CAVITATION DAMAGE OF METALS

by

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Professor A. L. Thompson, for his supervision and guidance throughout this investigation;

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STATEMENT OF ORIGINAL WORK

The test results contained in this thesis were conducted personally by the author in the Mechanical Research Laboratory at Dominion Engineering Works during 1953-60. Field experience has confirmed the experimental results that the metal properties are more important for hydraulic turbines, but the liquid characteristics are more important for diesel engines. The cavitation parameter for temperature is an important contribution for water cooling systems.

An abstract of this thesis was presented to the American Society of Mechanical Engineers in December, 1959 as paper 59-A52, and it has been accepted for future publication in the Transactions of the ASME, Journal of Basic Engineering.

CAVITATION DAMAGE OF METALS

1. Introduction

Cavitation is a well known hydraulic phenomenon which may be associated with its destructive effects in hydraulic turbines and diesel cooling systems, although its advantages have been utilized in numerous ultrasonic devices such as flaw detectors, cleaning baths, and navigational echo-sounders. It should be emphasized that cavitation refers to the formation and collapse of vapour bubbles, while cavitation damage refers to the destruction of the guiding surface at the point of bubble collapse.

This thesis presents additional experimental evidence of the role of corrosion attack in accelerated cavitation tests with a magnetostriction apparatus, with particular emphasis on the effects of the metal properties and the liquid characteristics which can be correlated to field experience in hydraulic turbines and diesel engines. The suppression of mild cavitation attack in tap water and sea water by cathodic protection has been investigated and a possible explanation is given.

2. Cavitation is the Cause

Cavitation can be described as a hydro-dynamic phenomenon which relates to the formation and collapse of vapour bubbles in a flowing liquid. These bubbles form in regions where the local pressure is reduced below the vapour pressure at that temperature; and conversely, these bubbles start to collapse as soon as the local pressure increases above the vapour pressure. The formation of cavitation bubbles at vapour pressure conditions is common and it implies that water has no tensile strength, while the breaking strength of water between its molecular layers has been estimated by Frenkel (25) at 150,000 psi.

Cavitation can be compared to boiling, but one major difference should be noted. In boiling, heat is being added continuously to a liquid at the vapour pressure in equilibrium with the existing temperature; while in cavitation, the thermodynamic condition is one of constant total heat and the bubbles form when the local pressure is reduced below the vapour pressure.

The fields of shipbuilding and hydraulic engineering have been traditionally concerned with cavitation, but recently, the role of cavitation has been extended to the medical field, with speculations concerning bullet wounds, brain concussions and diver's bends.

2A. Inception of Cavitation and Nuclei

Cavitation occurs in tap water and commercial distilled water with no appreciable sign of tensile strength, which Eisenberg (46) attributes to the presence of nuclei containing vapour or undissolved gases, and these nuclei are always present in ordinary liquids and in crevices in the bounding surfaces. Knapp (52) demonstrated that even air-saturated tap water, when "denucleated" by prior application of large pressures, exhibited considerable tensile strength.

Thus , the inception of cavitation is attributed to the presence of nuclei or weak spots, which allow vapour cavities to form if the local pressure is reduced below the vapour pressure of the liquid at that temperature. Supplementary factors associated with the inception of cavitation are surface active or wetting agents, impurities, air content, turbulence and pressure gradients in the boundary layers of flow.

2B. Types of Cavitation

Since there is no hydro-dynamical difference between the boiling of a liquid and cavitation in a flowing liquid, cavitation is often referred to as "cold boiling". However, this paper is restricted to cavitation only. Eisenberg (46) has classified the general characteristics of cavitation into four types:

2B. a) Transient bubbles are defined to be small individual bubbles which grow, sometimes oscillate, and eventually collapse and disappear. An expanding spherical bubble is essentially stable, but a collapsing bubble is generally unstable. The rate of cavitation attack in a flowing liquid is velocity dependent on the transport of transient bubbles to the affected area, as reported by Knapp (50).

b) Steady-State cavities are defined to be large smooth stationary voids, whose free boundary is a flow streamline, and whose average envelope does not vary with time. Naval architects may refer to steady-state cavities on propellers as sheet or vortex cavitation. At the boundary of wakes behind a disc or a cylinder, many so-called steady state cavities have been reported, but the average envelope of these vortex cavities does not define a free streamline flow.

c) Non-Stationary cavities are usually associated with the entry of a missile from air into water or the entry of an accelerating missile from a submerged launcher.

d) Supercavitation refers to fully cavitating hydrofoil sections which can attain very high operating speeds without inordinately high power requirements, and they operate with a stable flow configuration. Free streamline theory can be applied to a

2B. d) (Cont'd.)

supercavitating flow when the separation points are defined by the sharp leading and trailing edges of the hydrofoil.

2C. The Cavitation Number "K"

The cavitation number "K" is used to indicate the degree of cavitation or the tendency to cavitate in a flowing liquid.

$$K = \frac{Pe - Pv}{\rho \frac{V^2}{2}}$$

where Pe = pressure in the undisturbed liquid

Pv = vapour pressure of the liquid at that temperature

V = relative velocity between the body and the liquid

ρ = density of the liquid

The physical significance of the cavitation number "K" is very important: the numerator (Pe - Pv) is the net pressure acting to collapse the cavity, and the denominator ($\rho \frac{V^2}{2}$) is the velocity pressure available to induce the formation and growth of the cavity. Usually the cavitation number "K" is referred to a particular stage in cavitation, such as incipient cavitation when the first bubble has appeared, or supercavitation when a fully developed cavitating flow has been reached.

3. Cavitation Damage is the Effect

Cavitation damage can usually be distinguished as a localized, honeycomb-type of pitting, substantially free of corrosion products. The boundary around the pitted area is well defined, though irregular in outline, and often includes streaks of "temper blueing" which confirm the presence of plastic deformation.

Cavitation damage is undoubtedly the most spectacular and easily identified of the deleterious effects of cavitation, but other important effects noticed in hydraulic machinery are a decrease in efficiency, a reduction in power output, some occurrences of large but unsteady vibrations, and always present is the noise which may go unnoticed in a large power house; but in submarines, cavitating propellers are avoided at all cost so that echo-sounders have less chance of detecting any acoustic disturbances in the water.

3A. Mechanism of Cavitation Damage

The mechanism of cavitation damage can be considered as the mechanical indentation of a metal surface at the point of cavitation bubble collapse, in the presence of several possible chemical reactions, as suggested by Evans (23) who wrote: "Cavitation erosion is a conjoint action of mechanical-chemical effects, where the film of oxide that would usually stifle the initial rapid rate of corrosion is continually torn off by collapsing

3A. (Cont'd.)

bubbles, and the chemical corrosion attack continues at the initial rapid rate instead of stifling itself. Thus, cavitation erosion is mechanical in the sense that oxidized metal is being continually torn away, but chemical in the sense that the metal is continually reforming the oxide film which has been torn off".

3B. Chemical Effects of Cavitation Attack.

The chemical effects of cavitation attack were suggested in a completely realistic manner by Wheeler (42) who wrote: " The essential characteristics are namely the combination of repeated, severe disturbance of atoms in the lattice with the opportunity for chemical reaction with water vapour and oxygen created by elevated temperatures due to the conversion of work into heat, and the development of local electrolytic cells due to deformation." Taylor (44) has postulated that the release of dissolved gases such as oxygen at the reduced local pressures according to Henry's law and the dissociation of water into extremely reactive ions such as the hydroxyl group could account for the complete mechanism of cavitation attack.

3C. Mechanical Effects of Cavitation Attack

The mechanical effects of cavitation attack were reported by Knapp and Hollander (29), who traced the growth, collapse and rebound of cavitation bubbles with high speed photography. Later Knapp (45) considered the intensity of cavitation attack on soft aluminium where a "blow by blow" damage mechanism was clearly established. The separate, distinct impact force at

3C (Cont'd.)
the collapse of a cavitation bubble produces a stress concentration on a very small area, and plastic deformation and strain hardening occurs if the severity of cavitation produces a mean shearing stress greater than the yield strength of the metal.

3C. a) Initial Attack of Cavitation

The collapse of a cavitation bubble near a metal surface produces a distinct concentrated impact force of extremely short duration. (Knapp estimated less than a milli-second) on an area smaller than the crystal size of most metals. Each separate impact force produces a stress concentration which may cause an initial slip movement of the lattice structure if the mean shearing stress exceeds the yield strength of the metal. The initial slip movement will begin in the direction of the impact force along a preferred slip plane in the lattice structure with the lowest critical shearing stress. The crystal under the impact force will develop the first slip plane but adjacent crystals will develop inclined slip planes in their own preferred directions as they tend to correct the plastic deformation or local indentation in the small area directly under the collapse of the cavitation bubble.

3C. b) Etching of Grain Boundaries

The local shearing stress generated at the collapse of a cavitation bubble produces an initial slip movement which will progress until it is arrested by interference with adjacent inclined slip planes. Since the atomic arrangement at grain boundaries may be discontinuous, a dislocation or vacancy in the lattice will permit excessive slip movement in that plane, which can lead to fracture of small particles which appear to be extruded from the intersection of the inclined planes. "Etching" is

3C (b cont'd.)

applied to the loss of small particles by fracture at grain boundaries which visibly define the grain, and Wheeler (42) (54) and Shalnev (43) have both reported etching of metals by accelerated cavitation.

c) Propagation of Attack

Some plastic deformation including "etching" of the grain boundaries by the loss of small fragments, can occur without any appreciable loss of weight of the test specimen. But under severe cavitation, with mean shearing stresses at the indentations far greater than the yield strength of the metal, repeated and widespread slip at individual indentations will overlap and the honeycomb type of pitting will result. Cavitation damage will proceed as a mechanical action similar to fatigue, but it will be accompanied and perhaps accelerated by electro-chemical action between the metal crystals in the plastically deformed area, see (42) and (46).

4. Description of the Magnetostriction Apparatus

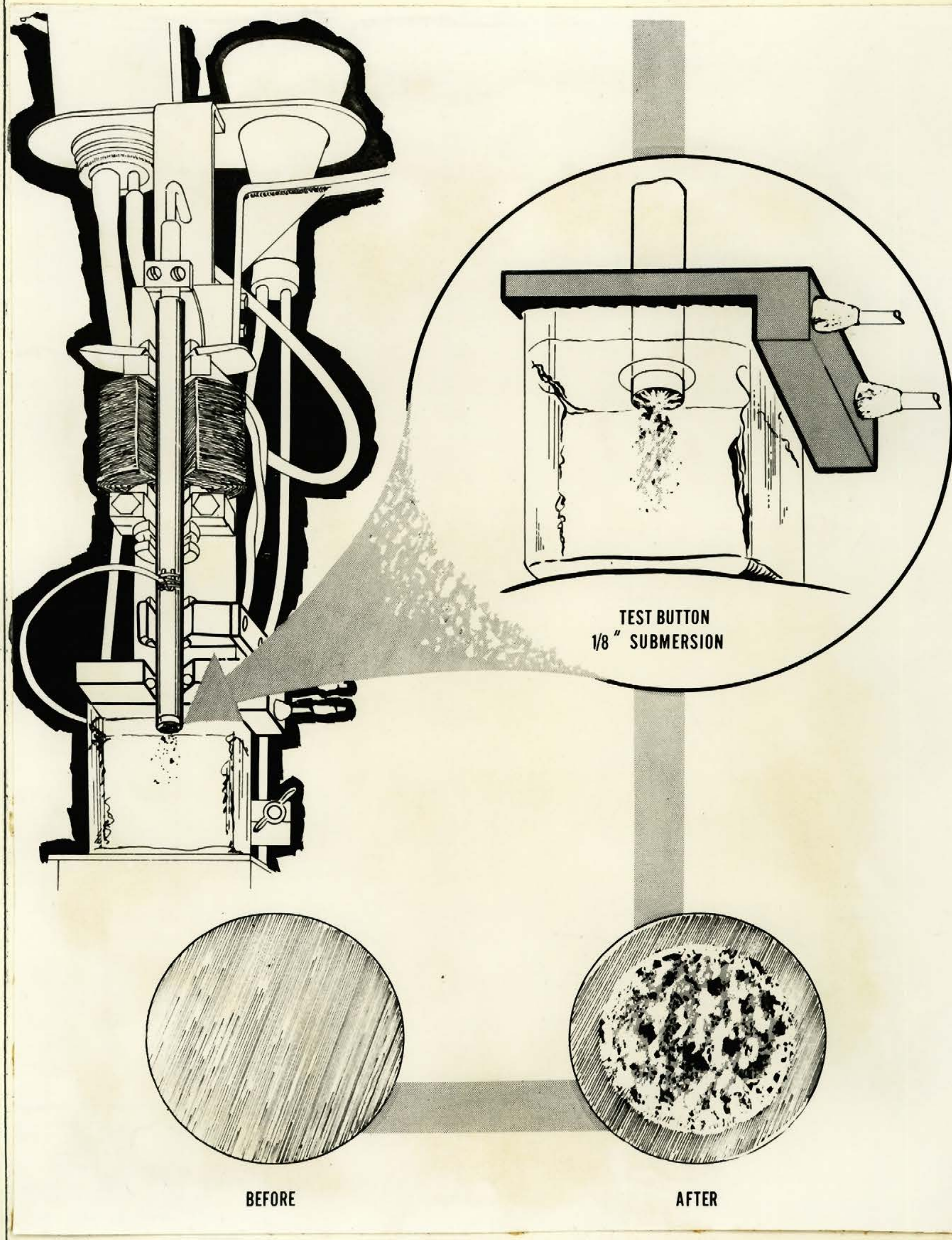
The need for rapid evaluation of metals' resistance to cavitation damage has prompted the commercial application of the magnetostriction effect under controllable and reproducible conditions. The magnetostriction effect is a broad term applied to ferro-magnetic materials which exhibit a change in physical dimensions when subjected to a magnetic field, or conversely, a change in magnetic properties occurs when the physical dimensions are altered by an external force. The most significant change is the "Joule effect" or the change of length along the axis of the applied magnetic field when the field is varied. Nickel contracts in length at a decreasing rate in an increasing magnetic field until a maximum or saturation value is reached.

The magnetostriction apparatus consists of a high frequency oscillator which produces a resonant longitudinal vibration of a nickel tube at its natural frequency by subjecting it to an alternating magnetic field. In the apparatus used by this author, the nickel tube vibrates at 6,500 cycles per second and each end has a total maximum amplitude of .0034 inches. The test button which is 5/8 inch diameter, is screwed into the lower end of the tube. The test button is immersed 1/8 inch in the test liquid (usually distilled water, except where noted) which is maintained at a constant temperature by a water bath. The tube is cooled by a water spray on the inner wall, and a vacuum aspirator removes the excess water from the bottom of the tube. The vibration amplitude is calibrated for some indicated output from the resistance strain gauge which is cemented on the vibrating nickel tube.

Figure 1 is a diagrammatic sketch of the magnetostriction apparatus, and the nickel tube assembly is shown in Figure 2. A complete description of the ASME Standard Procedure for the Vibratory Cavitation Test can be found in Appendix II.

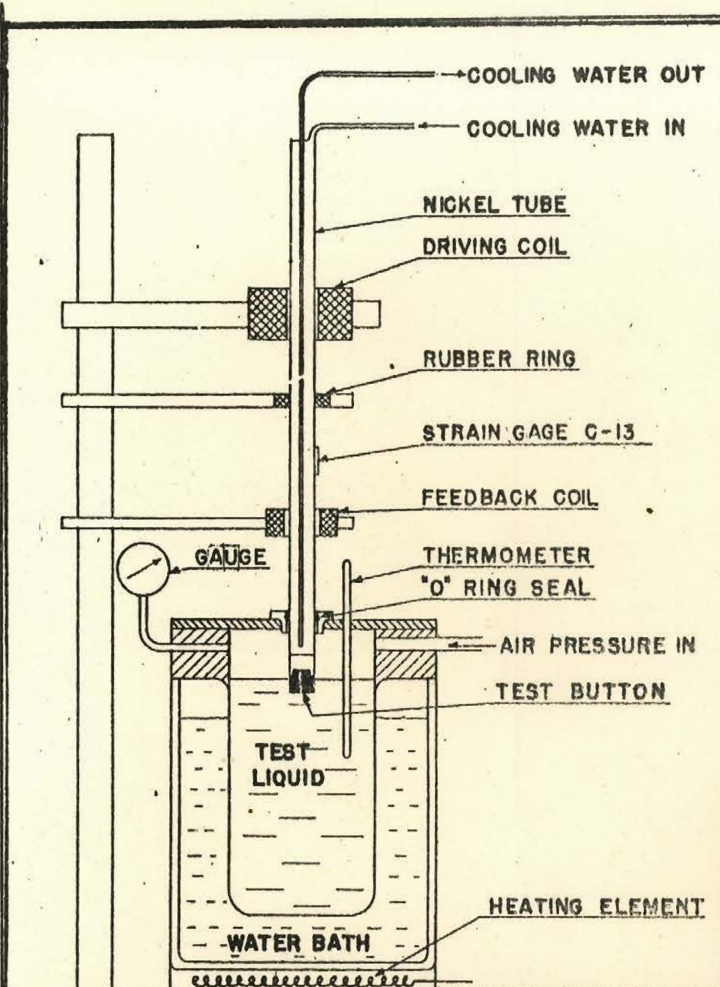
A table of mechanical properties of all metals tested is included for reference, and is shown in figure 42.

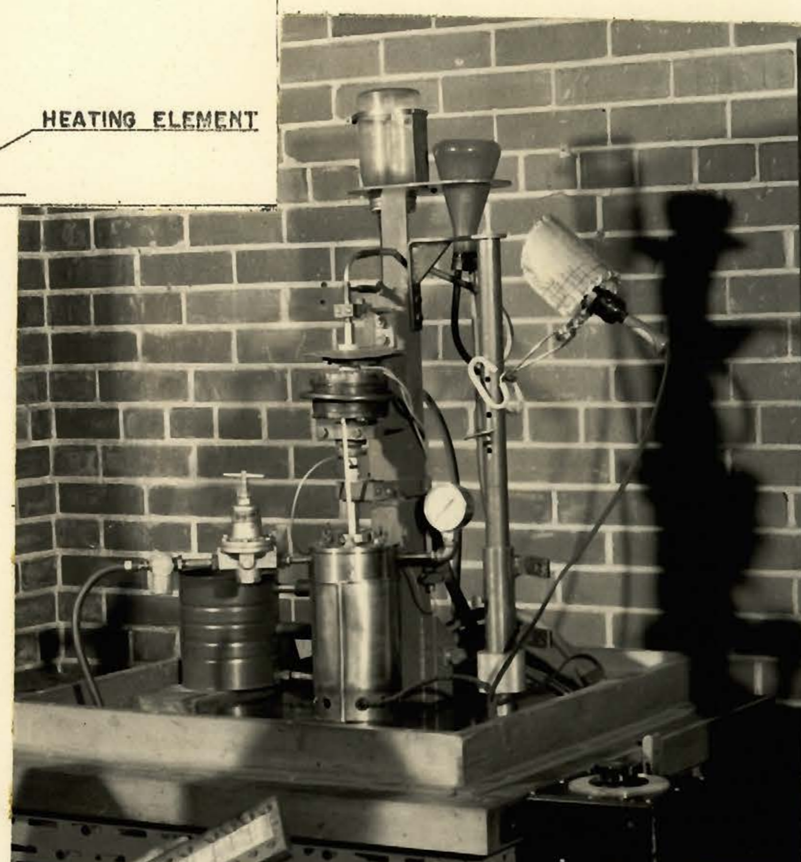
The test results shown are the average of three buttons for each material.



ACCELERATED CAVITATION APPARATUS

FIGURE 1





NICKEL TUBE ASSEMBLY FIGURE 2

5. High Speed Photography of Cavitation Bubbles

A Fastax Camera which takes up to 8,000 pictures each second on 16 mm film has been used to photograph the cavitation bubbles on the test button as it oscillates up and down in distilled water at 6,500 cycles per second. The film is pulled past the aperture in a continuous motion and a rotating prism exposes each frame in turn. A Goose Control unit provides the regulation of the camera speed, besides a remote control operation and synchronization of the camera with an event being studied. The Goose unit acts as a time delay mechanism to limit the camera voltage to 130 volts during the first .070 seconds, and then releases the higher voltage necessary to obtain the higher picture rate. This time delay action prevents tearing of the film perforations by the sprocket during the initial period of high starting torque. The central area on the test button where the cavitation bubbles oscillate is the low pressure zone during the upward motion of the vibrating nickel tube, and the size of this central bubble pattern corresponds to the size of the damage pattern in all cases.

Figure 3 shows the arrangement of the Fastax camera for photographing cavitation bubbles. The star-shaped bubble pattern on the vibrating test button is shown in Figure 4 which may be related to a third order radial vibration of the test button, as reported by Field (55). The film taken at 4700 frames per second appears to be near the peak of the amplitude cycle, while the films at 6500 and 8000 frames per second appear to show intermediate points along the amplitude cycle.

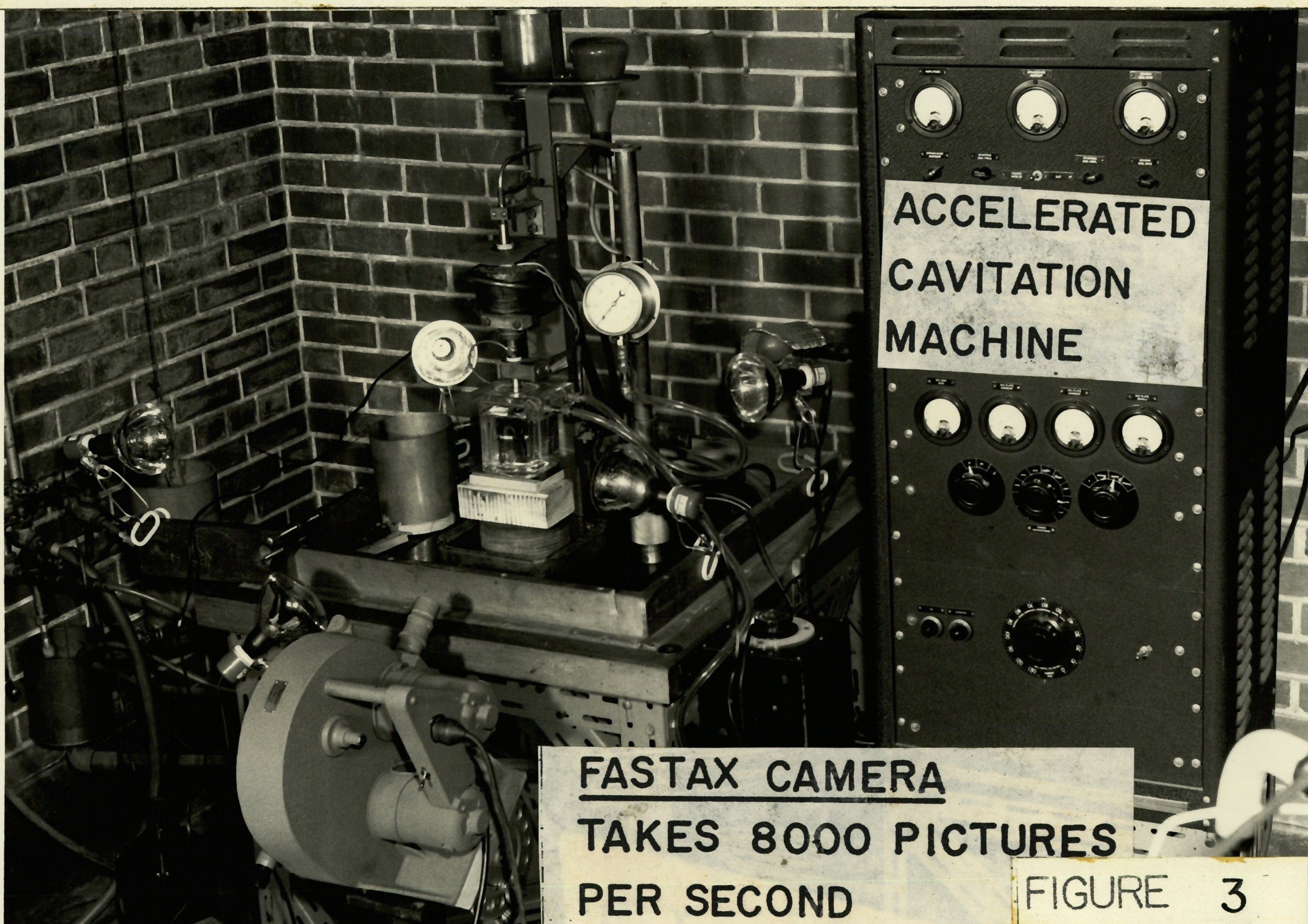
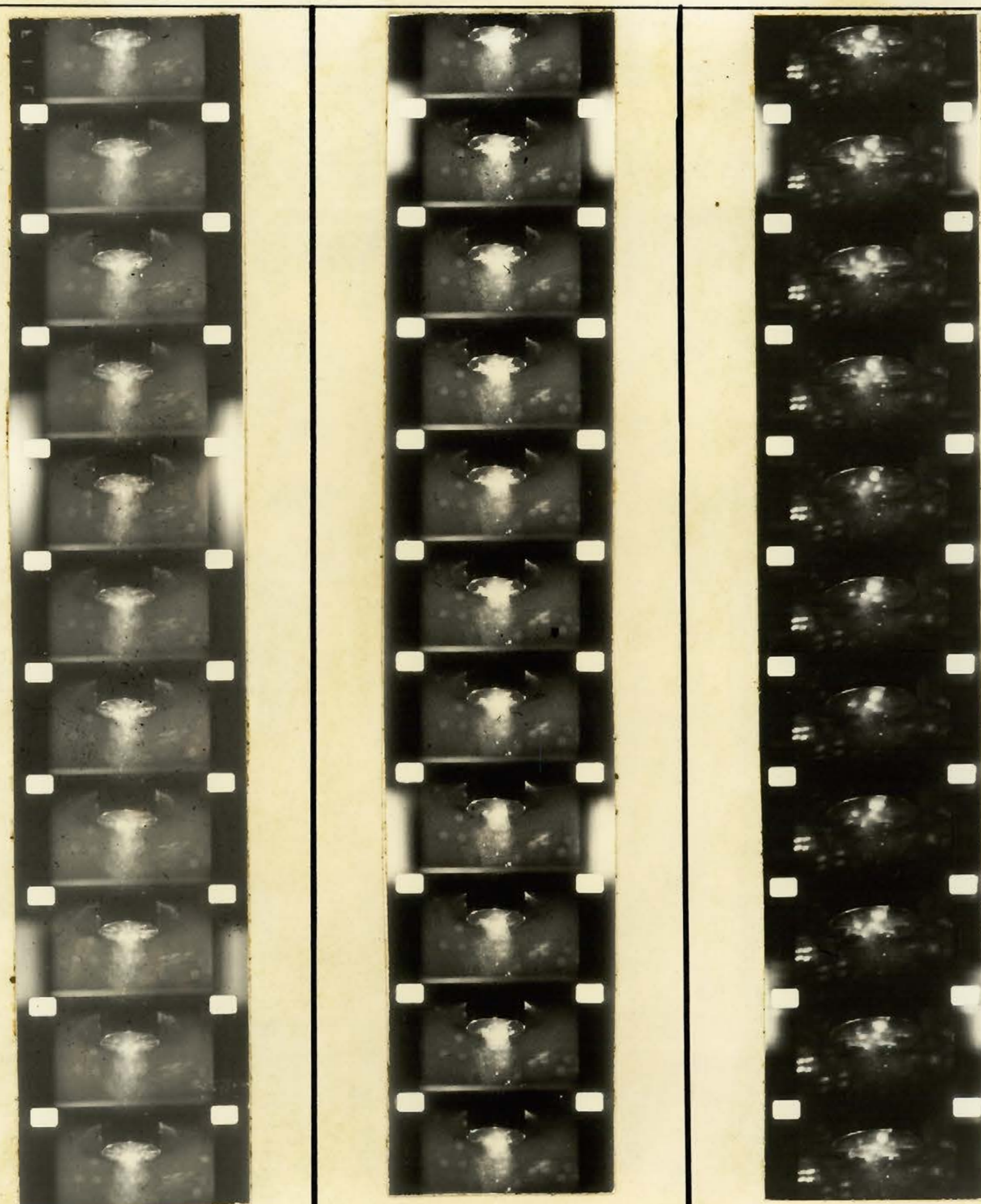

