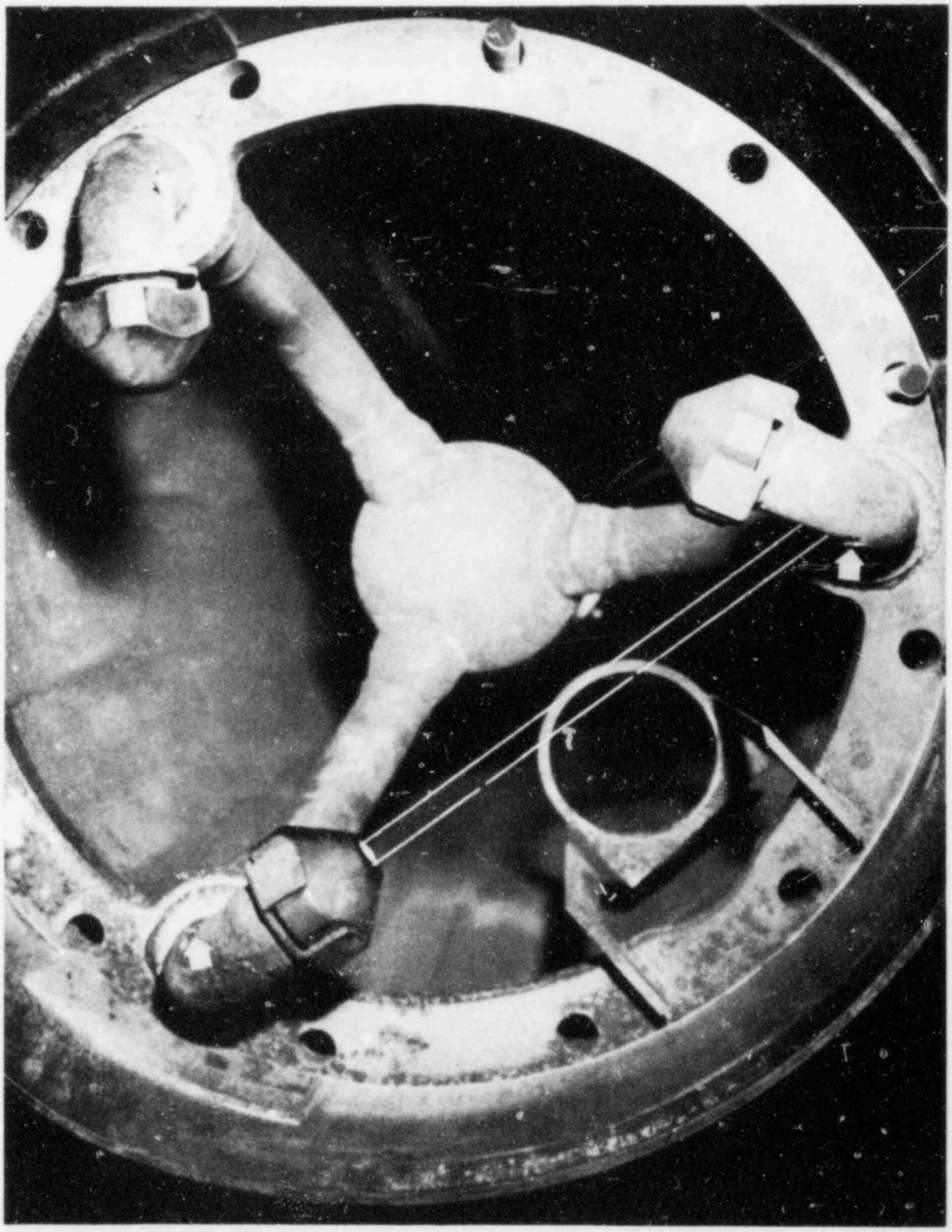


Figure 27 - Top View of the Pre-Nuclear Pelton Wheel Piping Showing the Damage to the Elbows and the Path of the Water Jet

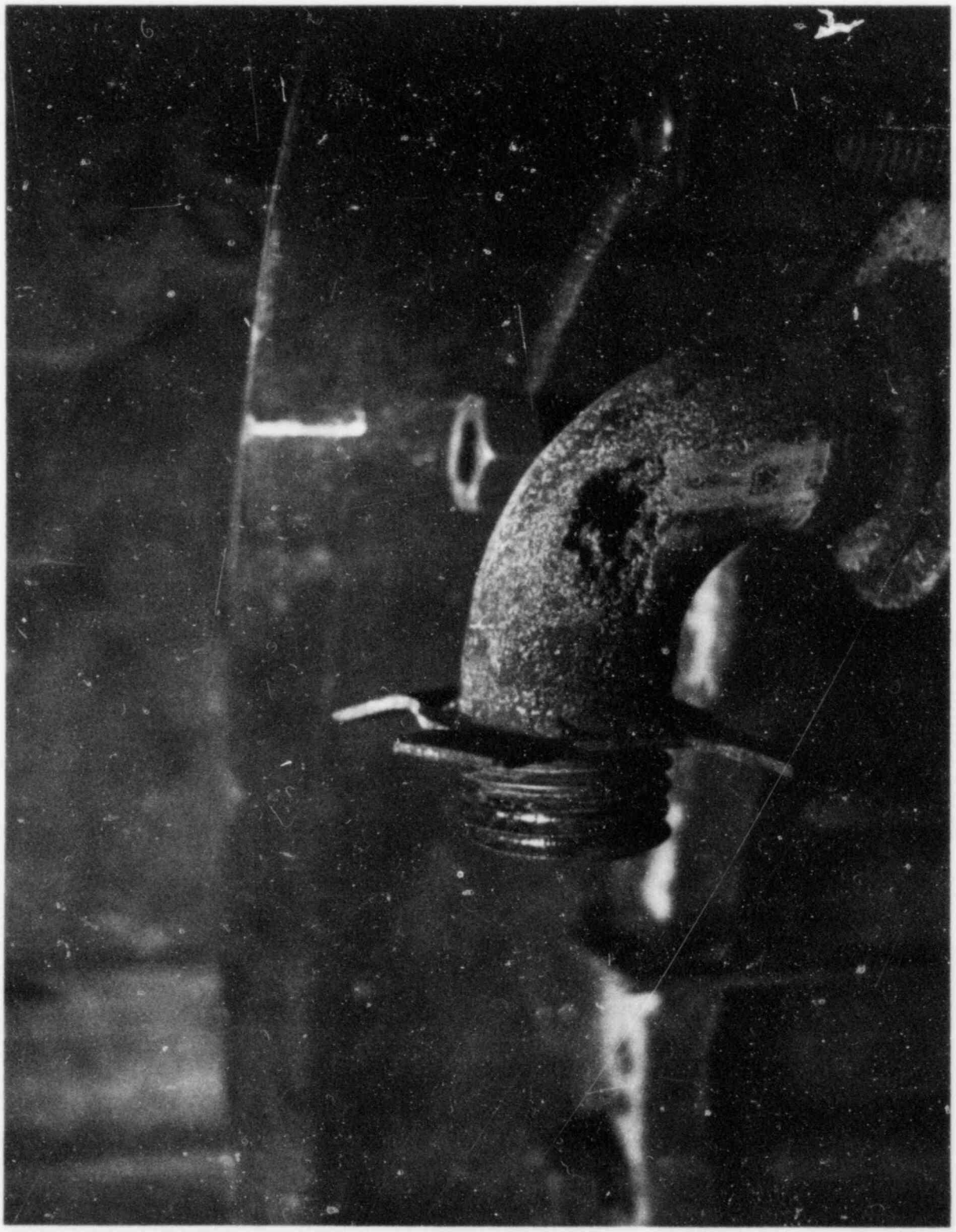


Figure 28 - Close-Up View of the Damage to One of the Elbows

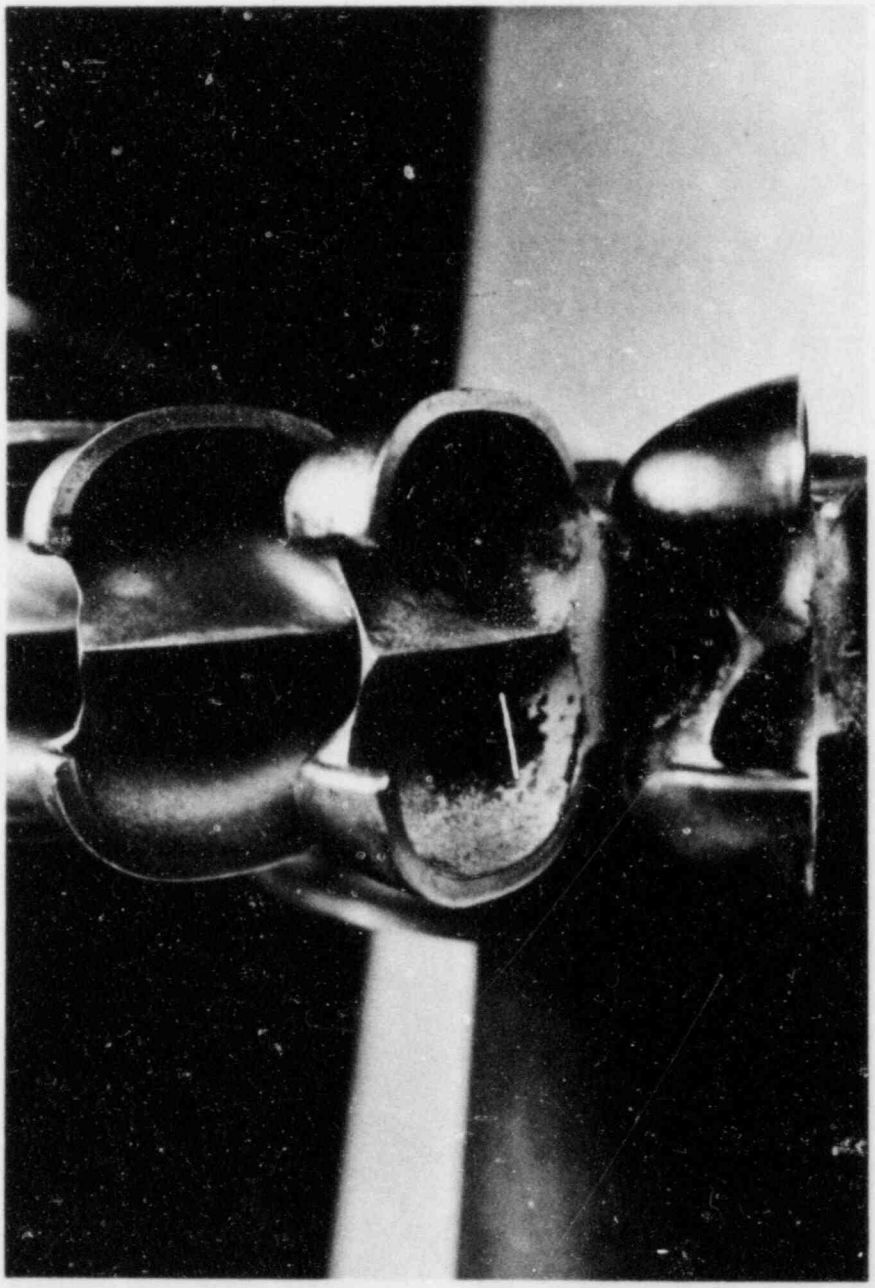


Figure 29 - View of the New B Wheel Bucket Tips

Figure 30 - View of the Old B Wheel Bucket Tips. Note the Damage at the Tip and the Spray into the Cusps.

Figure 31 - Side View of New B Wheel. Note the Frosting on the Back Side of the Bucket.