ACCELERATED
CAVITATION
MACHINE
FASTAX CAMERA
TAKES 8000 PICTURES
PER SECOND

FIGURE 3



4700 FRAMES PER SECOND

6500 FRAMES PER SECOND

8000 FRAMES PER SECOND

TEST LIQUID — DISTILLED WATER AT 76°F

BUBBLE PATTERNS ON A VIBRATING TEST BUTTON

FIGURE 4

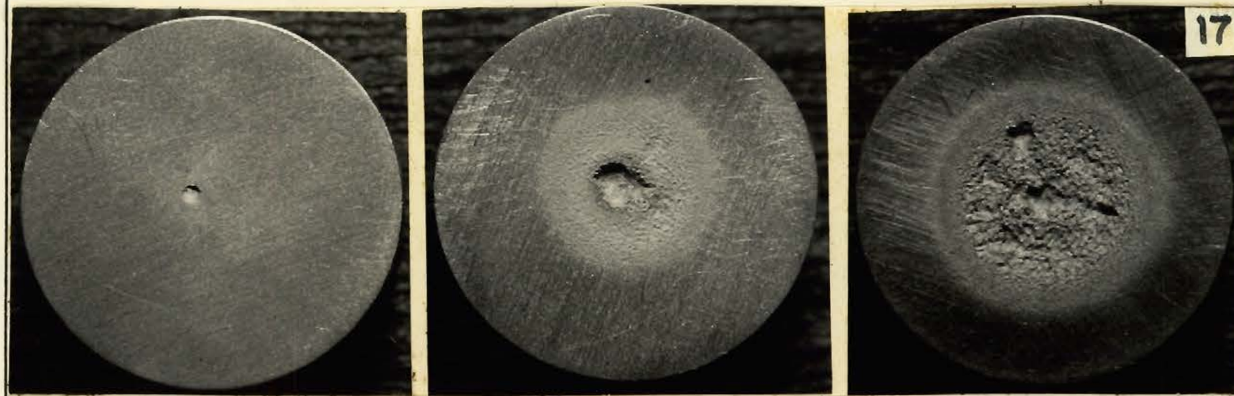
5. (Cont'd.)

High speed photographs of the cavitation bubbles at various vibration amplitudes indicate in Figure 5 that only one central bubble forms at the low amplitude. With increasing amplitude, a continuous formation of small bubbles grows from the outer edge of the test button and these bubbles enlarge as they move radially to the central mass of oscillating bubbles.

Aluminium test buttons in Figure 6 illustrate the appearance of the test surface before and after testing.

6. Intensity of Cavitation Attack

The mechanism of cavitation inception under measurable and reproducible conditions which are suitable for observation has been studied most successfully by Knapp (45), who correlated the measured history of an actual vapour bubble to the classical analysis of Rayleigh (7). The collapse of a spherical bubble in an incompressible liquid was considered assuming isothermal compression, and neglecting viscosity and surface tension. The excellent agreement of the experimental results with the theoretical postulates confirmed that the kinetic energy of bubble collapse was absorbed elastically in the water and given back largely undiminished in the rebound effects. The intensity of cavitation attack at various flow velocities has been reported by Knapp (50). Figure 7 illustrates that the vibration amplitude in this study has an effect similar to flow velocity, since both vibration amplitude and flow velocity show a threshold value of the metal's resistance, below which no metal is removed despite some plastic deformation, but above which the rate of metal removal increases rapidly with increased cavitation intensity.



AMP. = .001"   AMP. = .002"   AMP. = .003"

DAMAGE PATTERNS ON TEST BUTTONS

TEST LIQUID - DISTILLED WATER AT 76°F

AMP. = .001"   AMP. = .002"   AMP. = .003"

BUBBLE PATTERNS ON TEST BUTTONS

HIGH SPEED PHOTOGRAPHS OF CAVITATION BUBBLES

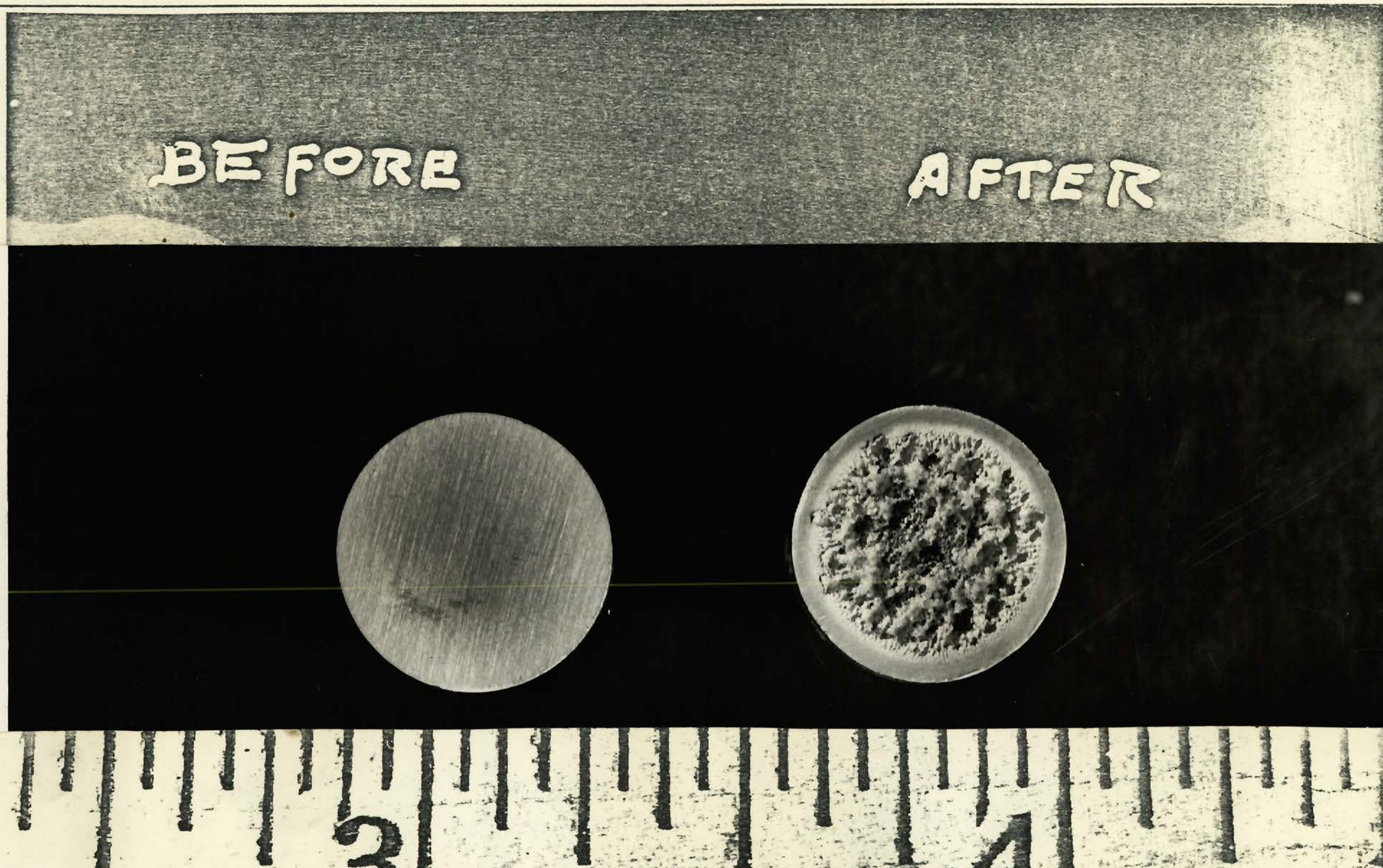
AT VARIOUS VIBRATION AMPLITUDES

SPEED - 8000 FRAMES PER SECOND

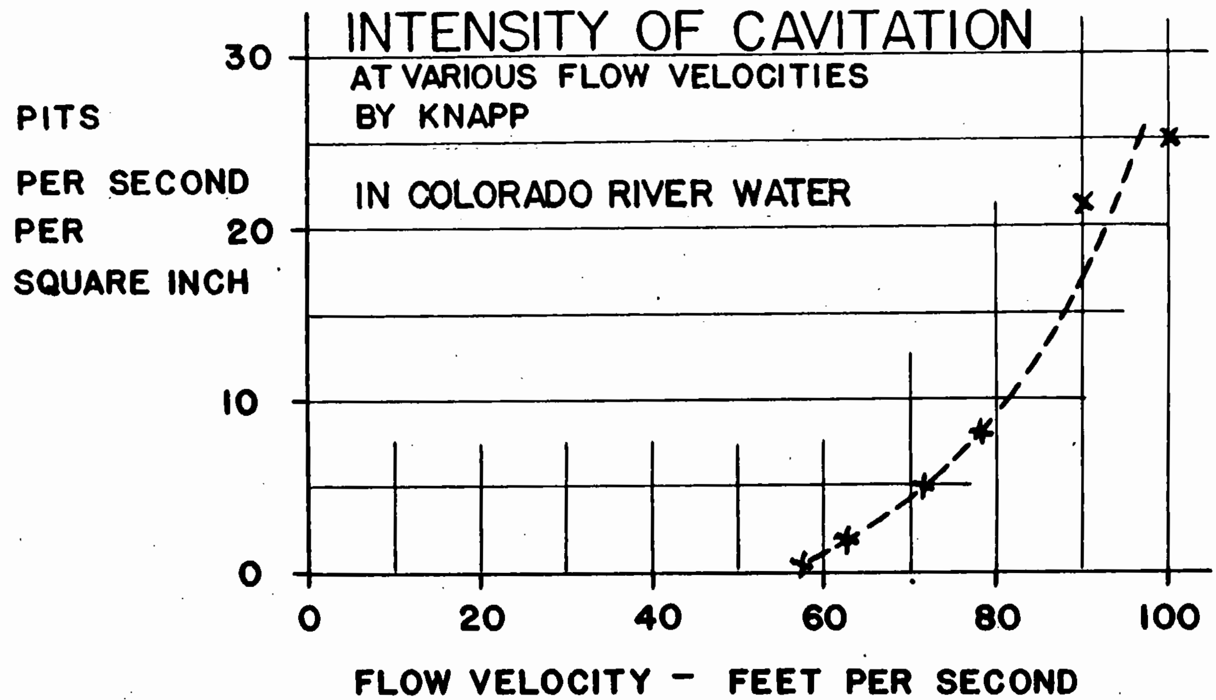
TEMPERATURE - 76°F

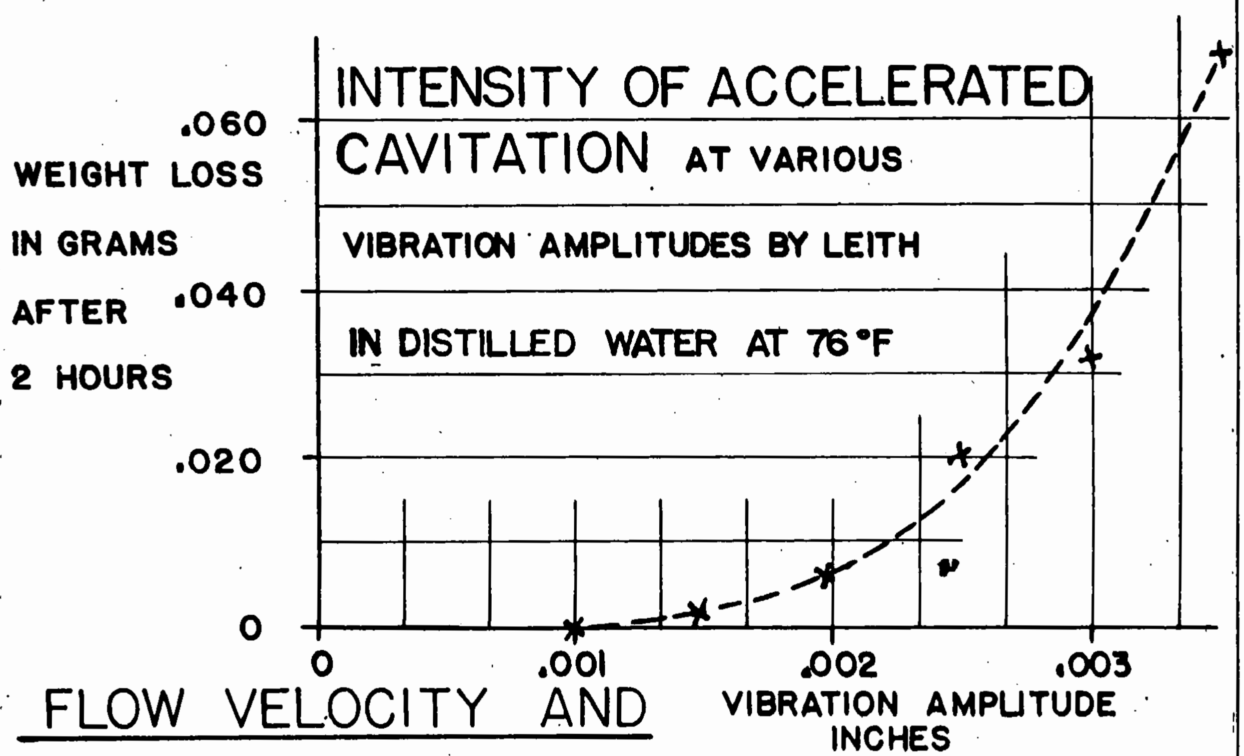
PRESSURE - 14.7 PSIA

FIGURE 5



ALUMINUM TEST BUTTONS FIGURE 6





FLOW VELOCITY AND

VIBRATION AMPLITUDE

FIGURE 7

7. Effect of Metal Properties

Many attempts have been made to correlate the resistance of a metal to cavitation erosion with some physical property, such as the tensile strength, but the local variations in cast metals have always disrupted comparisons that are valid for some rolled metals. If the weight losses after 2 hours for cast ductile iron and rolled stainless steel type 420, as shown in Figure 8, were taken as the important criteria, one might conclude that these two metals have similar resistance to cavitation damage.

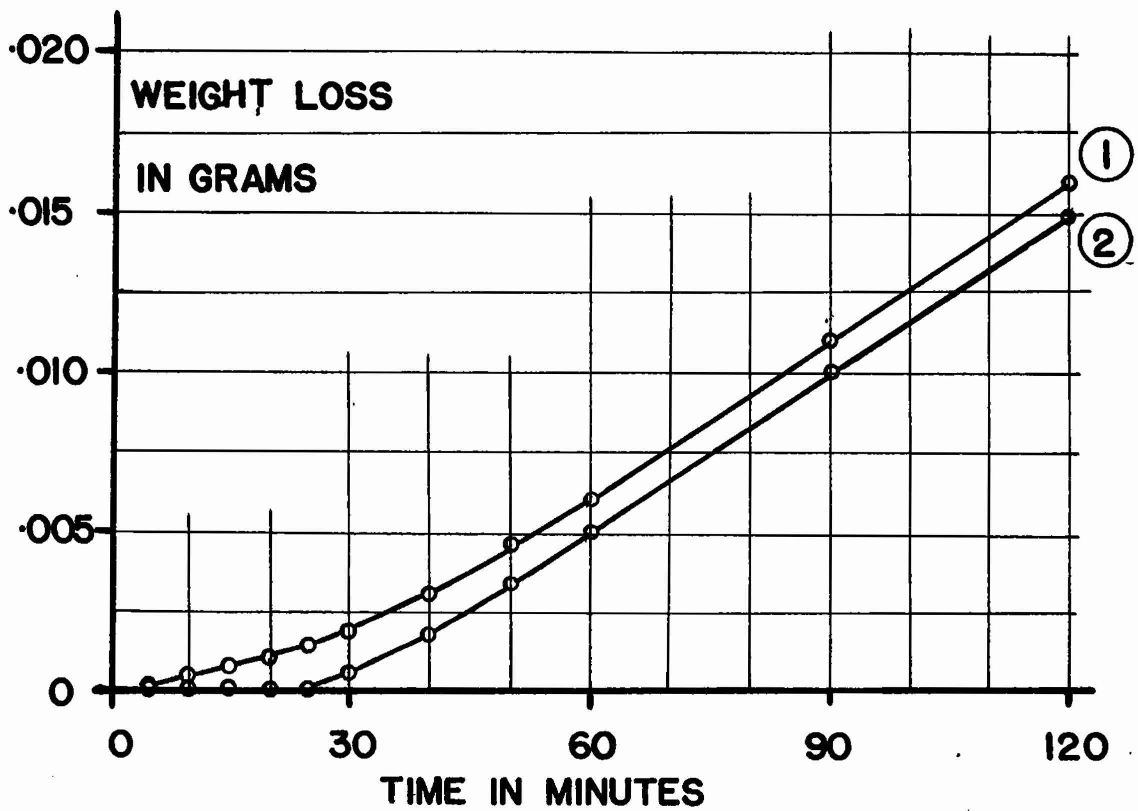
However, the presence of the incubation period for the stainless steel, or the time interval during which considerable plastic deformation of the test surface takes place without any apparent weight loss, confirms field experience that this rolled stainless steel will operate indefinitely in mild cavitation conditions or for about 1 year in severe cavitation conditions without suffering any cavitation damage. Thus, the incubation period is important where no dimensional change due to cavitation damage can be tolerated, such as in seal rings for pumps.

7A. Effect of Corrosion Fatigue Limit

One of the most useful results which applies only to rolled metals, is the determination of the incubation period, which can be converted into the number of cycles of accelerated cavitation attack necessary to develop corrosion fatigue in the central pitted area of the test button. Figure 9 suggest that the incubation time for rolled metals is proportional to the corrosion-fatigue limit.