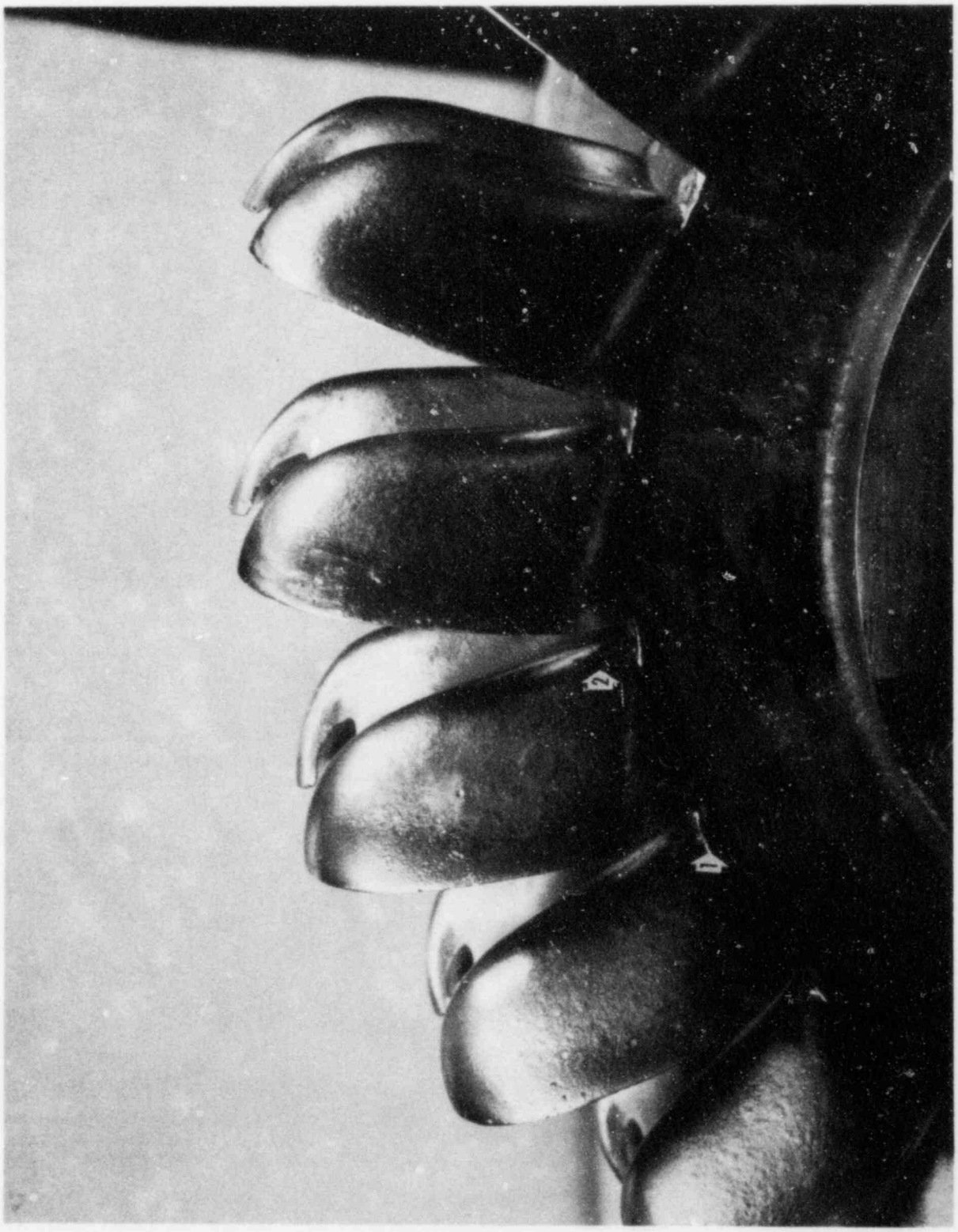


Figure 32 - Side View of Old B Wheel. Note: (1) the lip around the rim and (2) the damage on the backside