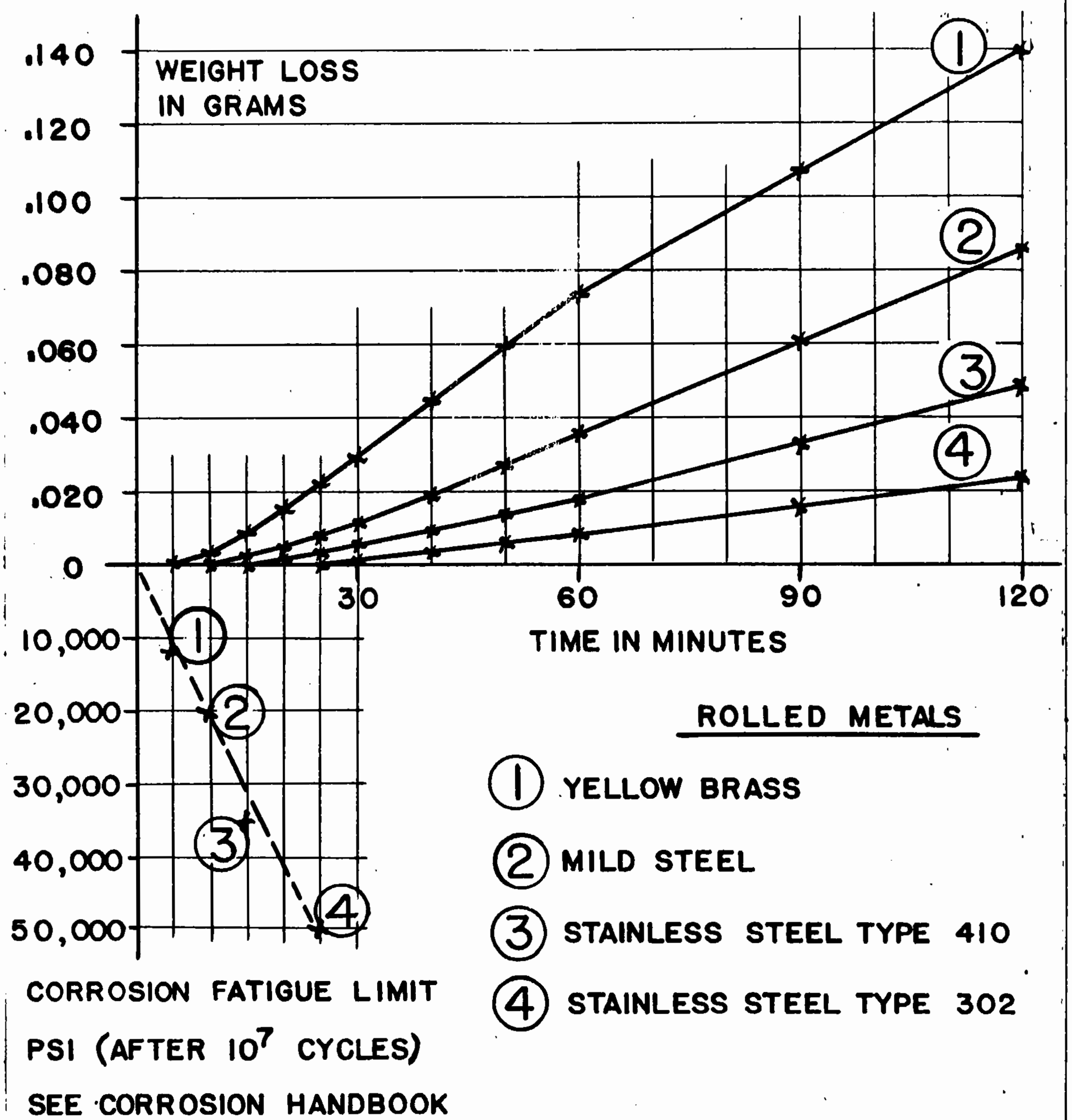
		BRINELL HARDNESS
①	INCO DUCTILE IRON	356
②	ROLLED STAINLESS STEEL	350

TEST LIQUID - DISTILLED WATER AT 76°F



EFFECT OF
INCUBATION PERIOD

FIGURE 8



TEST LIQUID – DISTILLED WATER AT 76°F

EFFECT OF CORROSION·FATIGUE LIMIT

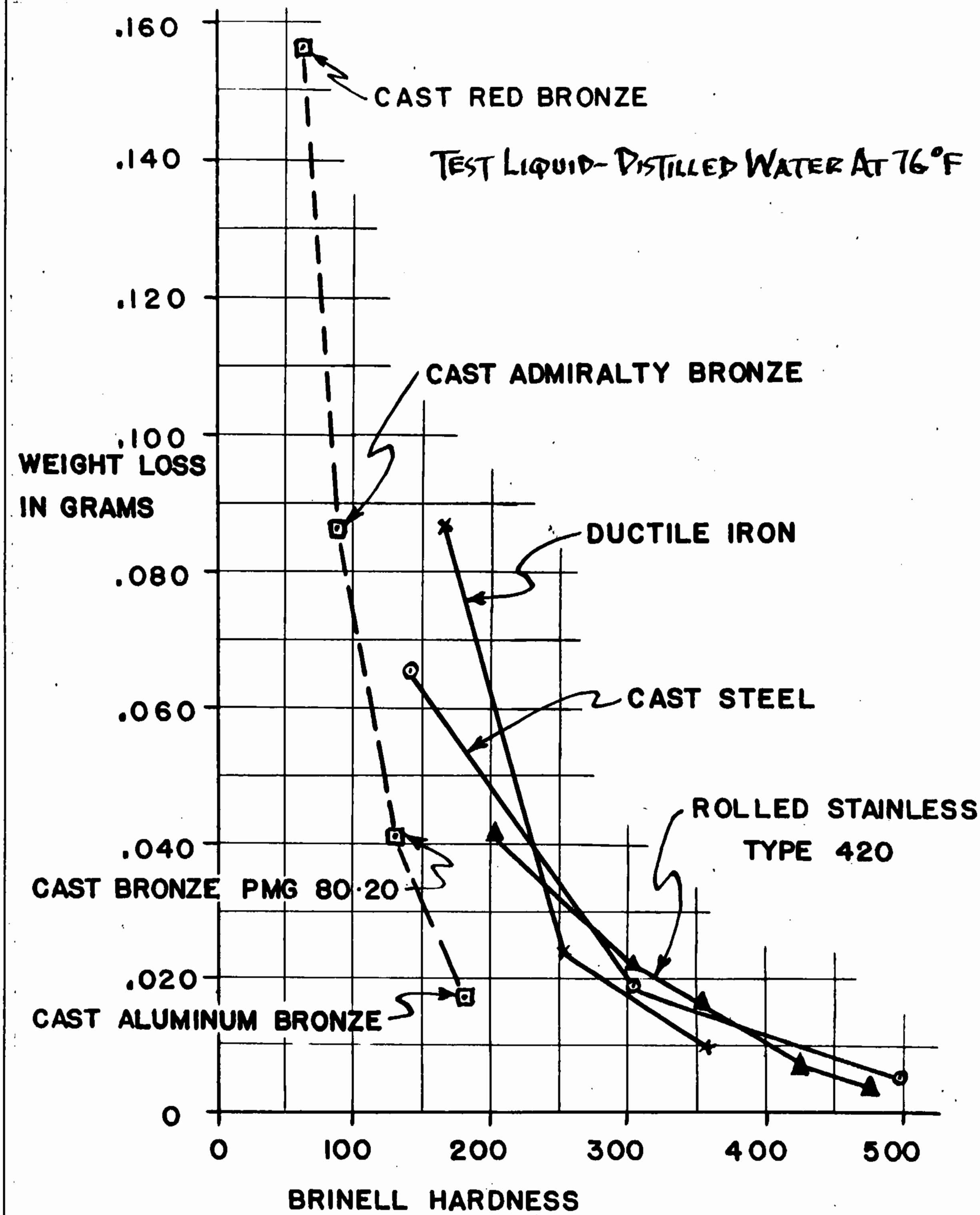
FIGURE 9

7B. Effect of Metal Hardness

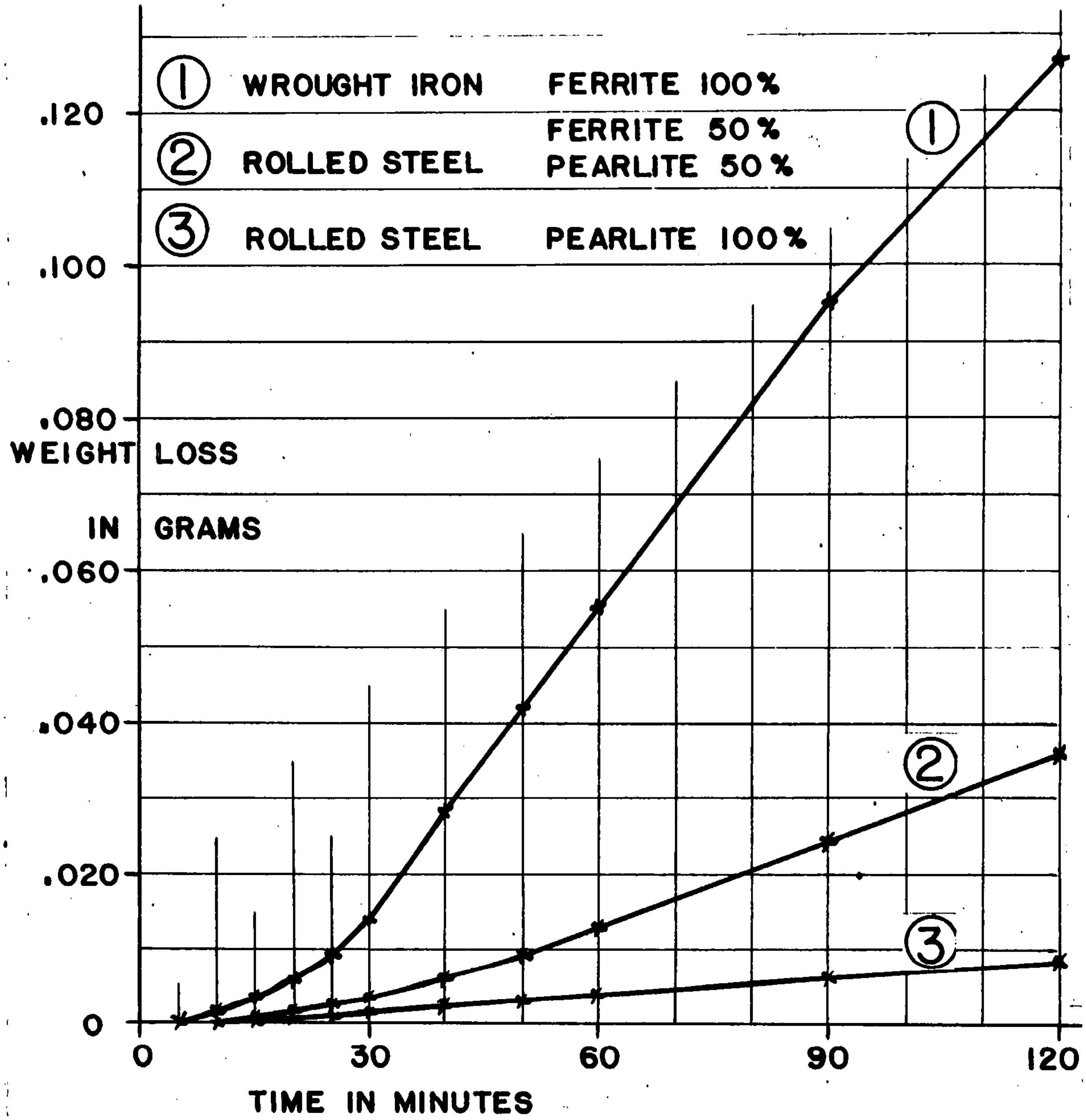
For homogeneous metals like rolled stainless steel 420 and heat-treatable cast steel, as well as for similar types of bronzes shown in figure 10, the loss of weight due to cavitation attack is inversely proportional to the hardness.

7C. Effects of Metallurgical Structure

It is well known that ferritic structure in metals has inferior mechanical properties compared to pearlitic structure in carbon steel, or compared to martensitic and austenitic structure in stainless steel. Figures 11 and 12 confirm the low resistance of ferritic metallurgical structure to cavitation attack.



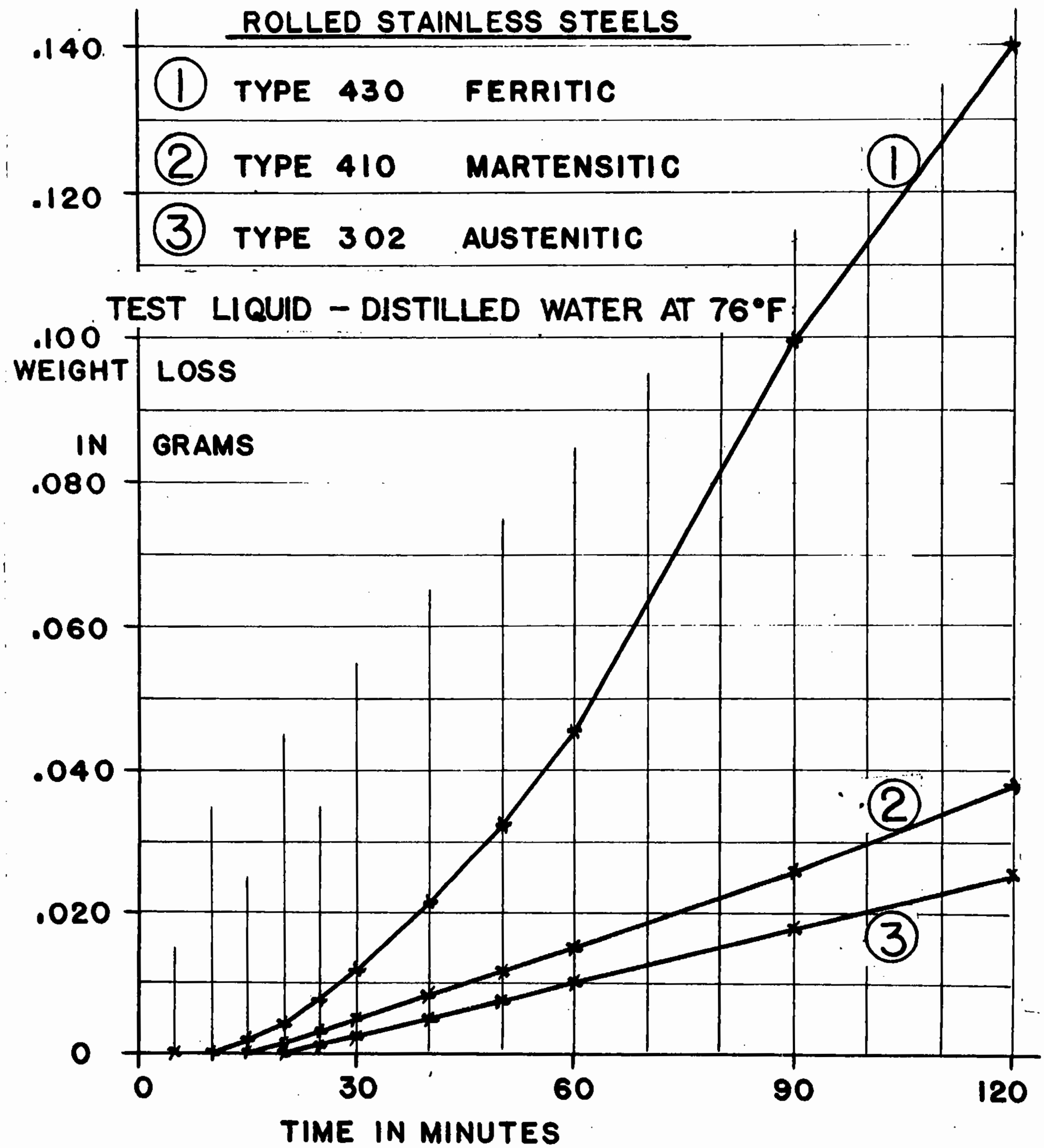
EFFECT OF METAL HARDNESS FIGURE 10



TEST LIQUID - DISTILLED WATER AT 76°F

EFFECT OF METALLURGICAL STRUCTURE OF CARBON STEELS

FIGURE 11



EFFECT OF METALLURGICAL STRUCTURE OF STAINLESS STEELS FIGURE 12

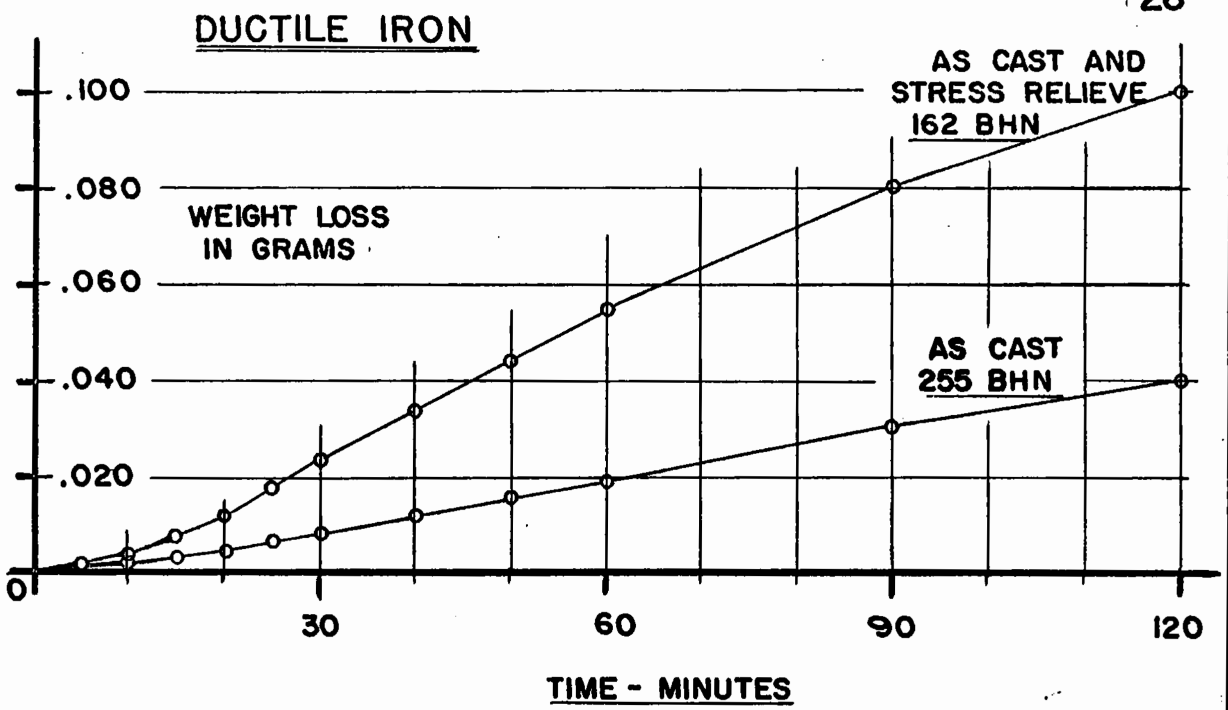
7D. Effect of Stress Relieving.

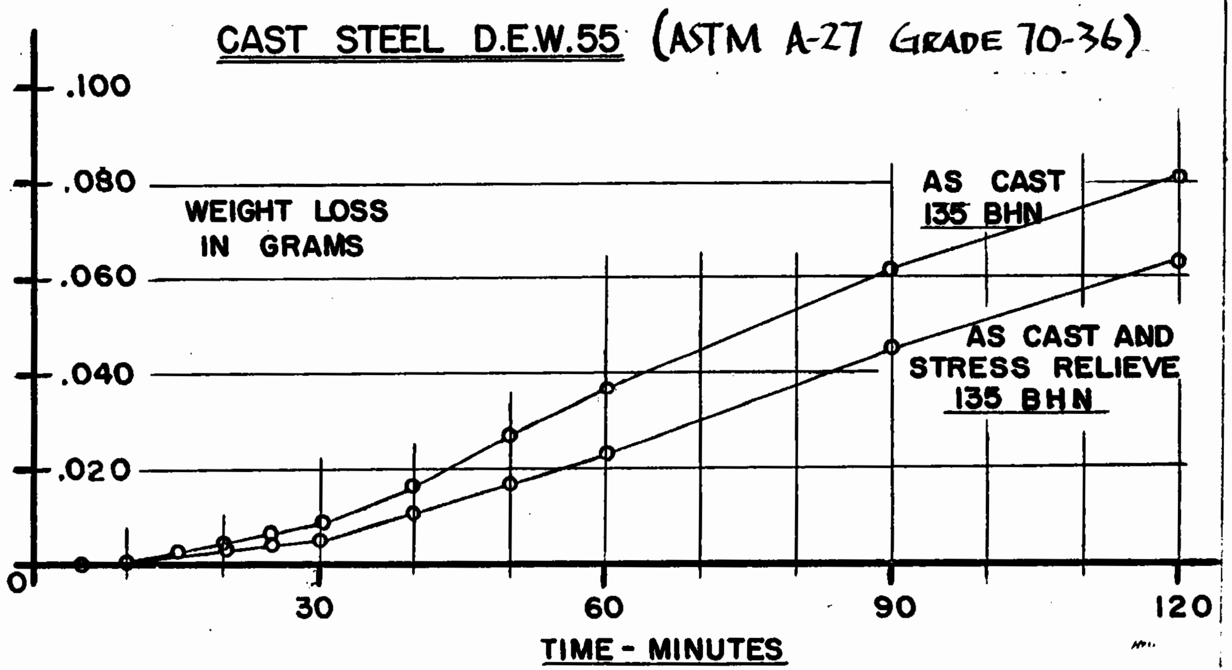
Large steel castings are stress relieved before machining to remove internal stresses which could distort finished surfaces of mating components. Figure 13 indicates that stress relieving of cast steel ASTM A-27 grade 70-36 improves its resistance to cavitation attack, although no appreciable change in hardness was noted.

Cast ductile iron at 256 Brinell hardness has a pearlitic matrix which was transformed to a ferritic matrix at 162 Brinell hardness by stress relieving. The ferritic structure has a much lower resistance to cavitation attack as shown in Figure 13.

7E. Effect of Peening

Users of hydraulic machinery are aware that peening of steel castings and welded stainless steel overlays will improve the resistance to cavitation attack as a result of the work hardening. Figure 14 shows the small improvement in resistance that results from peening these metals.



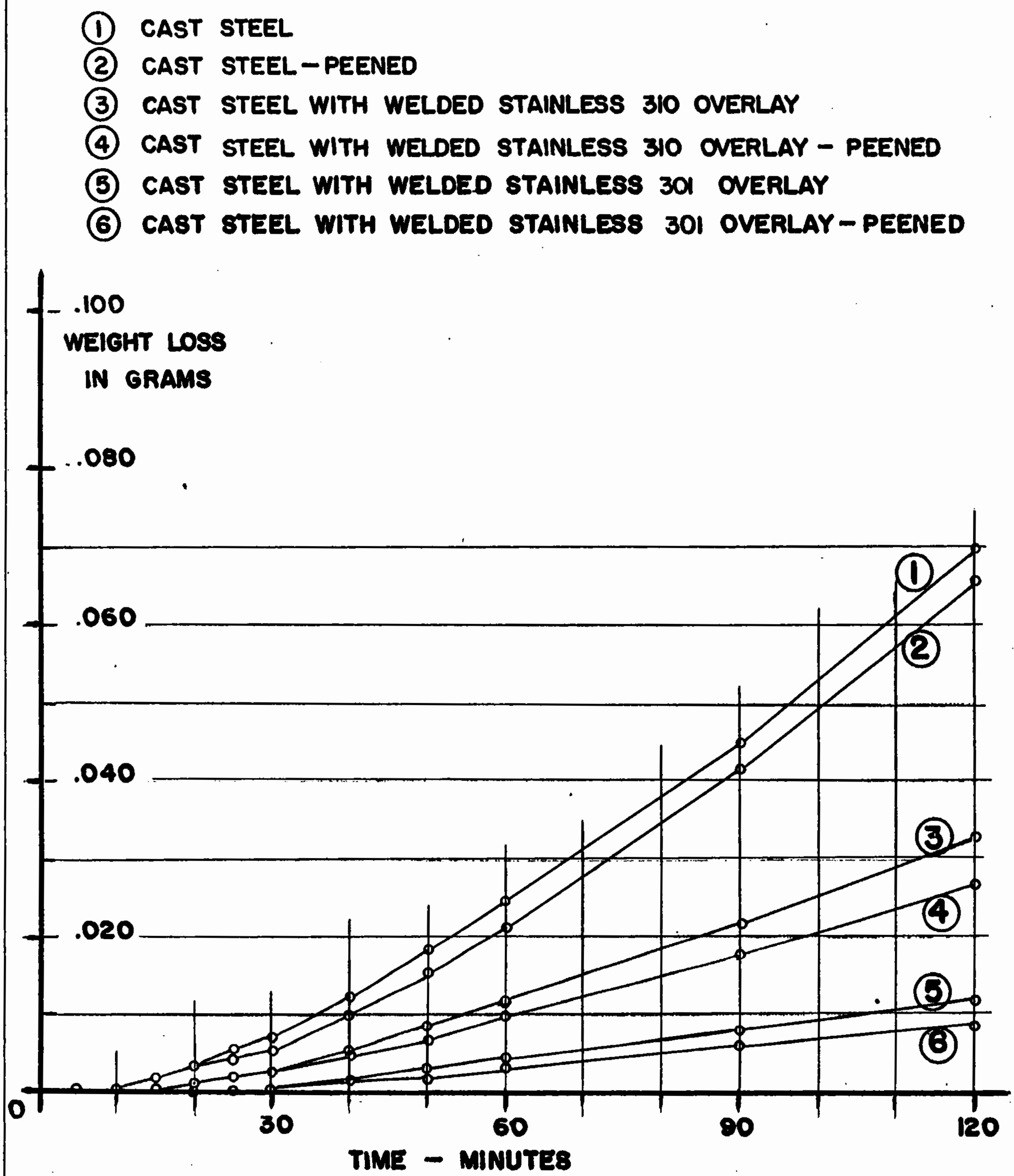


TEST LIQUID - DISTILLED WATER AT 76°F

EFFECT OF

STRESS RELIEVING

FIGURE 13



TEST LIQUID - DISTILLED WATER AT 76°F

EFFECT OF PEENING FIGURE 14

8. Effect of Liquid Characteristics

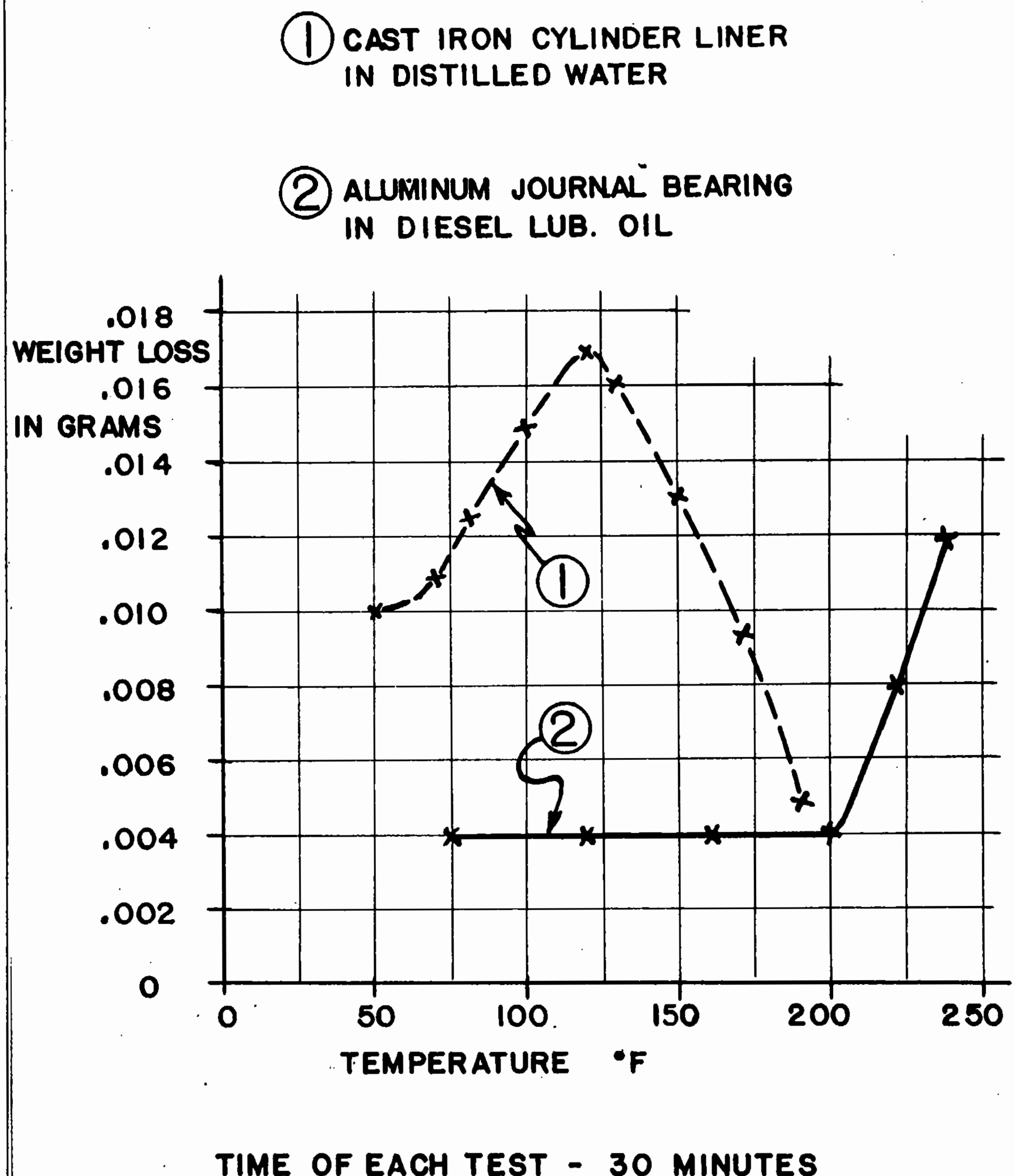
8A. Effect of Temperature

The effect of the temperature of the test liquid has been reported by Novotny (18), who compared various liquids on the basis of separate properties such as vapour pressure, viscosity and surface tension. But a cavitation parameter for temperature must combine all three properties of the liquid.

Figure 15 shows the typical effects of the liquid temperature, where the weight loss increases sharply above 60°F for water and above 200°F for lubricating oil, as a consequence of the increasing vapour pressures. The effect of the liquid temperature should be related to the test pressure, since the vapour pressure increases with higher temperatures, while the viscosity and the surface tension decrease, as shown in Figure 16. A suggested cavitation parameter for temperature effects in water is illustrated in Figure 17, and this parameter has been used successfully for water cooling systems in Dominion-Alco diesel engines.

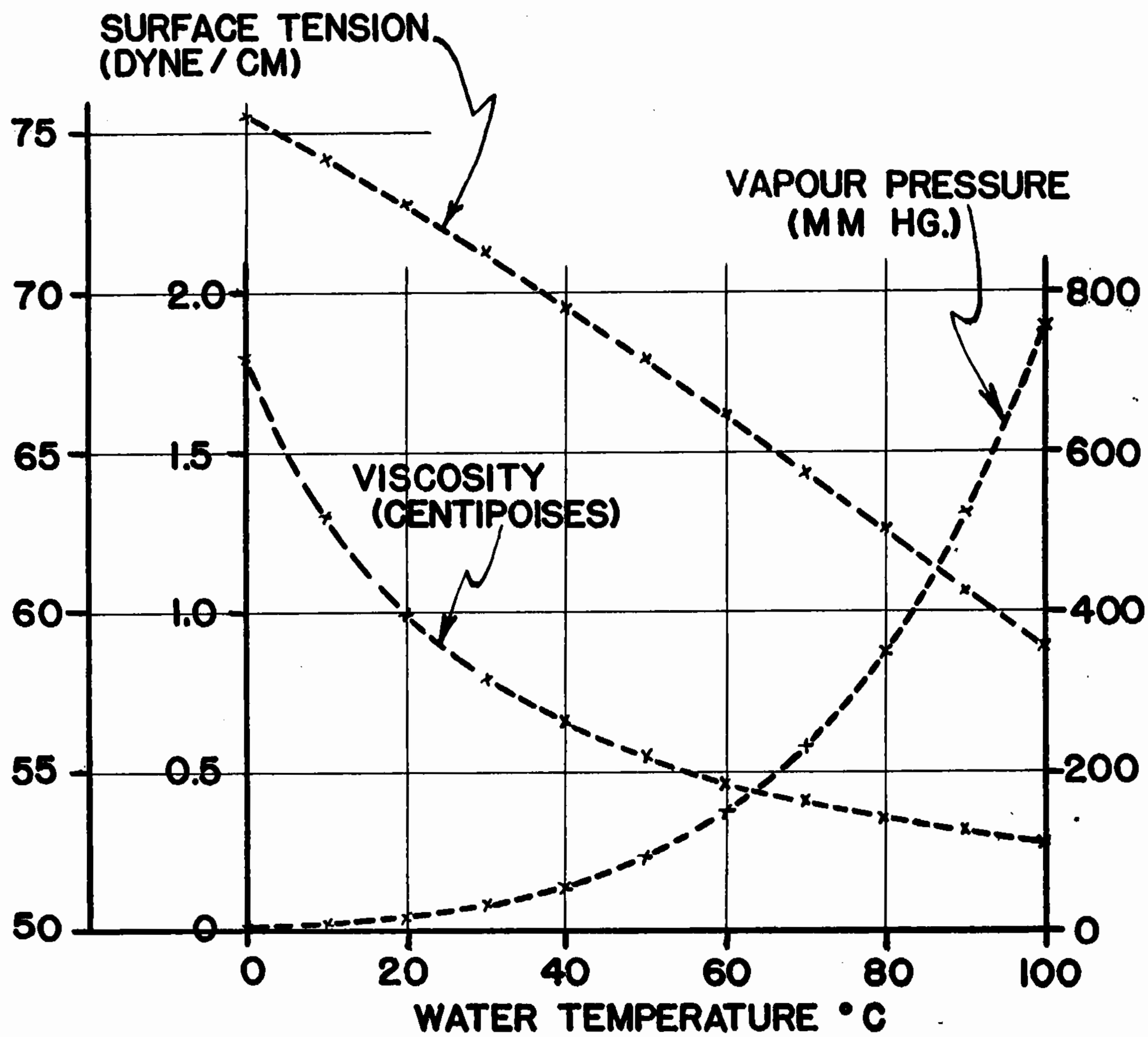
8B. Effect of Pressure

The effect of the pressure on the test liquid must be related to the difference between the test pressure and the vapour pressure, since this difference governs the formation or collapse of the cavitation bubbles. Figure 18 shows typical pressure effects for the cast iron used in diesel liners, where the maximum weight loss occurs at about 1 psig, presumably due to the large number of small bubbles that occur at this pressure.



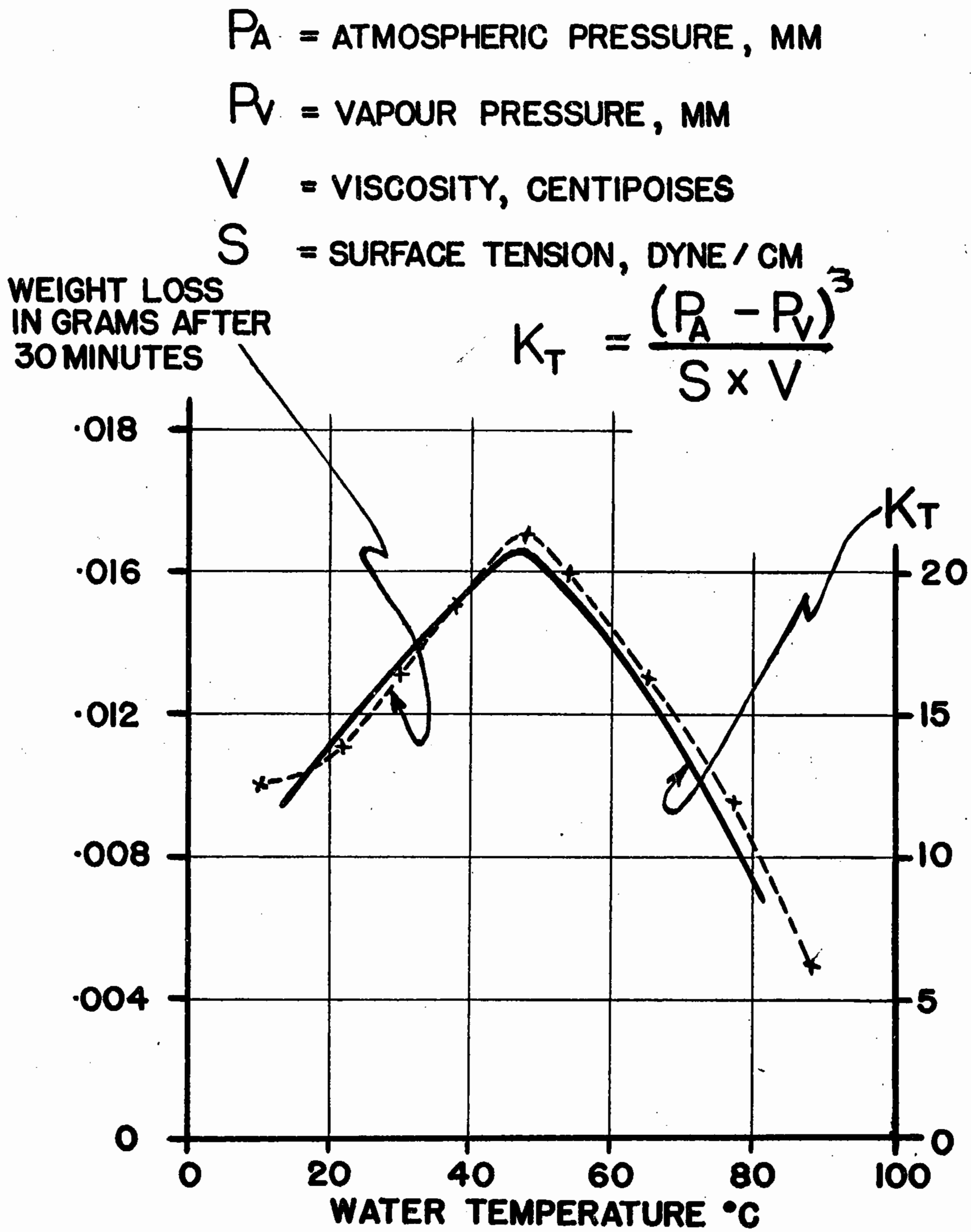
EFFECT OF LIQUID TEMPERATURE

FIGURE 15

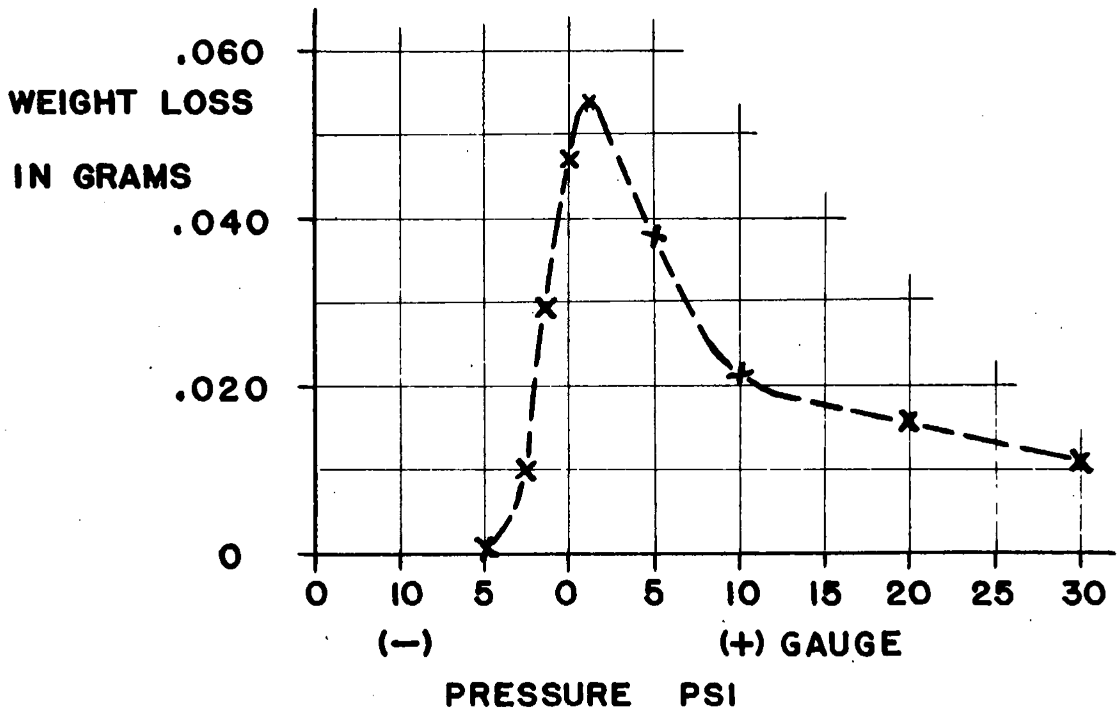


(FROM HANDBOOK OF CHEMISTRY AND PHYSICS)

SURFACE TENSION, VISCOSITY AND VAPOUR PRESSURE OF WATER AT VARIOUS TEMPERATURES FIGURE 16



CAVITATION PARAMETER K_T OF WATER FOR TEMPERATURE FIGURE 17



CAST IRON CYLINDER LINER

TEMP. 170 °F ~ DISTILLED WATER

TIME OF EACH TEST - 2 HOURS

EFFECT OF LIQUID PRESSURE

FIGURE 18

8C. Effect of Chemical Additives

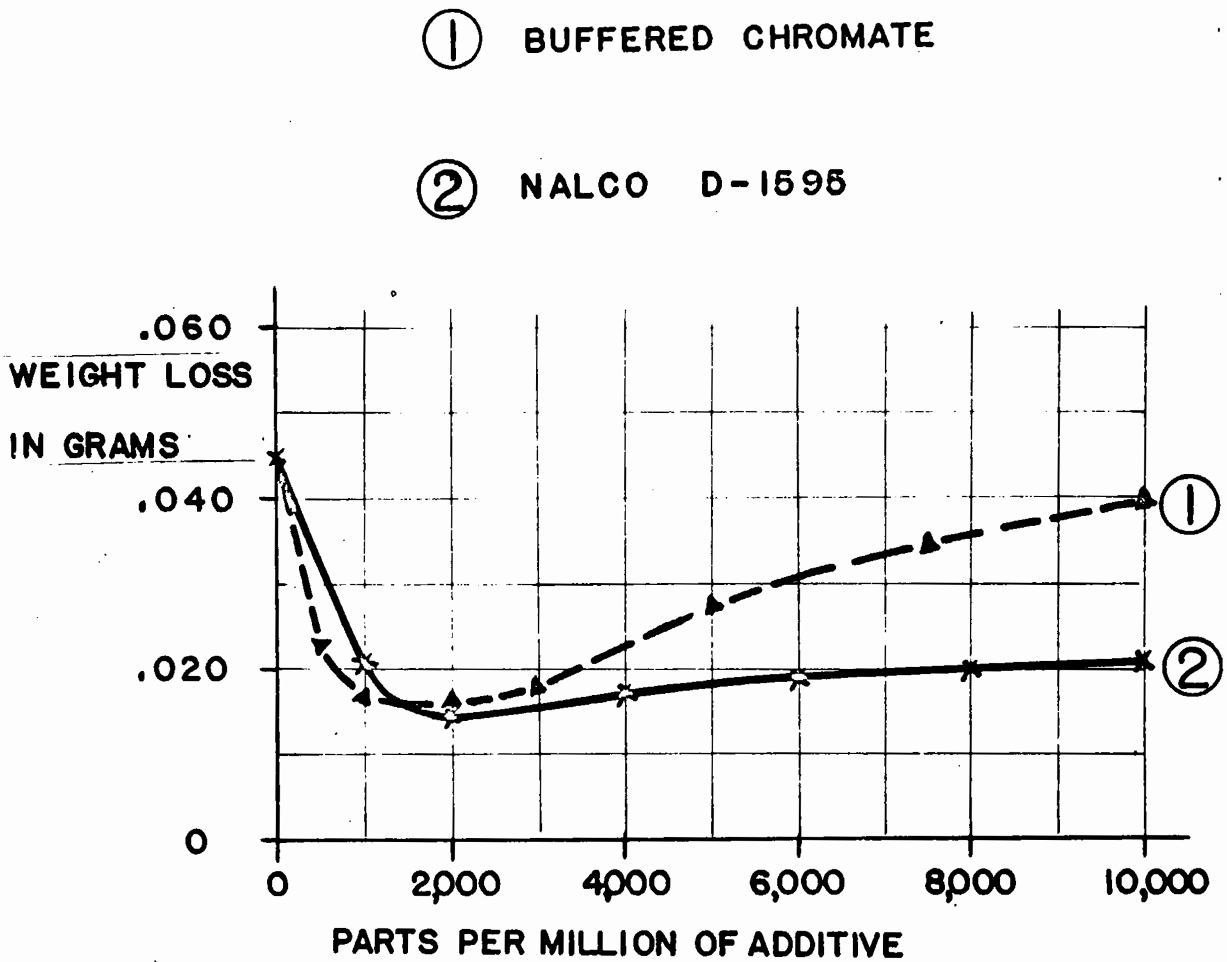
The mechanism of corrosion protection and cavitation prevention afforded by small amounts of chemical additives such as the buffered chromate and the organic compound Nalco D-1595 as shown in Figure 19, has not been clearly defined.

However, Dr. J.I. Bregman of the Armour Research Foundation has sent a private communication with the following information about Nalco D-1595.

"The ideal role of an inhibitor in a system subject to cavitation erosion would appear to be that of minimizing the contribution of chemical corrosion to the erosion and also of interfering with the erosive action of the collapse of large bubbles. It reduces the surface tension of the liquid, and the inhibitor protects by means of tough organic film formation. It might also be postulated that the resilient nature of the film might "cushion" the attack on the surface from the shock waves due to the collapse of the bubbles."

8D. Effect of Nitrogen Atmosphere

An inert gas such as nitrogen was considered as a possible atmosphere above water, which might reduce any chemical corrosion attack and thus decrease the cavitation damage. A nitrogen atmosphere above water decreases the maximum cavitation damage level by about half that for air near atmospheric pressure as shown in Figure 20, and an empirical curve for nitrogen based on the air atmosphere has been established, which is related to the greater solubility of air in water than nitrogen.



CAST IRON CYLINDER LINER

TEMP. 170 °F ~ DISTILLED WATER

PRESS. 20 PSI GAUGE

TIME OF EACH TEST — 2 HOURS

EFFECT OF CHEMICAL ADDITIVES

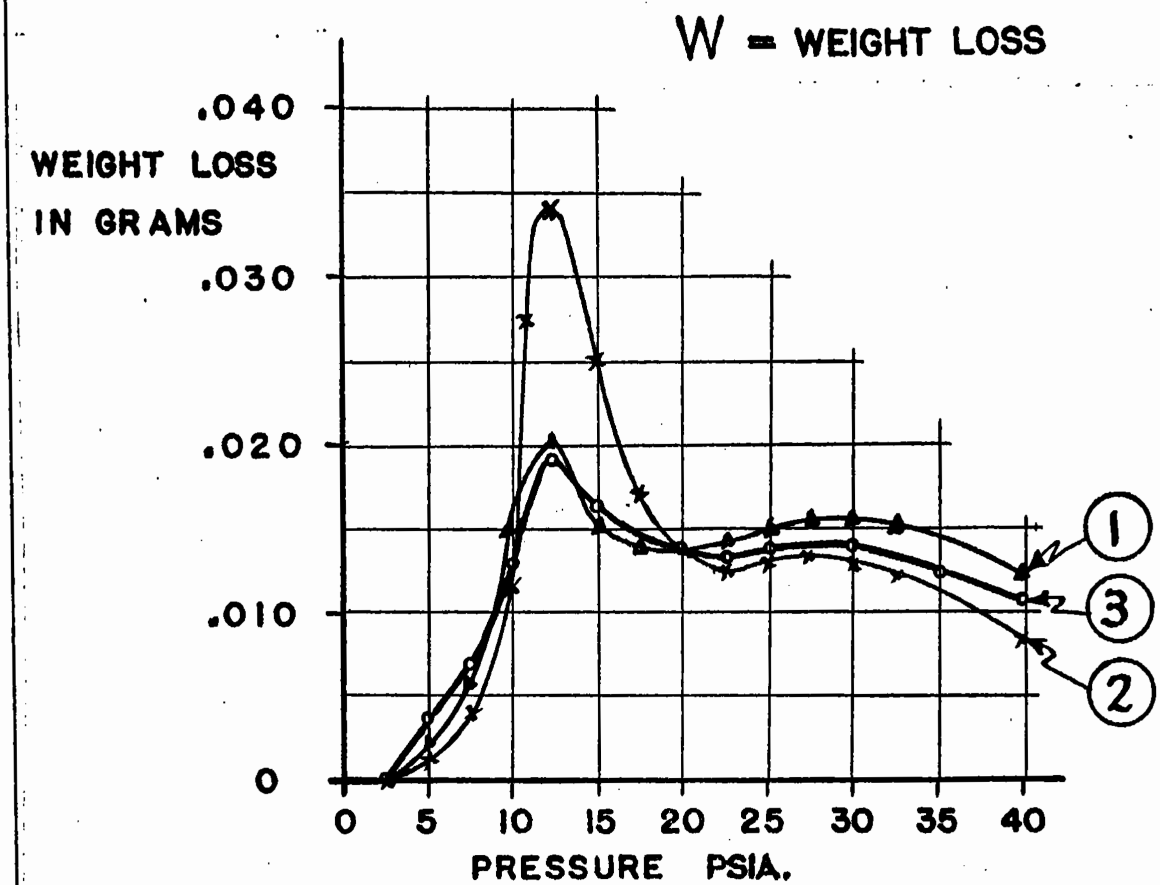
FIGURE 19

(1) NITROGEN ATMOSPHERE $= W_N$

(2) AIR ATMOSPHERE $= W_A$

(3) EMPIRICAL CURVE FOR NITROGEN $= W_T$

$$W_T = \frac{W_A}{2} + \frac{\text{PRESSURE}}{5} + \frac{3{\cdot}6 \text{ SOLUBILITY OF NITROGEN IN WATER}}{\text{SOLUBILITY OF AIR IN WATER}}$$



ROLLED ALUMINUM 6068·0

DISTILLED WATER AT 76 °F

TIME OF EACH TEST – 30 MINUTES

EFFECT OF NITROGEN ATMOSPHERE

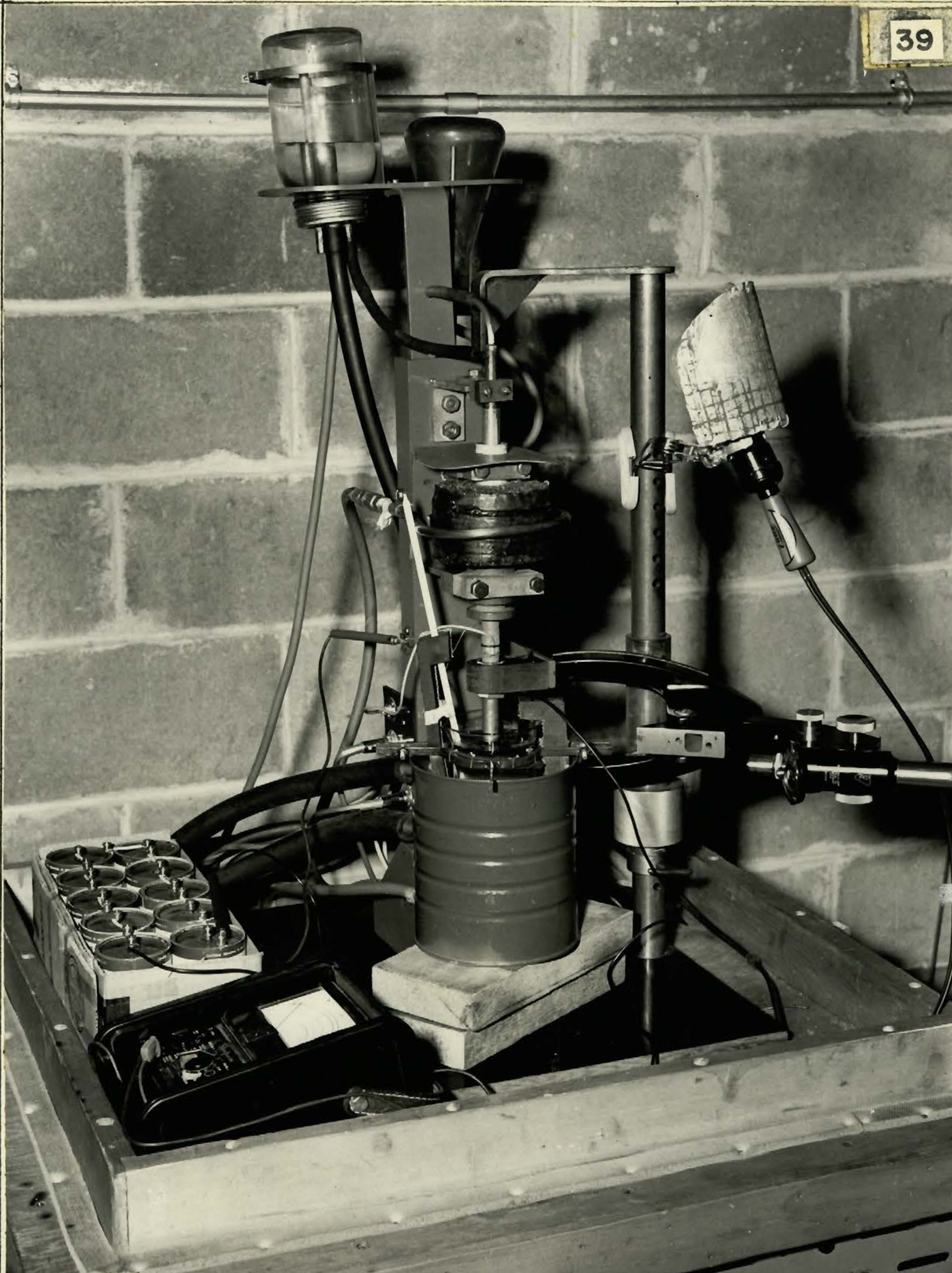
FIGURE 20

8E. Cathodic Protection and Cavitation

The suppression of mild cavitation attack by cathodic protection was demonstrated by Petracchi (32) in a venturi tube, and by Krenn (31) in a hydraulic turbine. The accelerated cavitation apparatus was fitted with a cathodic protection arrangement as shown in Figure 21. However, only tests in Montreal tap water and Halifax sea water are included in this thesis, since the resistance of the commercial distilled water was too large to show any effect of the cathodic protection.

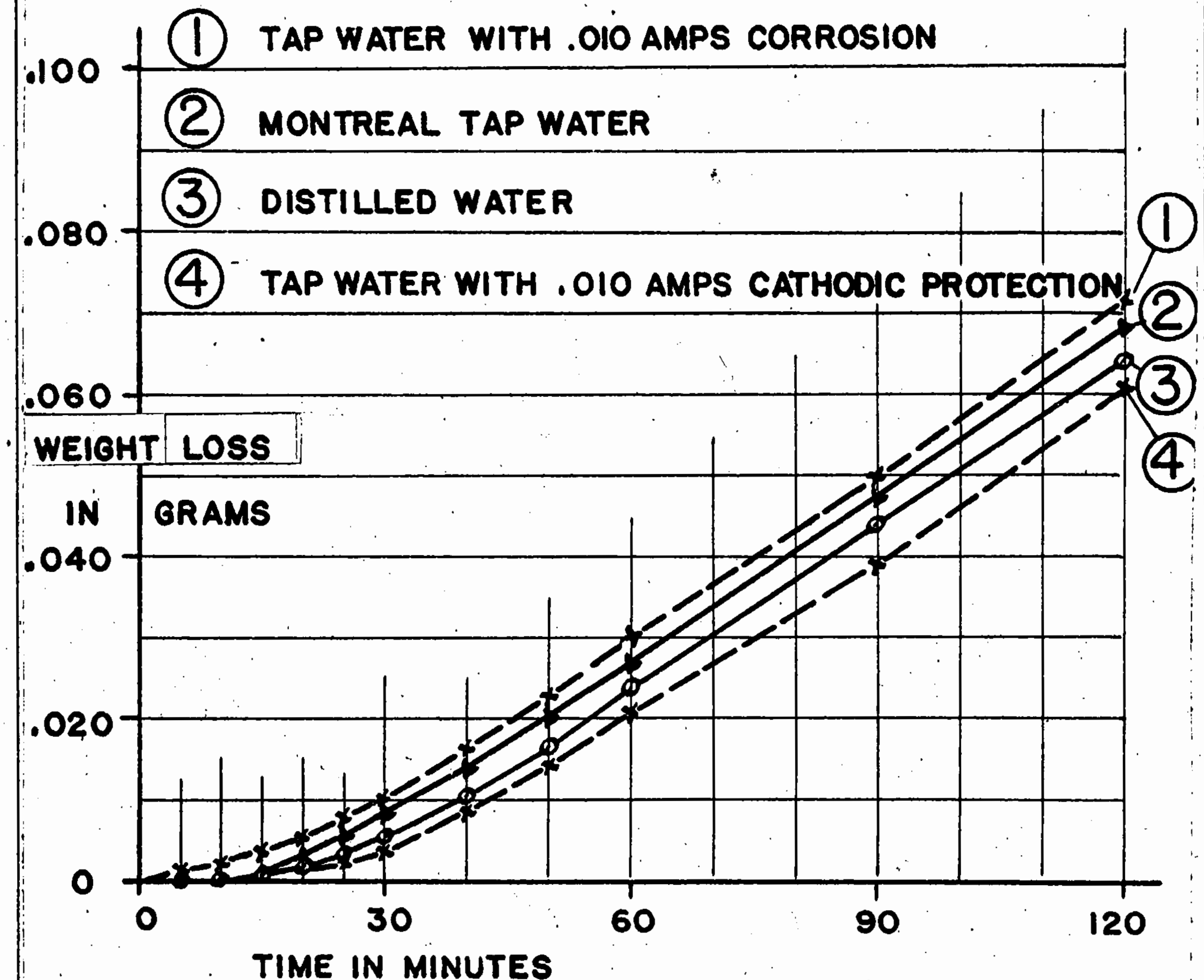
a) Cathodic Protection and Cavitation in Tap Water

It was found that the weight loss of cast steel as a result of erosion by cavitation is greater in tap water than in distilled water as shown in Figure 22, but cathodic protection increases slightly the incubation time and decreases slightly the weight loss. However, an increase in the impressed current up to .060 amps did not increase the protection. These results agree with Petracchi (32) that at small cavitation intensities, cathodic protection could suppress cavitation erosion. Anodic current applied in addition to accelerated cavitation eliminates the incubation period and increases the weight loss as shown in curve 1 of figure 22, which agrees with Wheeler (42), who studied ferrous materials in chloride solutions.