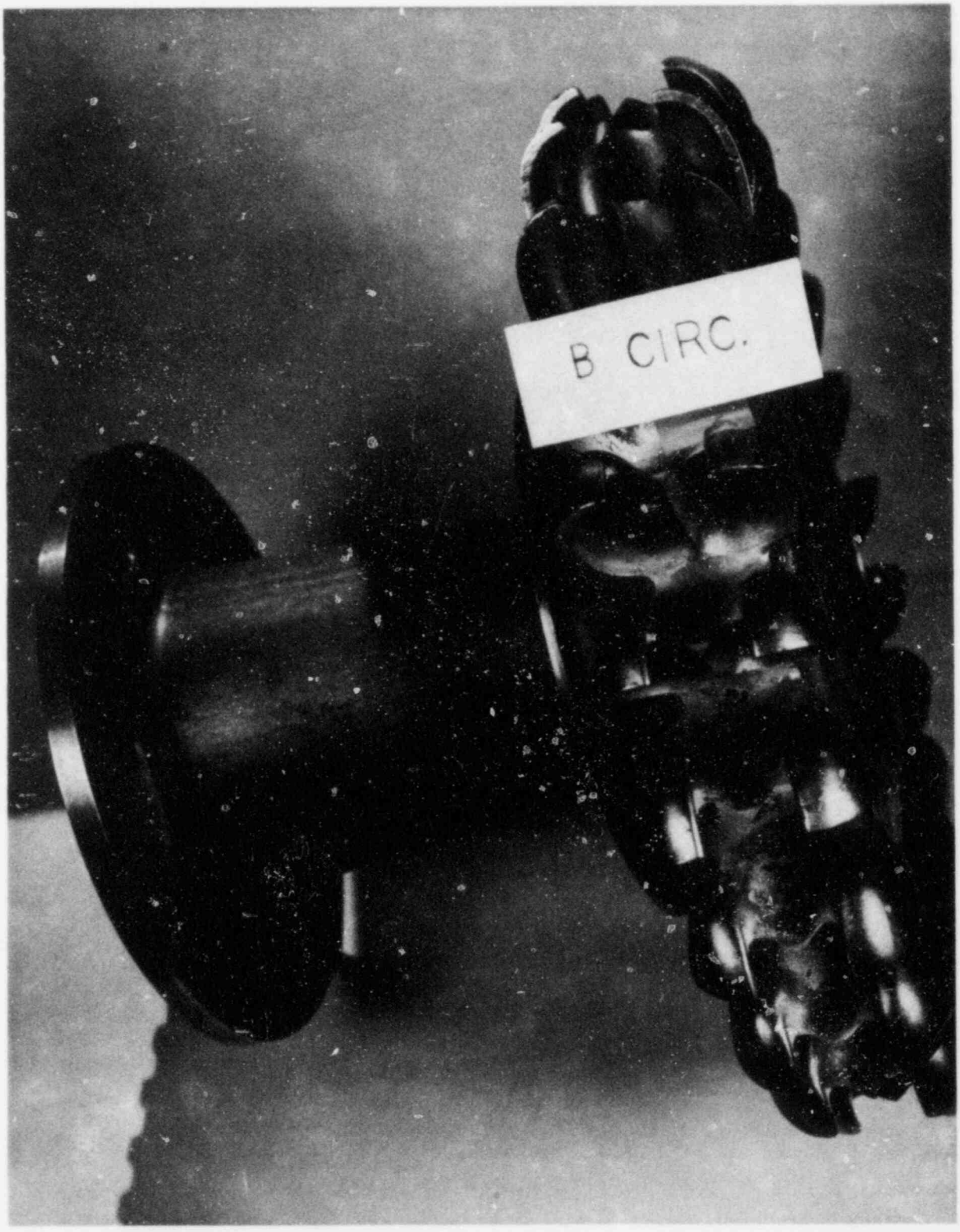


Figure 33 - Side View of New B Wheel Showing Cavitation Damage in the Rim Between the Buckets.