CATHODIC PROTECTION ARRANGEMENT

FIGURE 21



WATER TEMP. - 76°F

CATHODIC PROTECTION (OF CAST STEEL) IN TAP WATER

FIGURE 22

8E. (Cont'd.)

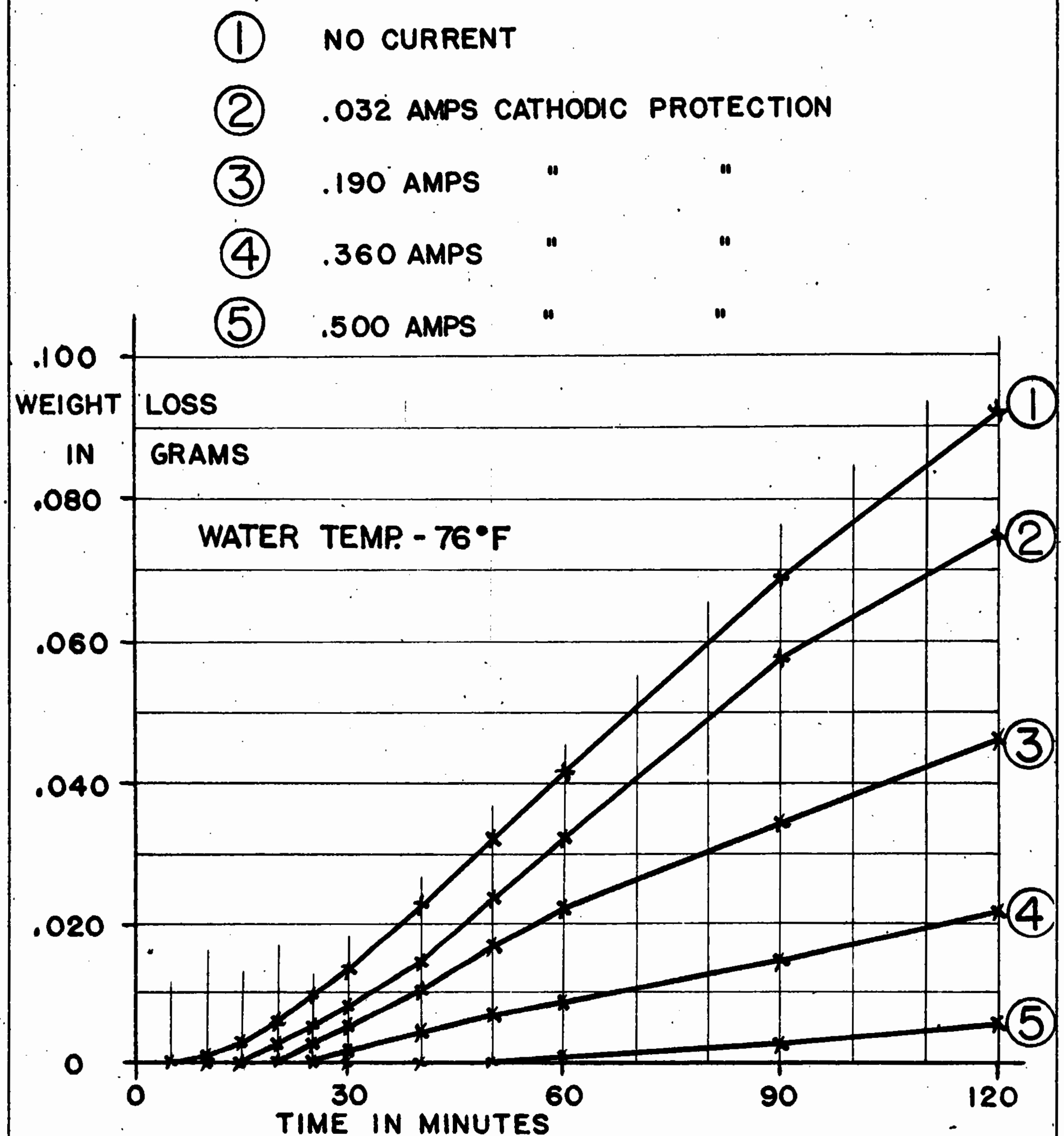
b) Cathodic Protection and Cavitation in Sea Water

The suppression of accelerated cavitation effects of cast steel in sea water by cathodic protection has caused some investigators to conclude that cavitation attack is of an electro-chemical nature. However, Figure 23 shows that the current density necessary to fully protect cast steel in sea water is about 3 amps per square inch which puts the equipment into a hydrogen generator category.

It is felt that the suppression of cavitation effects is due mainly to the formation of hydrogen bubbles cushioning the cavitation bubble collapses. This cushioning effect of hydrogen bubbles may be compared to the cushioning effect of injected air in hydraulic turbines.

9. Cavitation Damage in Hydraulic Turbines

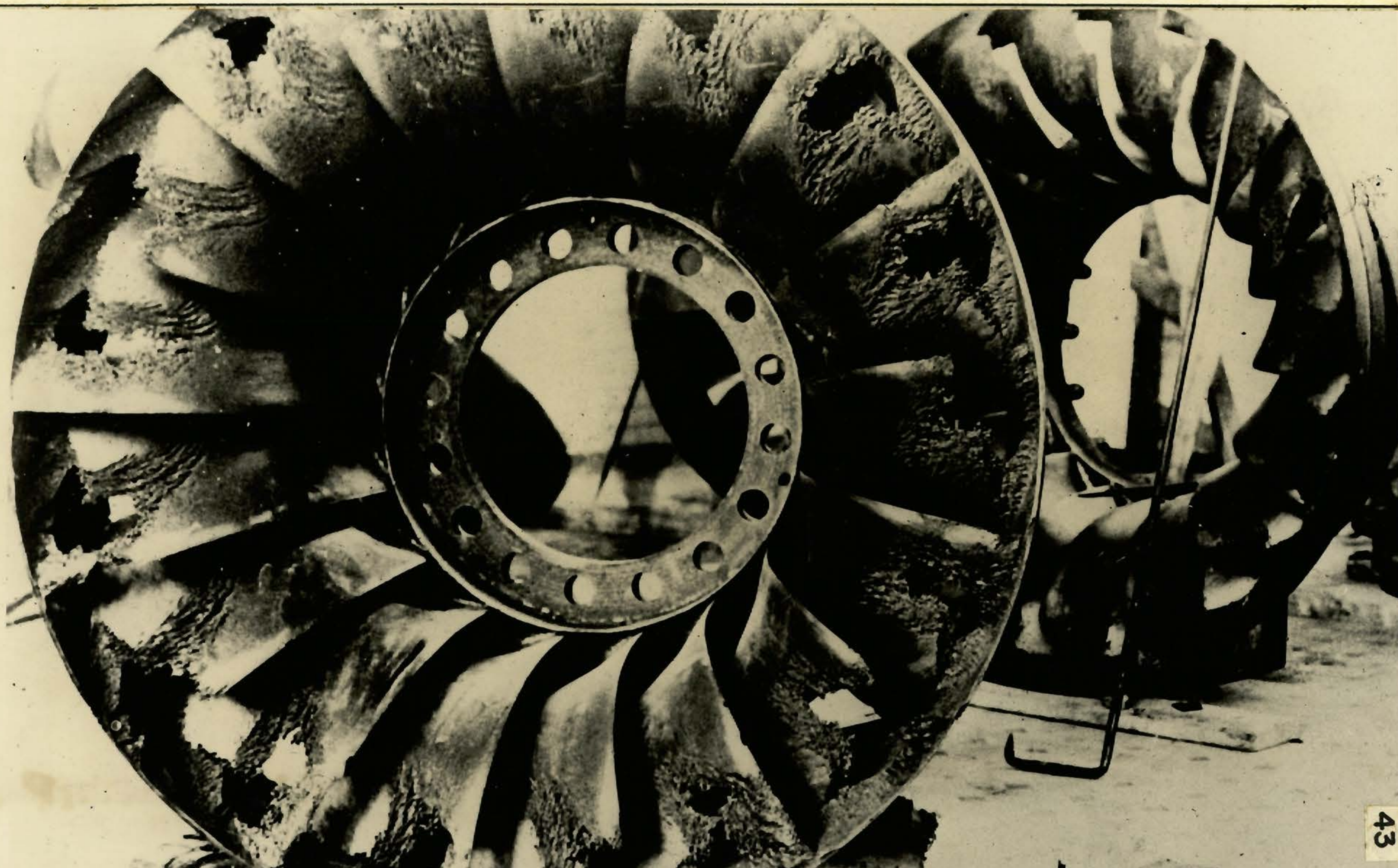
Hydraulic turbines utilize the change of momentum of water as accomplished by the guiding surface of the runner blades. The shape of these blades is designed for specific operating conditions where the velocity of the water is continuous across the flow area, and cavitation is avoided by maintaining the local pressure at critical areas above the vapour pressure of the water. Since most hydraulic machinery does not operate at the design condition, Figures 24 and 25 show severe cavitation damage which may occur in field installations.



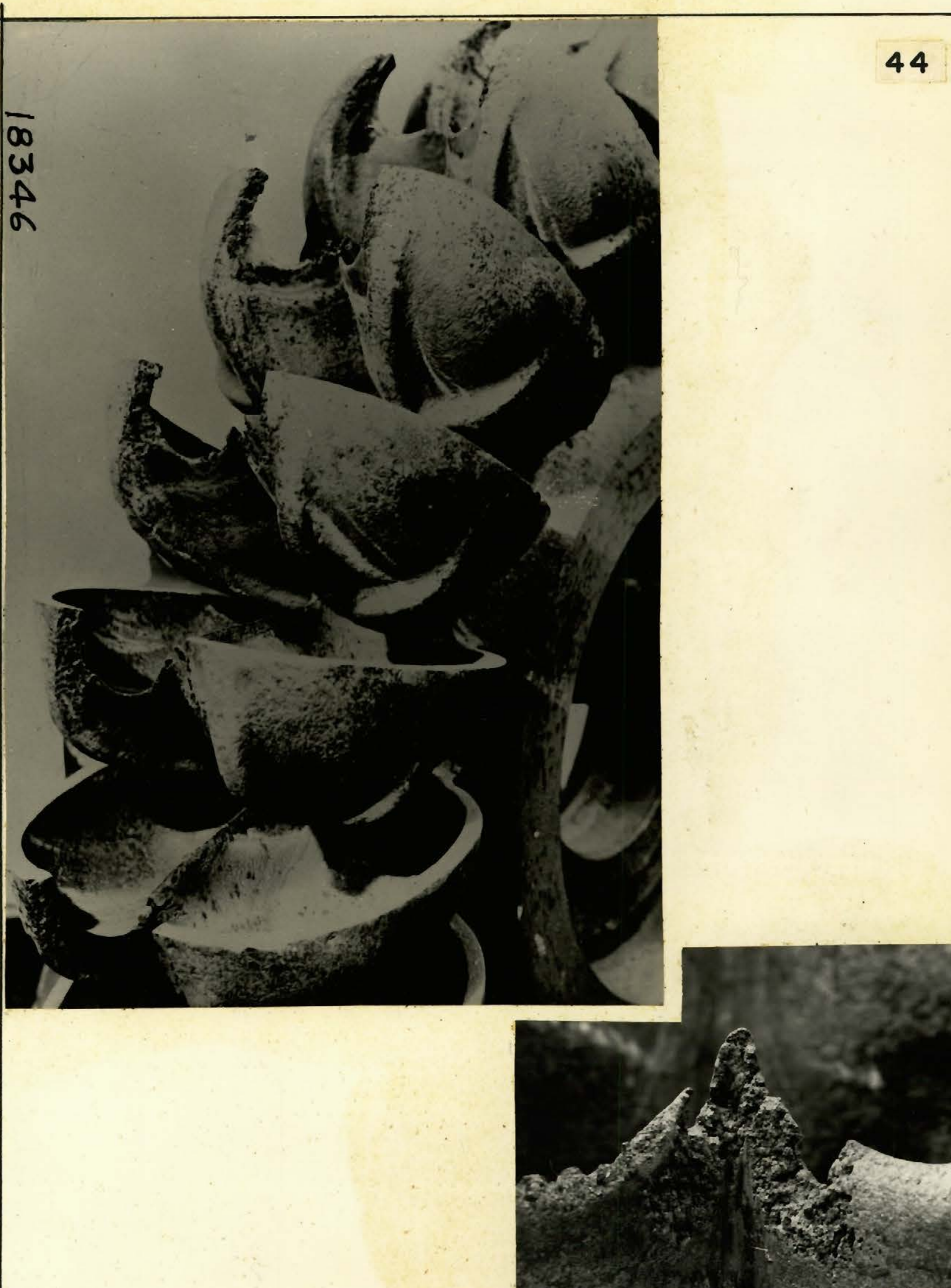
HALIFAX SEA WATER SUPPLIED BY NAVAL LAB.

CATHODIC PROTECTION (OF CAST STEEL) IN SEA WATER

FIGURE 23



CAVITATED HYDRAULIC TURBINE FIGURE 24



CAVITATED PELTON WHEEL FIGURE 25

9A. Rolled and Cast Metals

The usual hydraulic turbine is composed of rolled and cast metals, whose resistance to cavitation attack is indicated in Figure 26 and 27. The holes on the periphery of the test buttons are made by the Rockwell hardness tester.

9B. Welded and Plated Metals

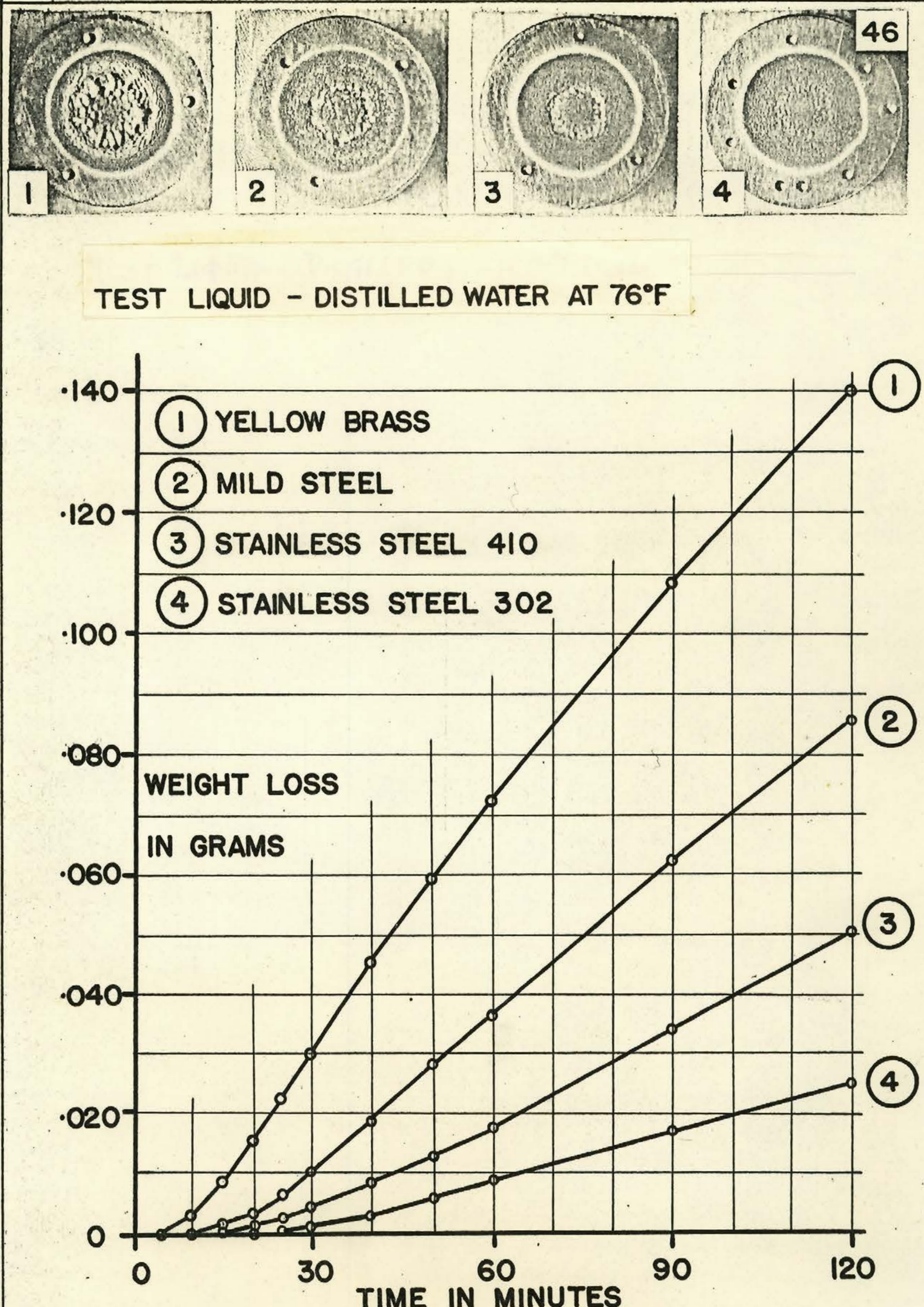
For severe cavitation conditions, welded overlays at the critical areas of cast steel runners are practical, see Figure 28. Plated metals on cast steel seal rings have been used occasionally, and figure 29 shows the advantage of hard chromium plating, which is much harder than the nickel plate.

9C. Relative Intensities of Cavitation Attack

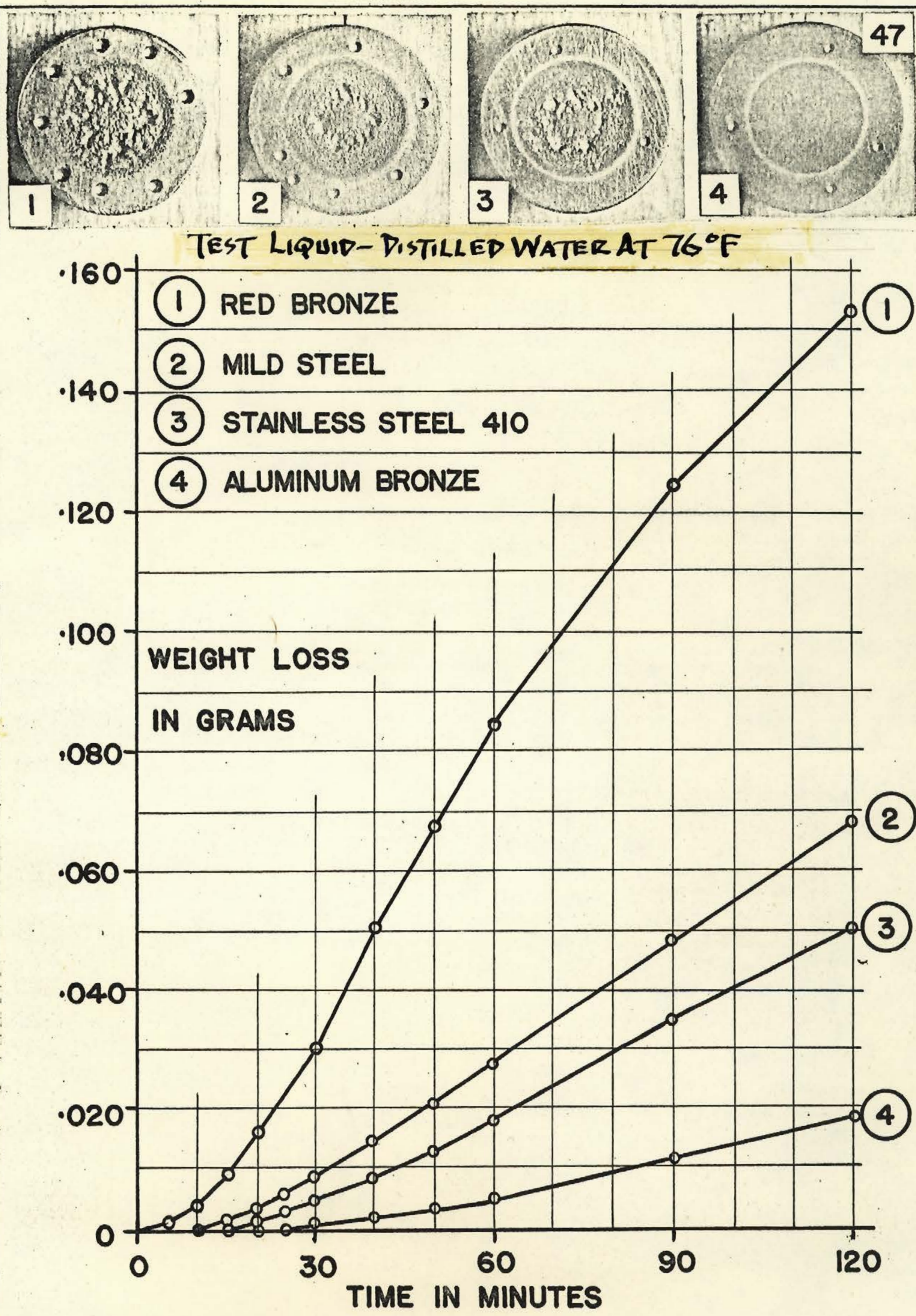
Field experience with hydraulic turbines has provided three relative intensities of cavitation attack which have been based on the observed damages to the original cast steel runner, mild steel welded overlay and stainless steel welded overlay.

1. minor pitting on the original cast steel runner
2. severe pitting on the original cast steel runner but minor pitting on the mild steel welded overlay
3. severe pitting on the original cast steel runner and mild steel welded overlay but minor pitting on the stainless steel welded overlay.

A minor pitted condition of a metal after one year of operation can be compared to the length of the incubation period for the same metal during an accelerated laboratory test, as shown in Figure 30.



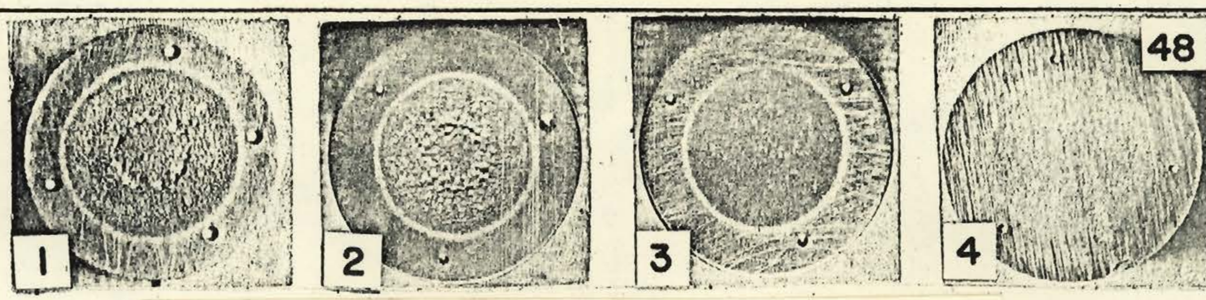
CAVITATION EROSION OF
ROLLED METALS FIGURE 26