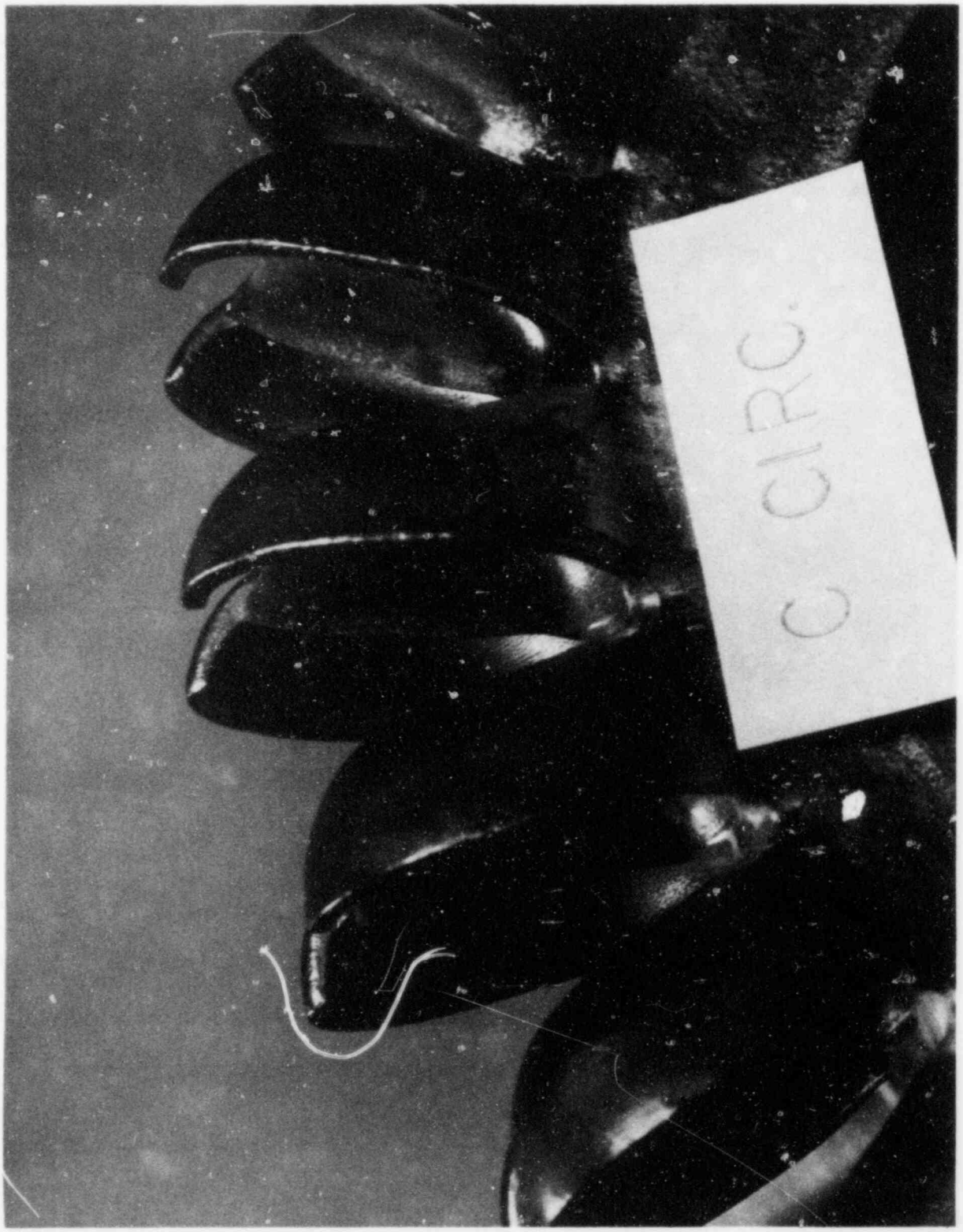


Figure 34 - End View of New C Wheel Showing Amount of Metal Removed from the Flow Splitter