CAVITATION EROSION OF CAST METALS

FIGURE 27

TEST LIQUID - DISTILLED WATER AT 76°F



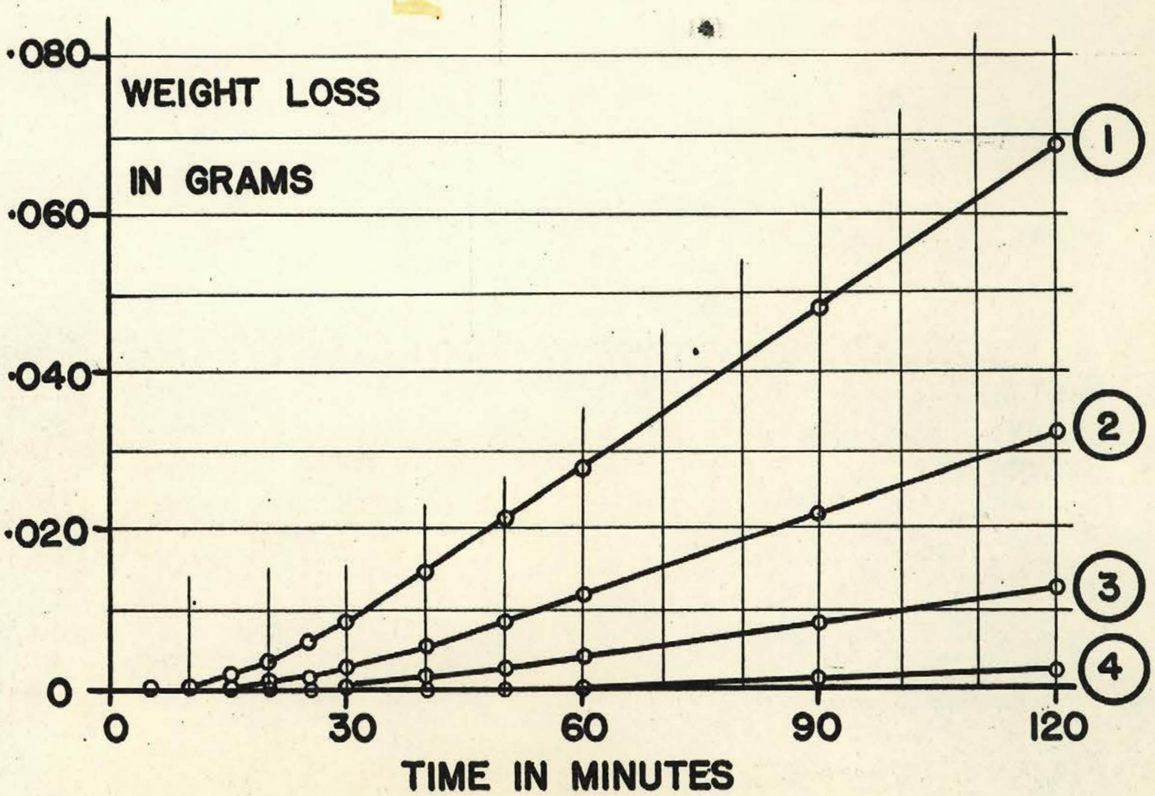
TEST LIQUID - DISTILLED WATER AT 76°F

(1) CAST STEEL

(2) STAINLESS STEEL 310 OVERLAY

(3) STAINLESS STEEL 301 OVERLAY

(4) STELLITE OVERLAY



CAVITATION EROSION OF WELDED OVERLAYS

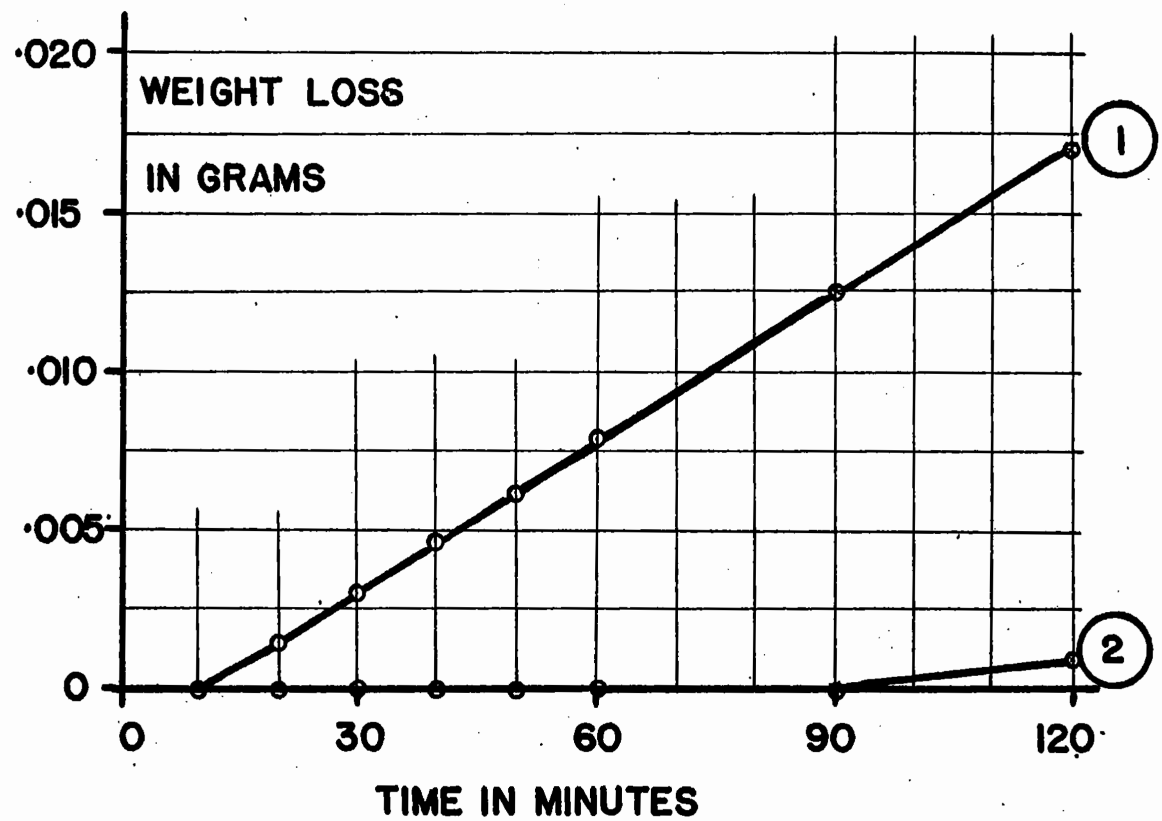
FIGURE 28

PLATED METALS ON CAST STEEL

(1) ·005" HARD NICKEL PLATE

(2) ·005" HARD CHROME PLATE

TEST LIQUID – DISTILLED WATER AT 76°F



CAVITATION EROSION OF
PLATED METALS FIGURE 29

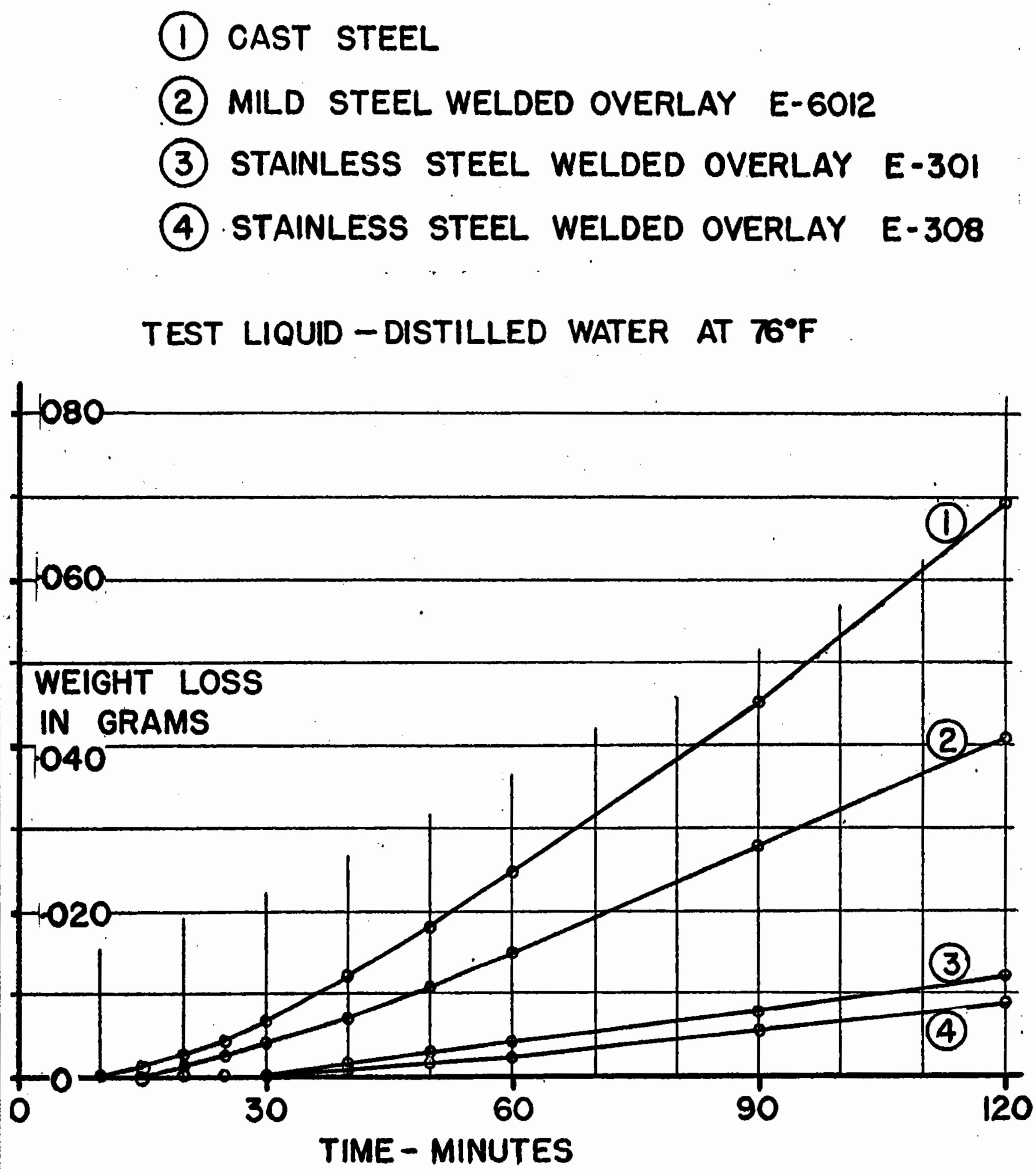
9D. Welded Stainless Steel Overlays

A cast steel runner with a welded stainless steel overlay on the critical areas is common practice, see Figure 30, since field repairs can be done in the turbine pit with a minimum of time out of operation.

Stainless steel deposited by manual welding using stick electrodes 3/16 inch diameter require only one pass to provide sufficient metal for the 1/8 inch finished overlay thickness. Certified manual welding deposits stainless steel E 308 with analysed alloy contents of about 17% chromium and 9% nickel, and it deposits stainless steel E 301 with about 16% chromium and 6% nickel as shown in Figure 31.

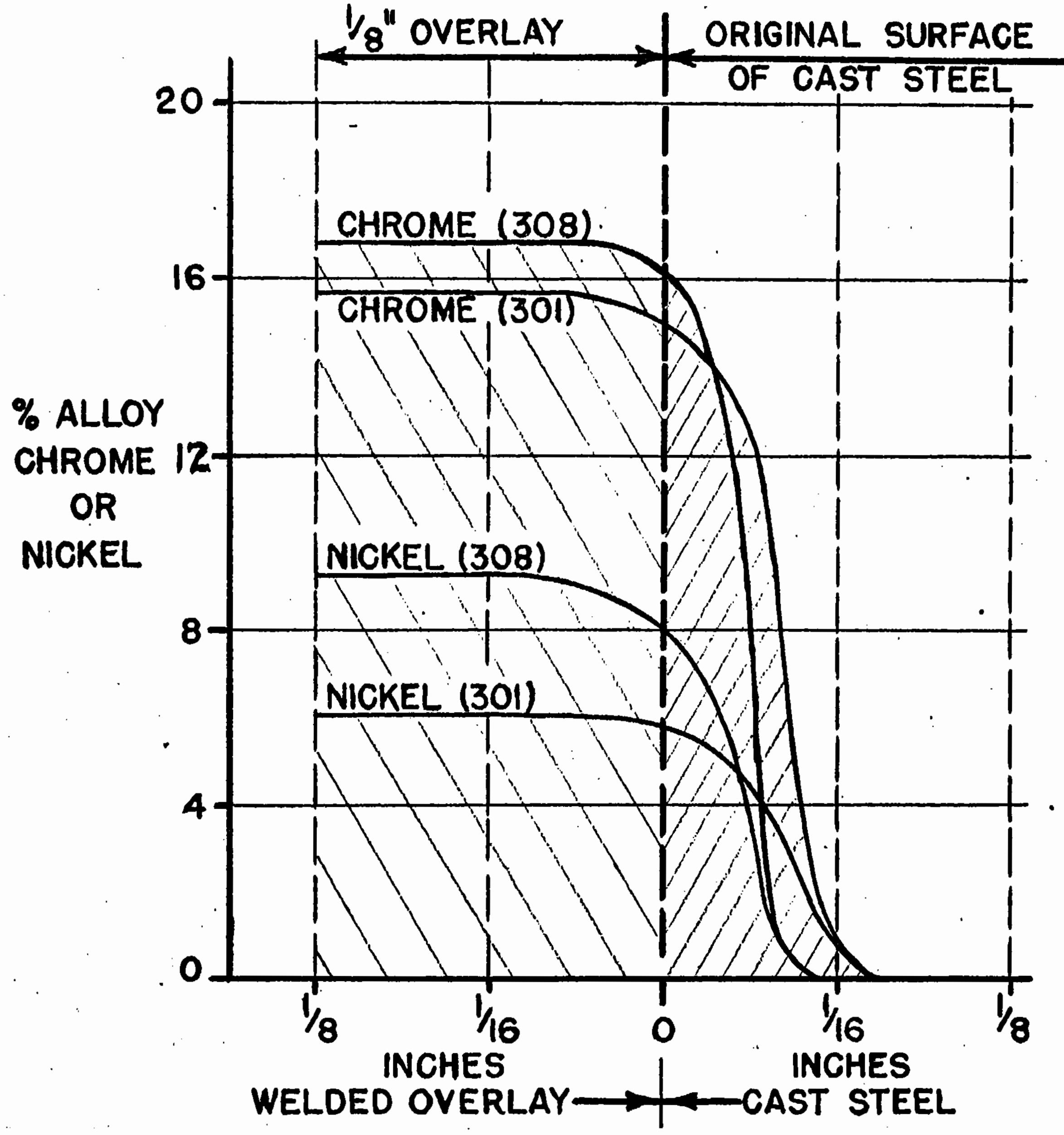
10. Cavitation Damage in Diesel Engines

The modern diesel engine, especially for the competitive market in transportation facilities, has a water-cooling system which is designed to operate at increased but stabilized cavitation levels, and this requires higher liquid pressure and chemical additions to minimize the formation of cavitation bubbles. These chemical additions include corrosion inhibitors to prevent initial chemical pitting, detergents to eliminate foaming, and wetting agents to provide an adhering liquid film on the metal by depressing the surface tension at the liquid-metal interface. The recent design trends toward higher speed and increased thermal and mechanical loading in diesel engines has intensified the degree of cavitation damage.



WELDED OVERLAYS FOR HYDRAULIC TURBINE RUNNERS

FIGURE 30



ALLOY CONTENT OF STAINLESS STEEL WELDED OVERLAYS

TYPE 308 AND 301 ON CAST STEEL

FIGURE 31

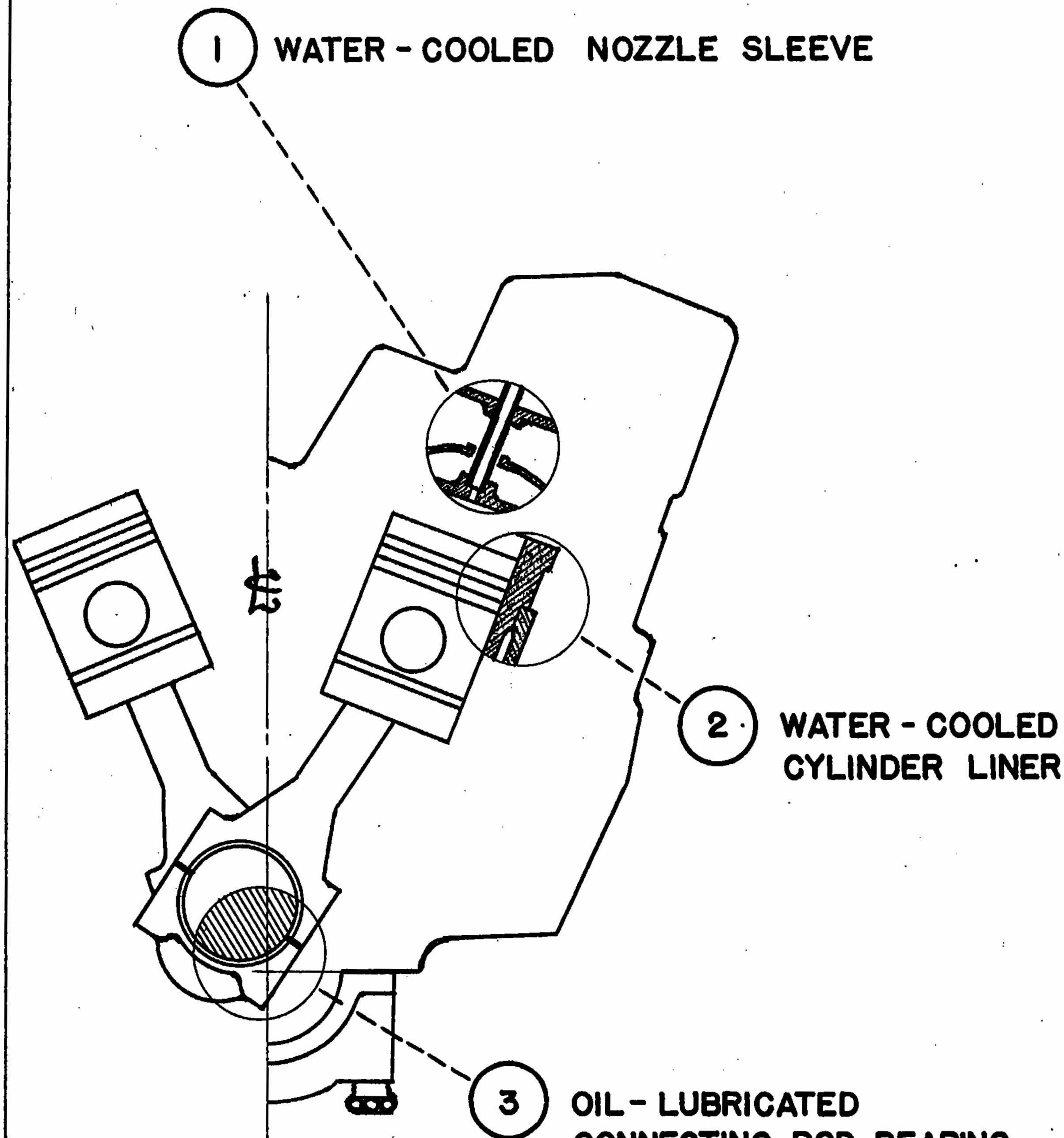
10. (Cont'd.)

Three instances of cavitation damage in diesel engines which have been corrected after extensive research are shown in Figure 32:-

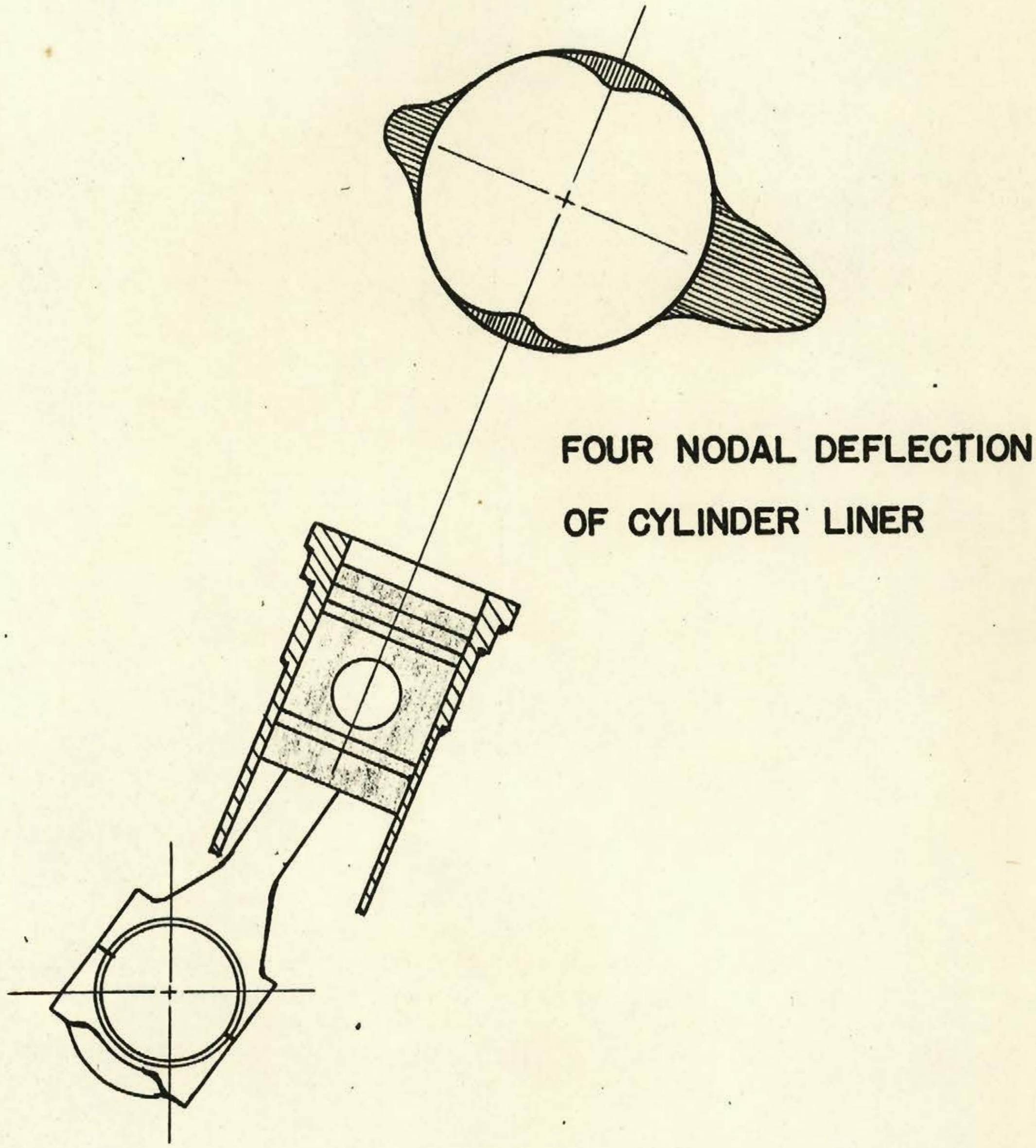
1) water-cooled cylinder liners, see Figure 34 and 35
2) water-cooled nozzle sleeves, see Figure 37
3) oil-lubricated connecting rod bearings, see Figure 39

10A. Water-Cooled Cylinder Liners

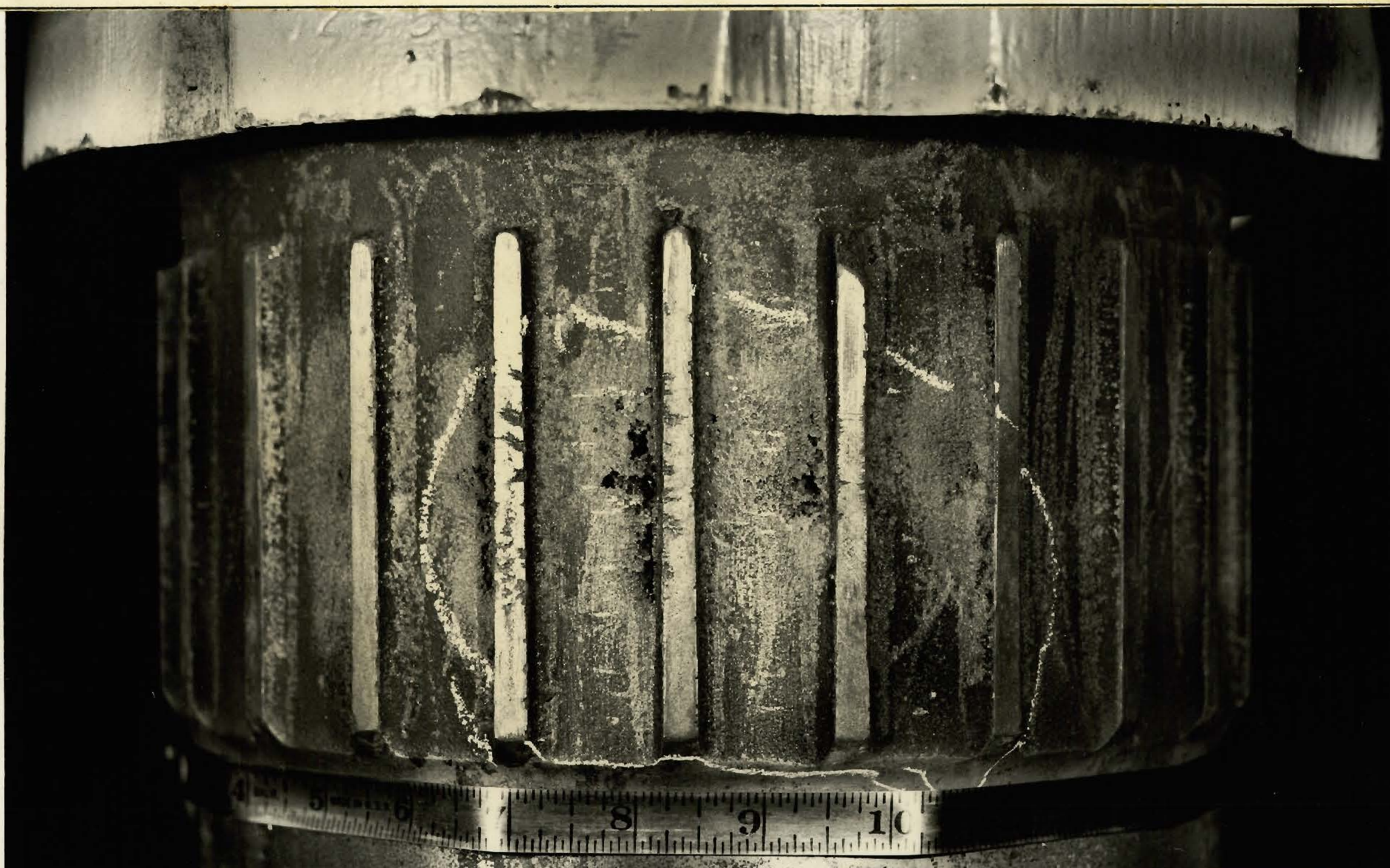
Cavitation combined with corrosion in the water cooling system of diesel engines has caused unusual damage on the water side of alloy cast iron cylinder liners. The pitted areas have the typical honey-combed appearance of cavitation damage and they appear free of corrosion products. It had been usual to consider the internal wear as the major problem in cylinder liners, but chromium plating has extended the service life of the internal bore considerably. In some older diesel engines, the cylinder liner erosion was traced to unusually high water velocities at convergent-divergent water passages, where the locations of the water inlet and outlet were primary factors. The recent serious increase in cylinder liner erosion could not be attributed to a flow condition, and further investigation revealed the presence of a major vibration problem. A vibration analysis revealed that the pulsating vibratory forces from the piston side thrust were creating a forced vibration of the cylinder wall, similar to the ringing of a bell. The resonant vibration reaches a maximum amplitude at the middle of the water jacket, where the cylinder liner gets the least support from the engine block.



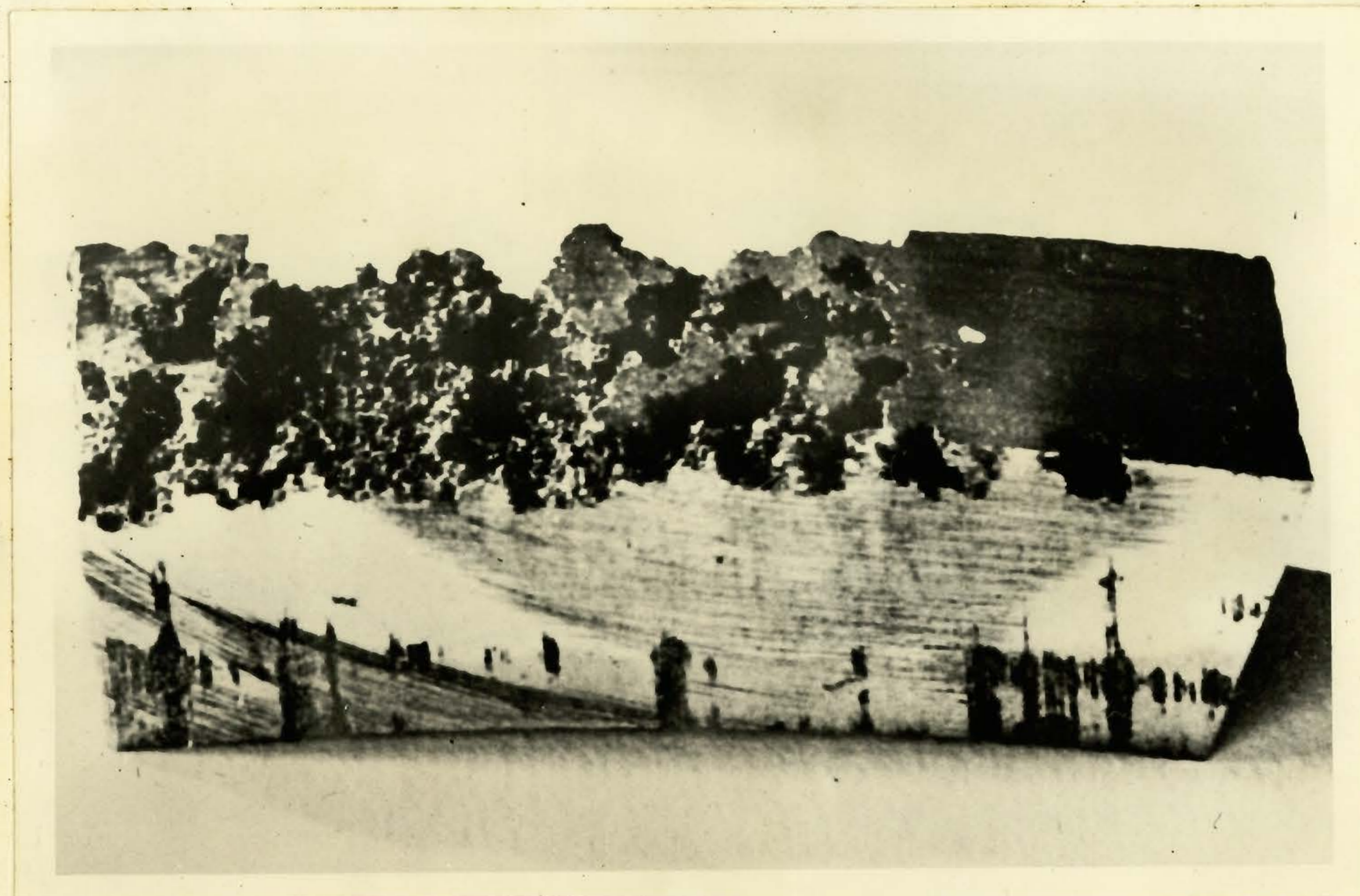
CAVITATION EROSION IN
DIESEL ENGINES FIGURE 32



FORCED VIBRATIONS IN DIESEL
CYLINDER LINERS FIGURE 33



CAVITATED CYLINDER LINER FIGURE 34



PERFORATED CYLINDER LINER WALL FIGURE 35

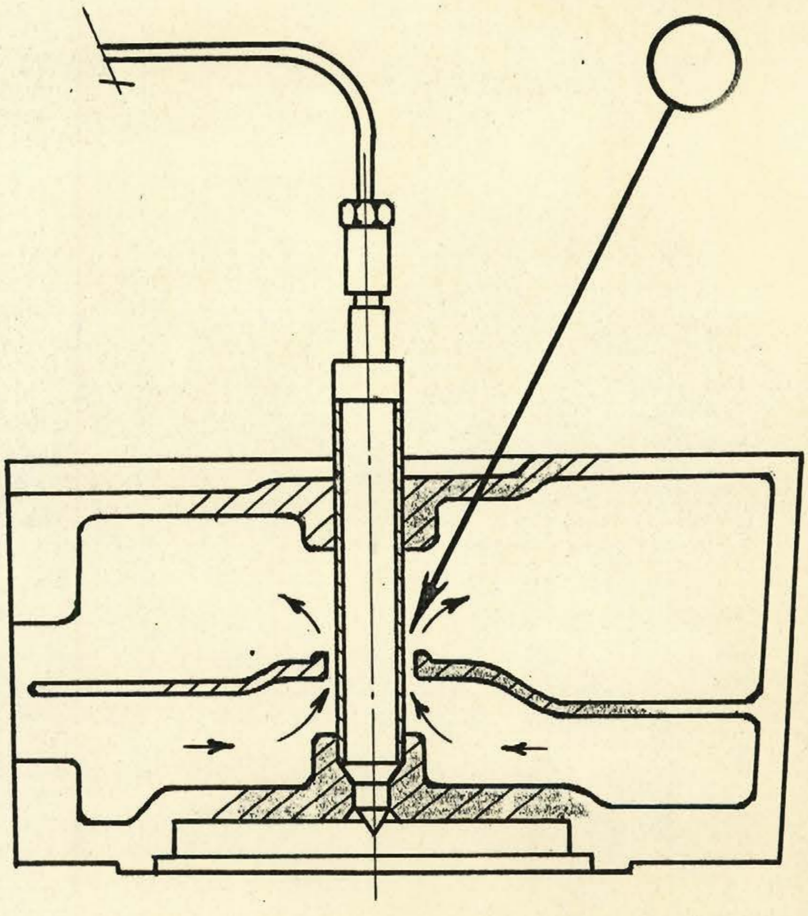
10A. (Cont'd.)

The worst pitted area is located on the water side of the liner exactly where the "side slap" of the piston takes place during the power stroke, which is 90 degrees from the crankshaft axis. The circumference of the liner vibrates with four nodes at 45 degrees from the crankshaft axis as shown in Figure 33, and as expected, the pitted areas occur between the nodes, see Figure 34. The side thrust from the piston distorts the liner into an oval shape, and the elastic properties of the cast iron permits the liner to vibrate alternately along the major axis and then the minor axis of the distorted elliptical shape. Figure 19 shows the advantage of chemical additives such as buffered chromate and Nalco D-1595 for diesel cooling water.

10B <u>Water-Cooled Nozzle Sleeves</u>

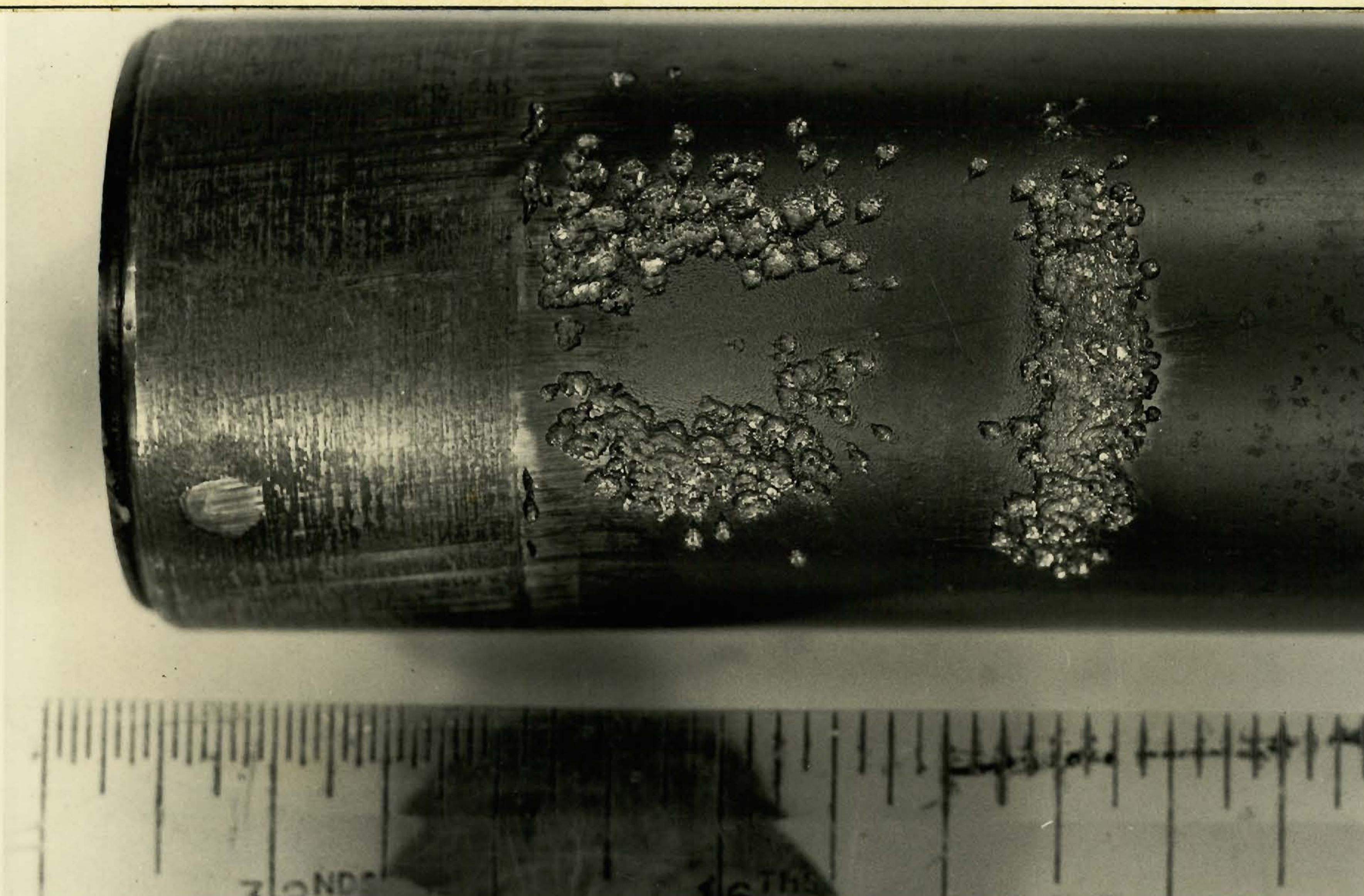
Cavitation damage on the water side of bronze nozzle sleeves was noticed first in the Rocky Mountains where maintenance shops service diesel locomotives at 4,000 feet elevation above sea level. The nozzle sleeve is made of highly cavitation-resistant aluminium bronze, and is rolled into the cast iron cylinder head at each end. The eroded area appeared in a band around the sleeve on the discharge side of an annular flow passage where there was a convergent-divergent flow condition, see Figure 36.

Since the reduction of the atmospheric pressure at 4,000 feet elevation is about 10%, the cavitation problem was solved by increasing the back pressure in the pump return line by 5 psi. On new diesel engines, the flow passage around the nozzle sleeve is corrected, and the increased back pressure in the pump return line



LOW PRESSURE ZONE AT WATER-COOLED NOZZLE SLEEVE

FIGURE 36



CAVITATED NOZZLE SLEEVE FIGURE 37

10B. (Cont'd.)

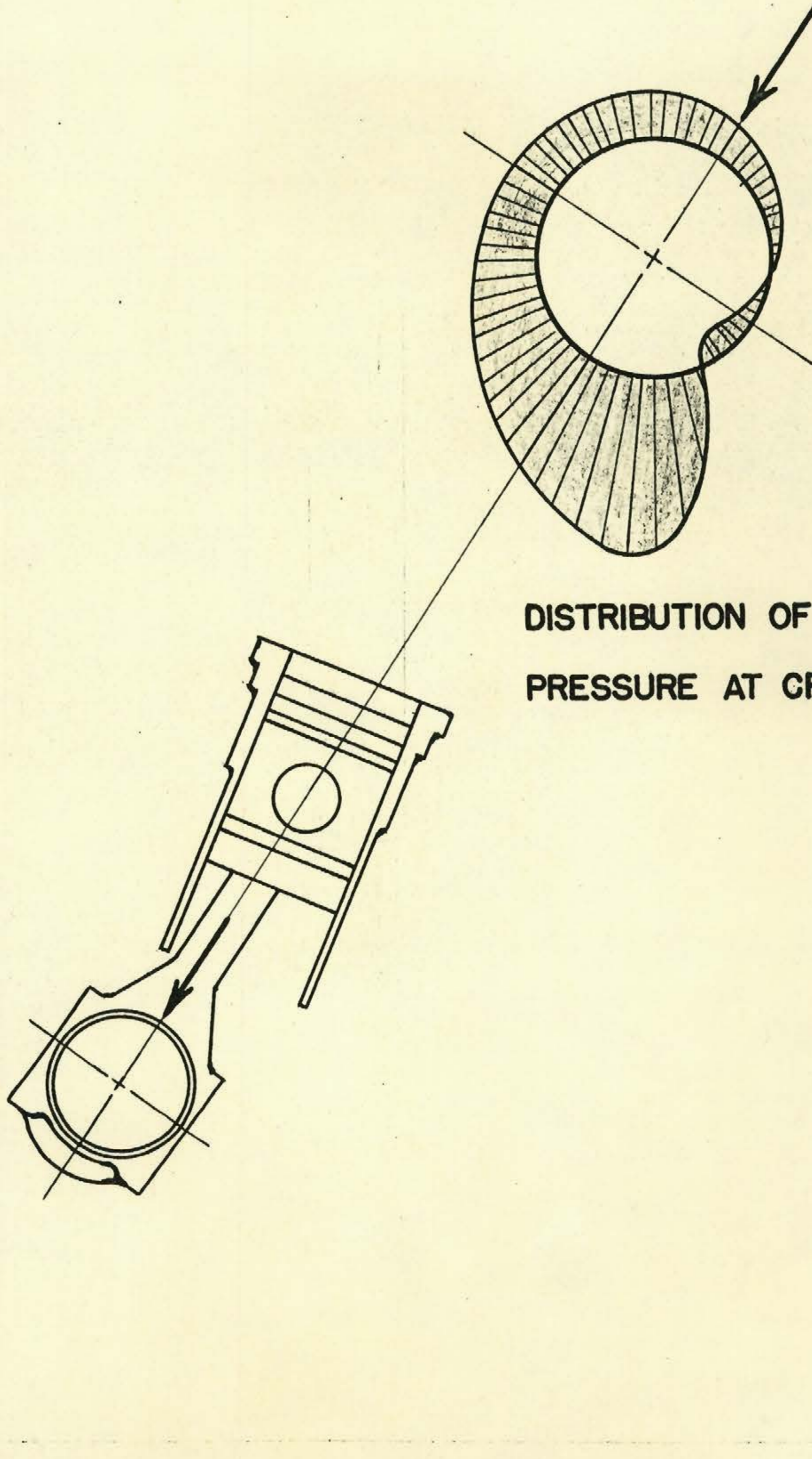
is still recommended for diesel locomotives operating in the mountains.

10C. Oil-lubricated Connecting Rod Bearings

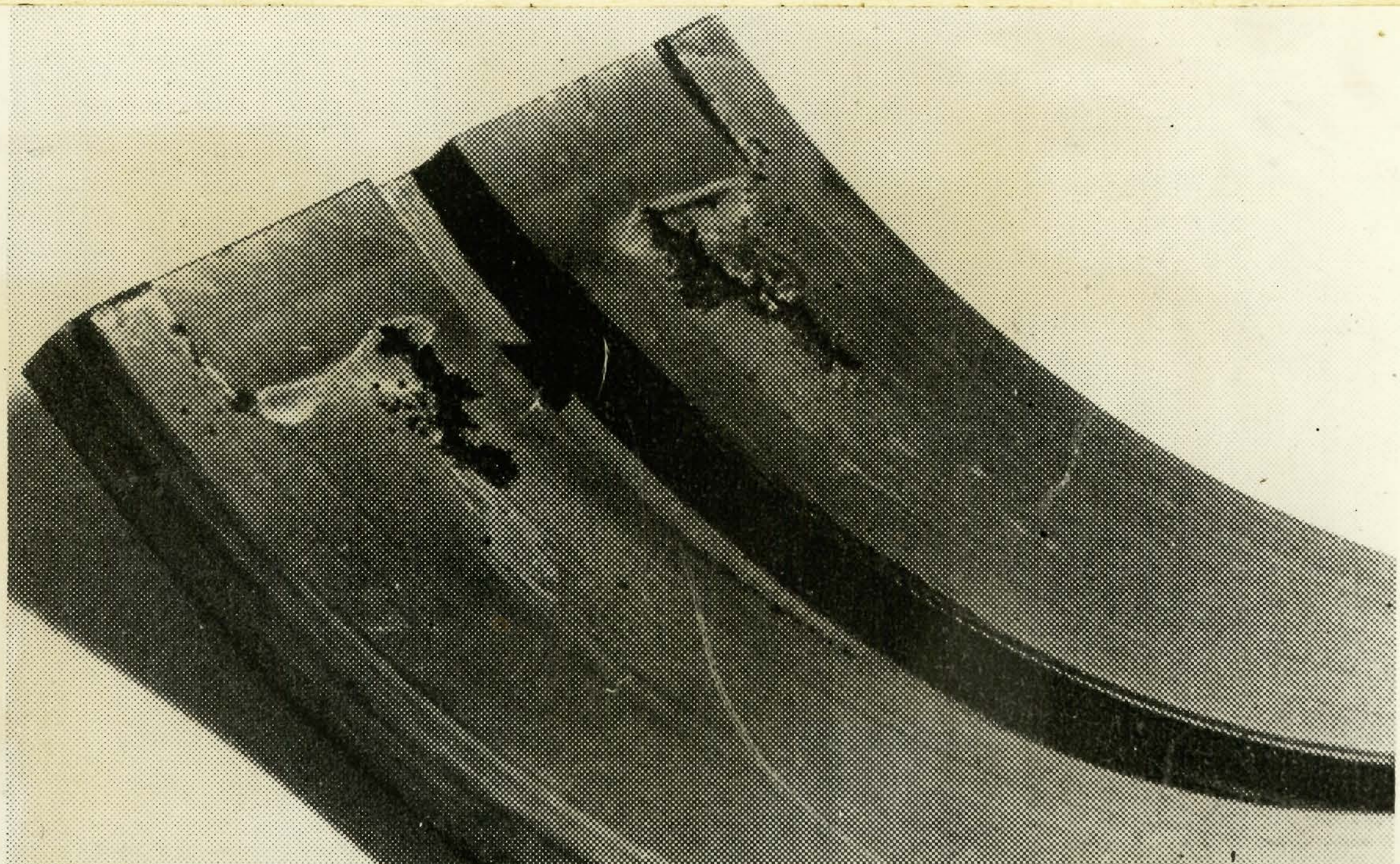
In a reciprocating piston, there is a maximum side thrust on the crank pin bearing during the power stroke, which may cause oil separation on the unloaded side of the bearing, see Figure 38. The cavitation bubbles form in the low pressure zone at oil separation, and the bubbles collapse when the piston passes bottom dead-centre. The test results show that the rate of cavitation attack is nominal as long as the temperature of the lubricating oil is below 200°F, but the rate of cavitation attack increases rapidly above 200°F, see Figure 15, which may be attributed to the increase in the vapour pressure with higher temperature.

11. Validity of Accelerated Cavitation Tests

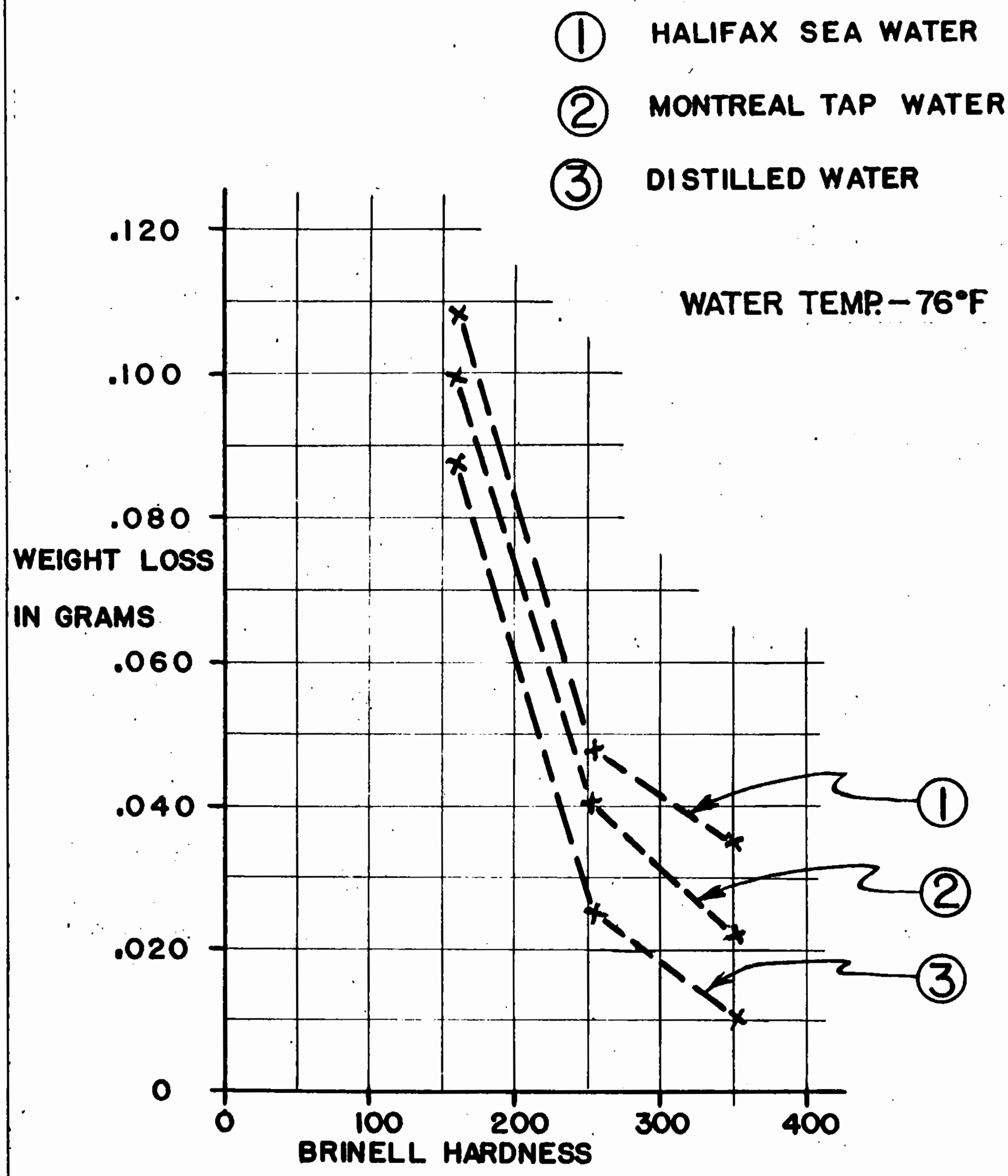
The validity of accelerated cavitation tests of two hours duration has been questioned by Speller and LaQue (37) in relation to cavitation damage occurring in diesel liners as illustrated in Figure 34, since their laboratory tests at 76°F did not show the beneficial effects of (a) chemical additives or (b) austenitic cast iron which were indicated by their field tests. However, accelerated cavitation tests at the operating conditions of 170°F and 20 psig have confirmed the optimum concentration of chemical additives shown in Figure 19. The advantage of austenitic cast iron at 356 BHN is shown in Figure 40. Figure 41 confirms field experience that Ni-resist cast iron cylinder liners at 145 BHN hardness are superior to the typical liner iron at 180BHN.



DISTRIBUTION OF OIL PRESSURE
AT CRANK-PIN BEARING FIGURE 38



CAVITATED CONNECTING-ROD BEARING FIGURE 39



TIME OF EACH TEST – 2 HOURS

DUCTILE IRON IN VARIOUS LIQUIDS

FIGURE 40

(Cont'd.)

11. Validity of Accelerated Cavitation Tests

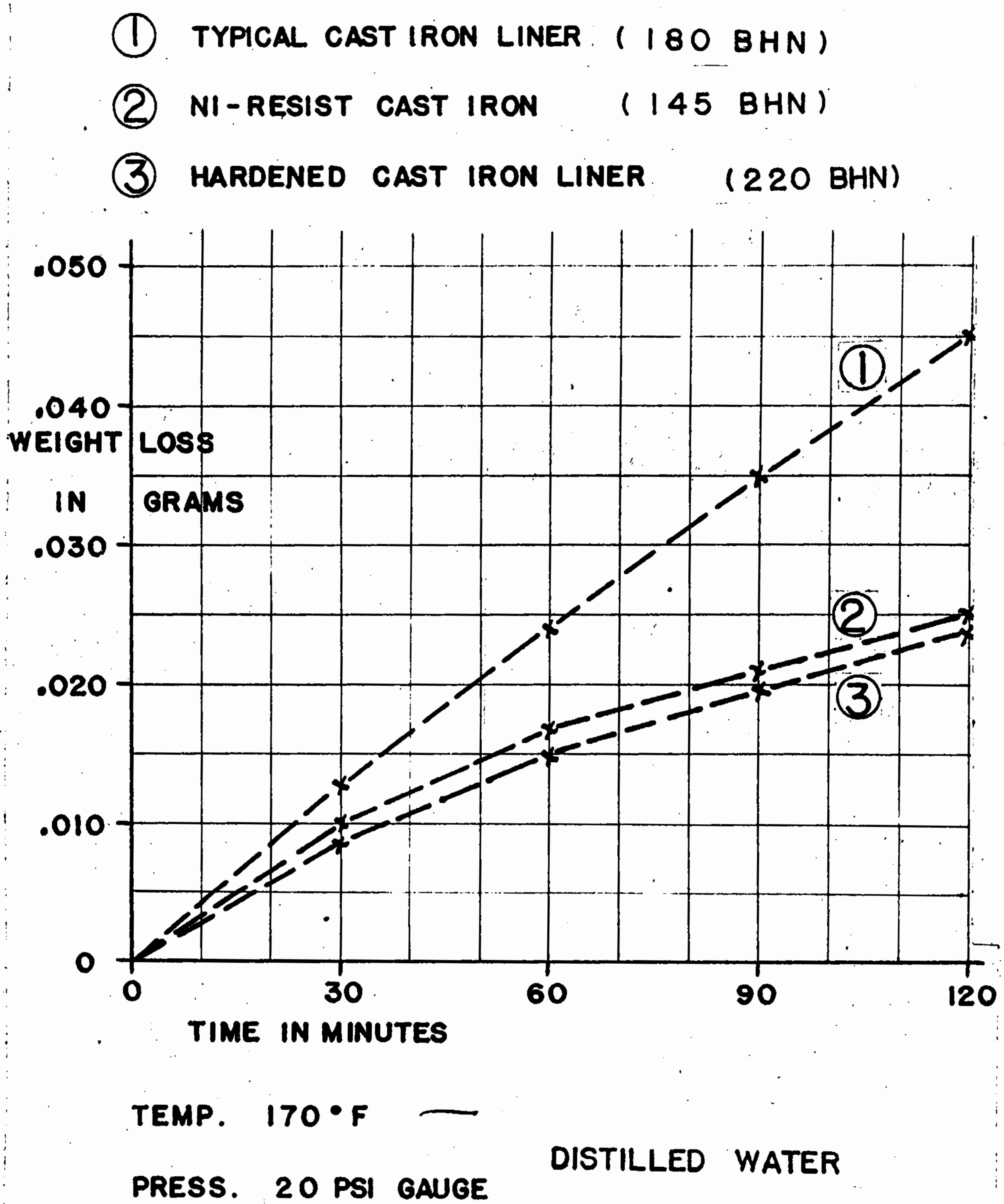
The validity of accelerated cavitation tests for the determination of the resistance of materials to cavitation damage was reported at the ASME 1956 Cavitation Symposium (48); and the order of relative resistance of various materials is the same regardless of the type of machine used. Field performance correlates well with the laboratory test results.