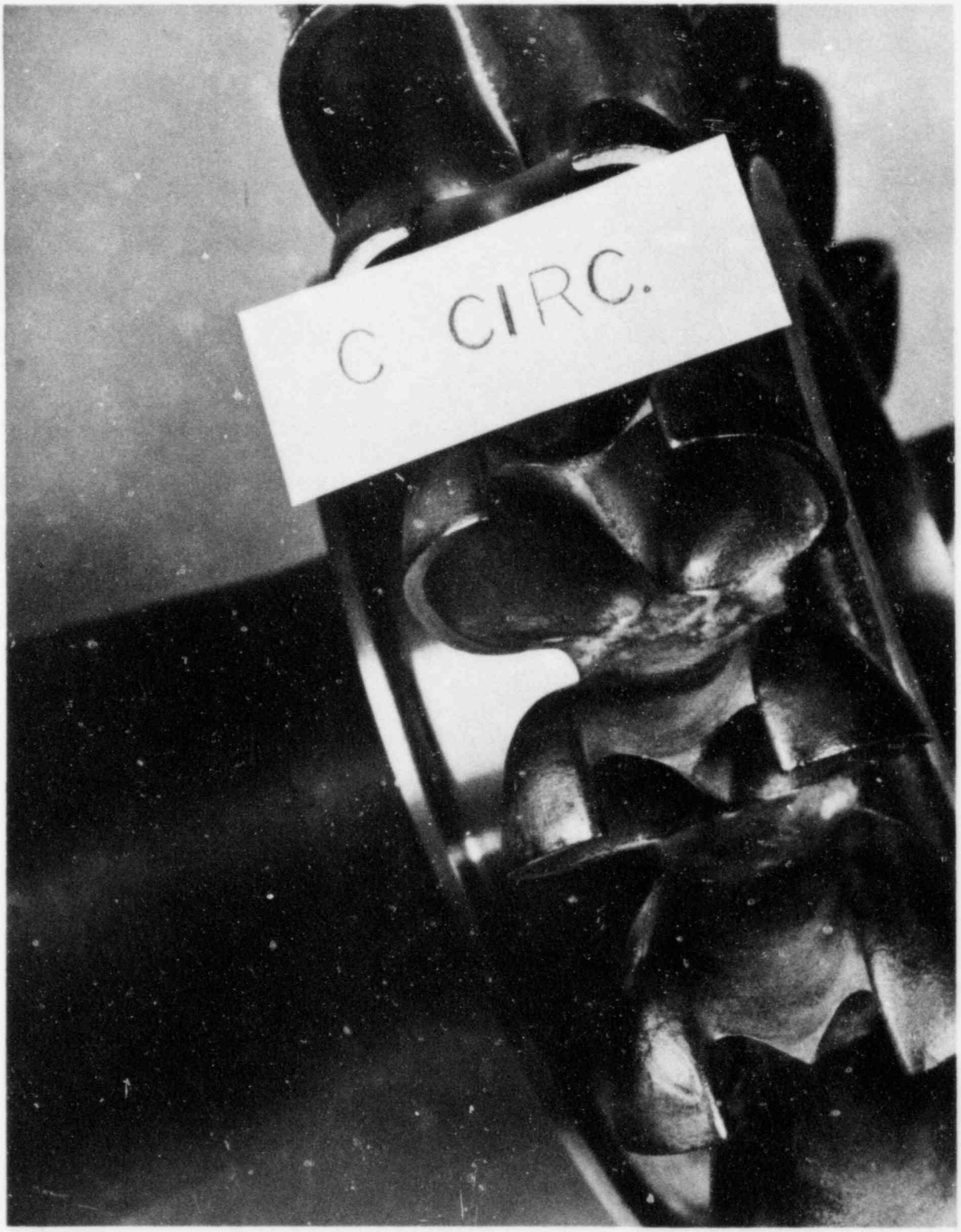


Figure 35 - Side View of New C Wheel. Note lack of damage at the bucket tip and rim.

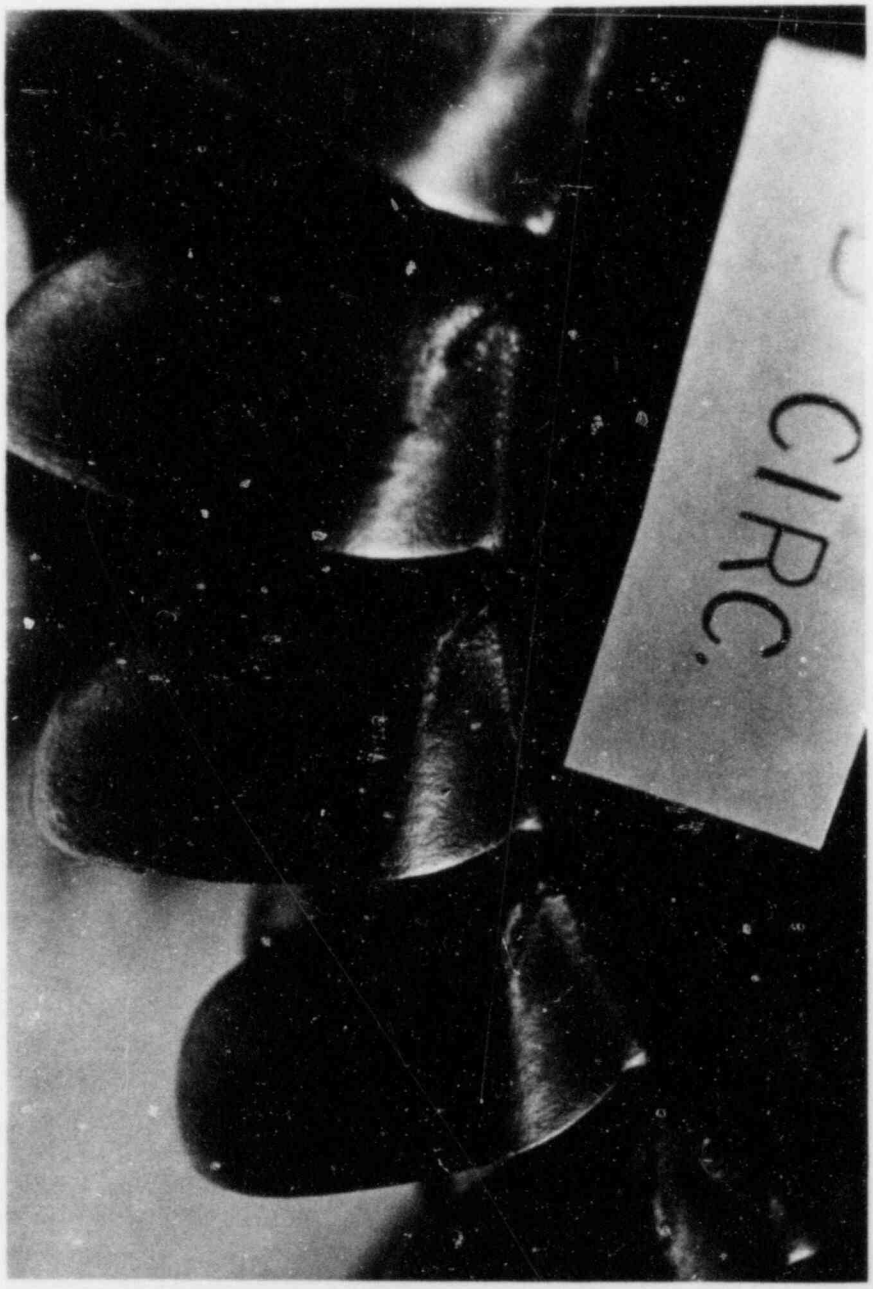


Figure 36 - End View of New D Wheel. Note the slight frosting on the buckets.

Figure 37 - End View of New D Wheel. Note: (1) the light frosting of the splitters and (2) the damage at the base of one of the buckets.

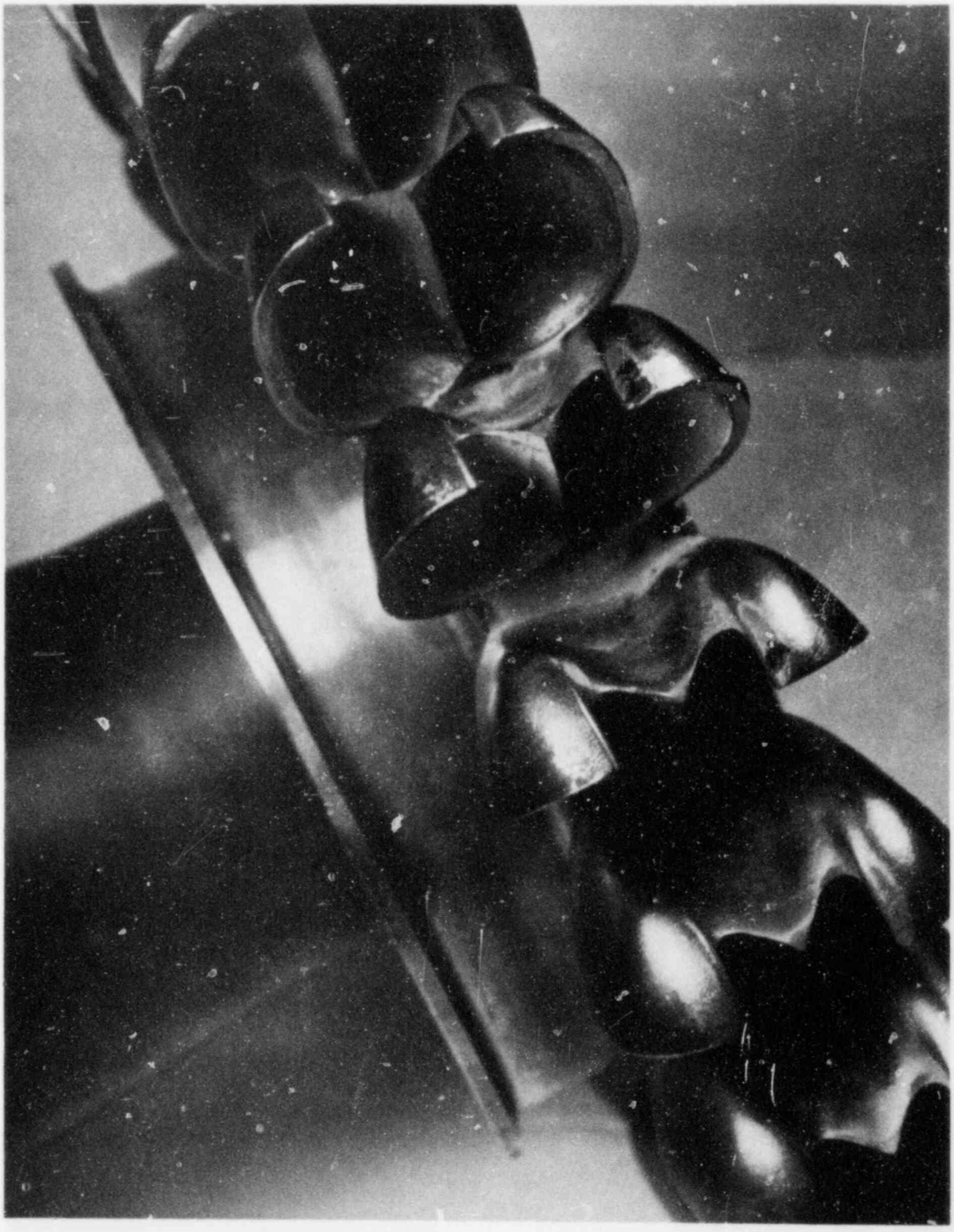


Figure 38 - Side View of New D Wheel Showing the Damage to One Side of the Buckets. This was caused by a misaligned nozzle.