The magnetostrictive - vibratory method has been recommended by the ASME (51), since the ease of parameter measurement and control permits excellent reproducibility of test results at a relatively low initial cost.

12. Summary of Results

The test results shown are the average of three buttons for each material, and the total variation in weight loss between the buttons is usually less than 5%; the results may be summarized as follows:

1. The corrosion-fatigue limit of a rolled metal is an indication of its resistance to cavitation attack.
2. The hardness of a heat-treatable metal is an indication of its resistance to cavitation attack.
3. A ferritic metallurgical structure in carbon and stainless steels has a low resistance to cavitation attack.
4. The cavitation parameter K_T as shown in Figure 17 is an empirical expression for the cavitation attack in water at various temperatures.



DIFFERENT TYPES OF CAST IRON CYLINDER LINERS

FIGURE 41

METAL	CONDITION	TRADE NAME OR SPECIFICATION	TENSILE STRENGTH	COMPOSITION PERCENT
ALUMINUM	ROLLED	2 SO	13,500 PSI	AL/ 99.5
DUCTILE IRON	CAST	A 339	90,000	C/3.5 Si/2.5 MN/0.6 Ni/1.0 MG/.06 P/0.1 S/.02
STAINLESS STEEL	ROLLED	420	165,000	CR/13 C/.15 P/.07 S/.07 ZR/0.6 MO/0.6
YELLOW BRASS	ROLLED	B 16	55,000	CU/62 ZN/35 PB/3
CARBON STEEL	ROLLED	1020	75,000	C/0.2 MN/0.5 P/.04 S/.05
STAINLESS STEEL	ROLLED	410	75,000	CR/12.5 C/.15 Si/1.0
STAINLESS STEEL	ROLLED	302	85,000	CR/18 Ni/8 C/.08
RED BRONZE	CAST	B 62	34,000	CU/83 SN/5 PB/5 ZN/5 Ni/1 P/.02
ADMIRALTY BRONZE	CAST	B 143	45,000	CU/88 SN/9 PB/0.1 ZN/2 Ni/1 P/.02
PMG BRONZE	CAST	80-20	40,000	CU/80 ZN/16 Si/4
ALUMINUM BRONZE	CAST	B 148	77,000	CU/85 FE/3.5 AL/11 MN/0.2 Ni/2.5
CARBON STEEL	CAST	A 27	70,000	C/0.3 MN/0.6 P/.05 S/.06 Si/0.5
WROUGHT IRON	CAST	1005	40,000	FERRITE 100% FE/99.9 C/.05 P/.07
CARBON STEEL	ROLLED	1040	75,000	FERRITE 50% PEARLITE 50% C/0.4 MN/0.8 P/.04 S/.05
CARBON STEEL	ROLLED	10100	95,000	PEARLITE 100% C/1.0 MN/0.4 P/.05 S/.05
STAINLESS STEEL	ROLLED	430	65,000	CR/16 C/.12
CARBON STEEL	WELD	E 6012		C/.08 MN/.27 P/.02 S/.03
STAINLESS STEEL	WELD	E 310		CR/25 Ni/20 C/0.1
STAINLESS STEEL	WELD	E 308		CR/19 Ni/9 C/.07
STAINLESS STEEL	WELD	E 301		CR/17 Ni/7 C/.15
STAINLESS STEEL	WELD	STELLITE 6		CO/55 CR/35 W/6 FE/4
IRON	CAST	A 48	60,000	Si/1.5 Ni/1.7 CR/0.3 MO/0.6
IRON	CAST	NI-RESIST	30,000	Ni/21 CR/2.2 MG/.09
ALUMINUM	ROLLED	6068-0	15,000	CU/0.1 FE/0.5 MG/0.8 MN/0.1 Si/0.5 Ti/0.15 ZN/0.1 CR/0.1
ALUMINUM	ROLLED	75 S	90,000	CU/1.6 MG/2.5 ZN/5.6 CR/0.3

MECHANICAL PROPERTIES OF METALS TESTED

FIGURE 42

13. Discussion of the Star-Shaped Bubble Pattern

The star-shaped bubble pattern on a vibrating test button as shown in Figure 4, has been the subject of so much oral and written discussion that the following three opinions are included for consideration:

(a) The author has postulated that a third order radial vibration of the test button can explain the cyclic appearance of the star-shaped bubble pattern on soft aluminium, since motion pictures give the impression that the bubbles nucleate at the star points, and then they enlarge as they move slowly inwards along a radial arm to the central oscillating cloud of bubbles.

(b) Dr. M. S. Plesset of the California Institute of Technology has reported in the ASME Paper 59-A-170 (see Appendix V) that the cavitation-bubble cloud should have an outward radial flow in the collapse portion of the cycle, which produces fingers of bubbles due to a Taylor instability, refer to (56) and (57). Dr. Plesset reported that a rimmed test button eliminated the star-shaped damage pattern by reducing the radial flow, but the author found little change with a rimmed button, see Appendix IV for the author's reply to Dr. Plesset's written discussion on the ASME Paper 59-A-52.

(c) Dr. J. W. Daily of the Massachusetts Institute of Technology has suggested in a written communication that there is probably a very complicated combination of button vibration and induced liquid flow.

14. Conclusions

1. The magnetostriction apparatus has provided a rapid evaluation of a metal's resistance and a comparative scale for the selection of more resistant alloys for severe cavitation conditions.

2. The ASME standard test procedure has enabled research laboratories in various countries to compare their test data on a common basis.

3. Welded stainless steel overlays form a thin, metallic barrier to cavitation attack, which is an economic solution for hydraulic turbines.

4. Chemical additives in diesel cooling water increase the wetting action and form an adhering liquid-film barrier to cavitation attack, which is a suitable remedy for diesel engines.

Recommendations for Future Research

1. A theoretical study of the nucleation, growth and collapse of one cavitation bubble should be made at small vibration amplitudes on the magnetostriction apparatus, with a higher speed camera and an enormous light flash, similar to the apparatus used by Ellis (47).

2. Cavitation effects in cryogenic liquids such as liquid oxygen, have been mentioned with regard to rocket fuel systems, and undoubtedly the accelerated cavitation machine could be adapted to study the cavitation resistance of materials suitable for this environment

3. The increase in cavitation attack due to water leaking into diesel lubricating oil is well known but the subject could be studied to advantage on an accelerated cavitation machine.

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16.

APPENDIX I

HISTORICAL NOTES ON CAVITATION DAMAGE

The role of cavitation in hydrodynamics covers a broad field, including such effects as nuclei, cavity inception, model scale, boundary layers, hydrofoil performance, and cavitation damage. The author has segregated these historical notes on cavitation damage to enable readers to become familiar with the background of this rather obscure subject.

HISTORICAL NOTES ON CAVITATION DAMAGE

Euler (1754) suggested the possibility of the occurrence of cavities in a flowing liquid at high velocities.

Thomson (1887) who later became Lord Kelvin, predicted the theoretical conditions necessary for cavitation based on his study of flow patterns on walls and spheres.

Barnaby (1897) conceived the term "cavitation" and he described a general theory of the formation of cavities in water which tended to become filled with water vapour and air in solution.

Reynolds (1901) reported the boiling of water in an open tube when the flow velocity was increased sufficiently to decrease the local pressure in the liquid below the vapour pressure at that temperature. He described the flow of water in a restricted tube and the appearance of cavitation bubbles downstream of the constriction as the critical velocity was exceeded. He noted the characteristic humming noise and he attributed it to the collapse of the bubbles.

Ramsay (1912) suggested that cavitation damage resulted from electrolytic corrosion at the strain-hardened indentations where cavitation bubbles had collapsed on the metal surface, since the strained areas would become anodic to the surrounding unstrained metal.

Allievi (1913) presented a general mathematical theory of water hammer which derived the maximum pressure rise due to acceleration of the flow. The water hammer effect or the storage of kinetic energy as elastic compression of the liquid can generate large local pressures.

Rayleigh (1917) considered the collapse of a spherical cavity in an incompressible liquid, neglecting viscosity and surface tension, and assuming isothermal compression of the vapour bubble. He derived the equations for the velocity of the bubble surface as a function of the radius, and for the pressure distribution in the surrounding liquid.

Parsons and Cook (1919) extended the Rayleigh equation and conducted tests which confirmed that large pressures are developed when cavities in water are suddenly collapsed. Parsons carried out further tests which indicated that cavitation erosion was a mechanical process.

Fottinger (1926) conducted many original tests on cavitation, including photographs of the formation and collapse of these cavities. He proposed that the mechanical destruction process was predominant and any electro-chemical effects were minor.

Richards and Loomis (1927) proposed several chemical effects including the disassociation of unstable molecules and the acceleration of the usual corrosion attack.

Boyle, Taylor and Froman (1929) described some of the first magneto-striction experiments to measure the energy intensity necessary to cause accelerated cavitation damage.

Spannhake (1931) determined the frequency of cavitation bubble collapse in venturi tubes as a function of flow velocity and cavity length.

Myers (1931) reported that cavitation damage on hydraulic turbines resulted from an electrolytic action of the impure water, stray electrical currents and the corrosive attack of atomic oxygen.

Gaines (1932) developed the magnetostriction apparatus which utilized the resonant longitudinal vibration of a nickel rod.

Kerr (1937) summarized magnetostriction tests on 80 materials in fresh water and sea water, for the Passamaquoddy tidal project.

Schumb, Peters and Milligan (1937) reported some of the first test data using the magnetostriction apparatus at Mass. Inst. of Tech., and the influence of liquid properties as related to the cavitation resistance of metals was discussed.

Peters and Rightmire (1938) reported the effects of static pressure and temperature on accelerated cavitation damage.

Novotny (1942) published a comprehensive study on the general effects of surface tension, viscosity, gas content, chemical solutions, temperature and pressure.

Poulter (1942) proposed that cavitation pitting resulted from high pressures at bubble collapse which caused penetration of the liquid into the grain structure, and the subsequent breaking up of the surface after sudden release of the pressure. However, his tests showed that 5 minutes at the high pressure was necessary for liquid penetration into the metal, while Knapp has estimated the life cycle of a cavitation bubble at approximately .003 seconds. Poulter reported that iron cavitated in alcohol gave eroded particles of pure iron, but iron cavitated in water gave eroded particles of iron hydroxide.

Silver (1942) considered the temperature rise of the vapour due to work done on the bubble during collapse, and he suggested that the latent heat of condensation of the vapour would slow down the bubble collapse, and thus reduce the local impact pressure.

Beeching (1942 and 1946) suggested that vapour-filled bubbles would develop intense pressures at collapse, while air filled bubbles would tend to cushion the pressure variations. He reported the definite occurrence of corrosion during accelerated cavitation and he concluded that the corrosion attack accelerated the mechanical erosion.

Reiner (1943) proposed that cavitation erosion results from metal fragments being torn out by a negative pressure, presumably liquid compressional waves initiated at bubble collapse. The theoretical tensile strength of water far exceeds the tensile strength of most metals, but experimental values of the tensile strength of water have been very small.

Evans (1943) suggested that cavitation erosion was a conjoint action of mechanical-chemical effects, where the film of oxide that would usually stifle the initial rapid rate of corrosion is continually torn off by collapsing bubbles so that the chemical corrosion attack continues at the initial rapid rate instead of stifling itself. Thus, cavitation erosion is mechanical in the same sense that oxidized metal is being continually torn away, but chemical in the sense that the metal is continually reforming the oxide film which had been torn off.

Kornfeld and Suvorov (1944) discussed the forces of attraction and repulsion between cavitation bubbles, and they conclude that the destructive action of cavitation is a mechanical mechanism.

Frenkel first suggested that the gases present in cavitation bubbles can have a chemical influence on the deformed metal after a collapsing bubble has indented the metal surface.

Josso and Bonnard (1947) reported that the hardness, grain structure or corrosion resistance of metals could not be correlated to the cavitation resistance in a definite manner.

Raven, Feiler and Jespersen (1947) compiled an annotated bibliography on cavitation which is a valuable reference.

Knapp and Hollander (1948) used high-speed photography to trace the growth, collapse and rebound of cavitation bubbles, and their results agree remarkably well with the Rayleigh equation. They concluded that the kinetic energy of bubble collapse is absorbed elastically in the water and given back largely undiminished in the rebound effects.

Petracchi (1949) reported the suppression of mild cavitation in sea water by cathodic protection in a venturi tube, and he concluded that cavitation erosion is a chemical mechanism.

Krenn (1949) proposed that cavitation erosion was an electrolytic action resulting from temperature gradients or heat flow between metal parts submerged in an electrolyte.

Weyl and Marboe (1950) proposed that the formation of reactive unstable ions from the dissociation of the water at the instant of cavitation bubble collapse would cause cavitation pitting.

Eisenberg (1950, 1953, 1957) has summarized the physical phenomena comprising the field of cavitation, including the mathematical results available for their analysis and representation.

Rheingans (1950) presented magnetostriction test results on many new materials for hydraulic machinery, and for various test liquids such as alkalis, acids, and oils.

Noltingk and Neppiras (1950) developed equations to describe the motion of a gas-filled cavitation bubble in a liquid subjected to alternating pressure gradients, such as found in accelerated cavitation.

Richardson (1950) summarized the available knowledge on cavitation and discussed the application of ultrasonic techniques.

Grossman (1952) reported that shot peening on steel and brass reduced the weight loss due to accelerated cavitation attack.

Crewdson (1953) extended Rayleigh's equation for the assumption of adiabatic compression of the vapour bubble, and he concluded that the super-heated steam softened the metal and the high pressure caused the metal deformation.

Wheeler (1954) separated the eroded and corroded materials in an accelerated cavitation test, and he concluded that the weight loss due to the chemical attack was numerically additive to the weight loss due to accelerated cavitation.

Shalnev (1954) proposed that the initial stage of cavitation erosion involves an electro-chemical attack due to the "balloelectric" potential of the cavitation bubbles.

Taylor (1954) presented a more realistic proposal for an instantaneous chemical attack due to the dissociation of water at the instant of cavitation bubble collapse.

Knapp (1955) presented original data about the type and intensity of cavitation attack by studying the pitting pattern on aluminum which revealed a "blow by blow" damage mechanism, and a variation of cavitation intensity with velocity.

Philosophical Library (1957) published a volume containing 25 papers presented at the Symposium on Cavitation in Hydrodynamics held at Teddington, England, in September, 1955.

Margulis, McGowan, and Leith (1957) reported accelerated cavitation test results which show the importance of testing at the operating conditions of the specific example, such as 170°F and 20 psig for diesel water cooling systems.

Knapp (1958) reported a new technique for measuring the intensity of cavitation attack in a Francis turbine, and the pitting rate was similar at the same flow velocity for aluminum test samples exposed in the turbine and in a water tunnel.

Robinson, Holmes and Leith (1958) presented a standard test procedure at the request of the ASME Cavitation Committee for magnetostriction tests, which is comparable to the published works of Kerr and Rheingans.

Knapp (1958) discussed the role of nuclei in cavitation and he suggested that a nucleus is a pocket of undissolved gas in a re-entrant crack in the surface of a solid particle.

Leith (1959) reported that cavitation damage in diesel cooling systems can be reduced by controlling the dominant liquid characteristic (temperature, pressure, wettability) at a stabilized cavitation level, while the increased metal resistance of stainless steel welded overlays is more practical for hydraulic turbines.

Wheeler (1959) suggested that the mechanism of cavitation erosion involves the ejection of brittle strain-hardened oxide layers by a later blow releasing the stored elastic energy beneath the oxide layer.

17. APPENDIX II

ASME STANDARDIZED PROCEDURE FOR VIBRATORY-CAVITATION TESTS

During the 1955 Cavitation Symposium, the Hydraulic Division of the American Society of Mechanical Engineers proposed the standardization of the vibratory-cavitation test; and an Ad Hoc Committee was established to determine the minimum apparatus required, and to specify a standard test procedure. The members of this committee were L. E. Robinson of Allis Chalmers (Milwaukee), B. A. Holmes of Ontario Hydro (Toronto), and the author, W. C. Leith of Dominion Engineering (Montreal).

SPECIFICATIONS OF THE ASME CAVITATION APPARATUS

1. Nickel tube transducer
2. Frequency - 6500 cps
3. Amplitude - .0034 inches
4. Flat test button
5. Amplitude Indication - electric strain gage

Paper No. 56—A-85

Progress Report on Standardization of the Vibratory-Cavitation Test

By L. E. ROBINSON,[1] B. A. HOLMES,[2] and W. C. LEITH[3]

A description is given of the apparatus required for the accelerated testing of materials for relative resistance to cavitation damage by the magnetostrictive-vibratory method. Tentative standards of test conditions and test procedures are defined.

In November, 1955, the first Seminar on Cavitation Resistance Testing was held in conjunction with the annual meeting of the Society. For the first time, those active in the field of cavitation were given the opportunity to discuss exhaustively the techniques of evaluating material-resistance properties, and to exchange views on the problems encountered in the various methods of testing. Before the session was ended, there was agreement that the vibratory method of accelerated-cavitation testing of materials offered more advantages to the investigator than any other method. The ease of parameter measurement and control inherent to the vibratory method permits a reproducibility seldom obtained with other techniques. The short test time and low cost, compared to other methods, and the compactness of the apparatus are advantageous. Further, and of greatest importance, the vibratory-method, laboratory test results correlate well with the performance of tested materials in the field. During the seminar an Ad Hoc Committee was appointed to formulate a schedule of standard practices in the use of the vibratory method. The committee was to determine the minimum apparatus required to test materials by the vibratory method, and make tentative specifications of standard test conditions and procedures.

General

The vibratory method can be practiced with any transducer which produces a mechanical vibration of sufficient output energy and permits close control of the output-energy level. For practical reasons, the particular transducer must produce sufficient damage by cavitation attack within a short test period to permit evaluation with a small percentage of error. The transducer should be capable of a peak-to-peak amplitude of sustained vibration of 0.004 in. in a test liquid at a frequency of 6500 cps ± 100 cps. If the transducer is electromechanical, a power supply of approximately 500-watt output is necessary.

Of the transducers which have been tried or offer possibilities, the electromechanical-magnetostrictive type of vibrator is recommended as possessing the virtues of (1) compactness of apparatus, (2) precise control, (3) relatively low initial cost, and (4) economical operation.

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[2] Structural Research, Hydro-Electric Power Commission of Ontario, Toronto, Canada.

[3] Mechanical Research, Dominion Engineering Works Ltd., Montreal, Quebec, Canada.

Contributed by the Hydraulic Division for presentation at the Annual Meeting, New York, N. Y., November 25–30, 1956, of The American Society of Mechanical Engineers.

Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Manuscript received at ASME Headquarters, August 3, 1956. Paper No. 56—A-85.

The magnetostrictive-vibratory accelerated test has been used by many investigators, and conclusive correlation has been established between resistances to cavitation damage determined by laboratory test and the performance of tested materials in field applications.

The recommended magnetostrictive transducer is a tube of commercially pure Grade-A nickel, 12 in. long, $^5/_8$-in. diam with a $^1/_{32}$-in. wall thickness. The tube material is specified as cold-drawn and stress-equalized with a hardness of Rockwell 15T 90–95. This hardness has been found to be the best compromise between magnetostriction and physical strength. The nickel tube is used in the as-tempered state and must not be ground, turned, or polished to size.

A prepared specimen holder bushing of half-hard brass is silver-soldered into the end of the tube with a minimum of heating by the brazing torch. The bushing weight should be between 23.5 and 24.0 grams. An internal $^7/_{16}$–20 thread is machined to a depth of $^3/_8$ in. in the bushing to mate with the test specimen, Fig. 1.

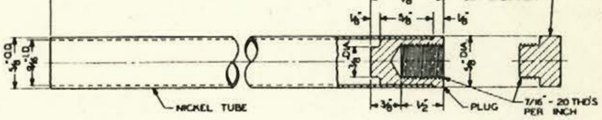

Fig. 1 Assembly of Cavitation-Tube Plug and Test Specimen

The test specimen is machined from the material in a single piece weighing 13.25 ± 0.25 grams. Its test surface is circular and flat, $^5/_8$-in. diam. The edges of the test surface must be square and uniformly sharp without burrs or imperfections. The specimen has a $^1/_4$-in. shank with a $^7/_{16}$–20 thread mating with the transducer bushing, Figs. 2 and 3.

The transducer is suspended vertically with the test specimen at the lower end. The means of support is a thin rigid clamp at the center of gravity of the loaded tube. The clamp may be of neoprene or of metal, Fig. 4. During oscillation the tube must not come in contact with other parts of the apparatus except at its plane of suspension.

The loaded transducer can be driven at its resonant frequency by various means. A high-voltage electronic power supply may be used. The transducer is made a part of a tank circuit which is capacitatively tuned to the resonant or natural frequency of the transducer assembly. The powerful alternating magnetic field required is generated by a 1000-turn driving coil. In operation, the transducer may be driven in self-oscillation at resonance by controlling the power supplied to the tank circuit with a negative feedback from an auxiliary pick-up coil. As an alternative, the transducer may be driven by a manually controlled external audio oscillator which is adjusted to the predetermined resonant frequency.

Low-voltage, high-current power applied to a coil of relatively few turns also can be used successfully. The driving magnetic field can be generated by a commutator switch driven at a constant speed and designed to produce the resonant frequency.

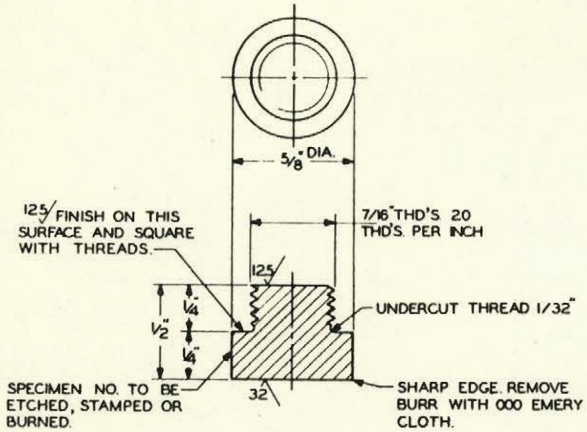

Fig. 2 Cavitation Test Specimen With Undercut

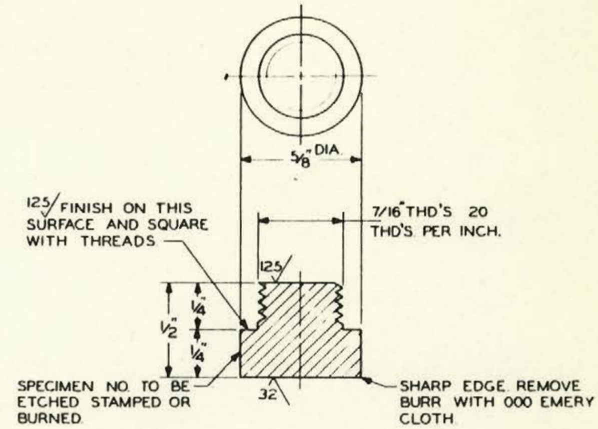

Fig. 3 Cavitation Test Specimen Without Undercut

The magnetostrictive characteristic is temperature sensitive. The nickel tube must be maintained at a constant temperature well below its curie temperature throughout the test. Since the eddy-current losses in the nickel are high, considerable cooling is required. Usually, the transducer tube is cooled internally by a multiple-jet spray of cold water against the inner wall. The coolant removes the heat of electrical losses by gravity flow down the tube wall and is removed by vacuum aspiration from the bottom of the tube. The cooling system should be designed to provide a constant tube temperature and a constant loading of the tube with a vibration-damping mass of coolant throughout the test.

The fluid properties of the test liquid must be carefully controlled if the cavitation intensity is to remain constant throughout the test. For a particular liquid, this control may be obtained by maintaining a constant liquid temperature. The test liquid container is placed in a controlled tempering bath which is regulated by a temperature detector immersed in the test liquid. With simple apparatus, temperature regulation to within a fraction of a degree can be obtained.

The transducer must be calibrated in vibration amplitude before it is used for testing. The calibration is made with optical displacement-measuring instruments and a stroboscopic light source. During operation, the amplitude of vibration may be indicated electrically by strain gages bonded directly to the transducer tube or the amplitude may be measured optically.

The magnetostrictive transducer in vibration acts as a high-intensity sound generator, creating a strong sound field in the test liquid below the vibrating test specimen. Reflected sound waves have a noticeable effect on the intensity of cavitation at the test surface. As a result, the choice of the test-liquid container shape and material is a critical factor in accelerated-test results. The container should be small enough to permit economical renewal of the test-liquid sample, and it should be made of glass to allow continual observation of the specimen during the test. As a matter of past usage, a thin-walled cylindrical vessel of pyrex glass, approximately $3^1/_2$-in. diam and with a flat bottom, is recommended. The apparatus is illustrated in Fig. 5.

Tentative Standard Conditions of Test

Accelerated-cavitation test conditions have been adopted from the arbitrary experimental conditions of the first investigators to use the vibratory method, Hunsaker, Peters, Kerr, and Rightmire.

To standardize the vibratory accelerated cavitation-resistance test and make possible the comparison of results obtained by

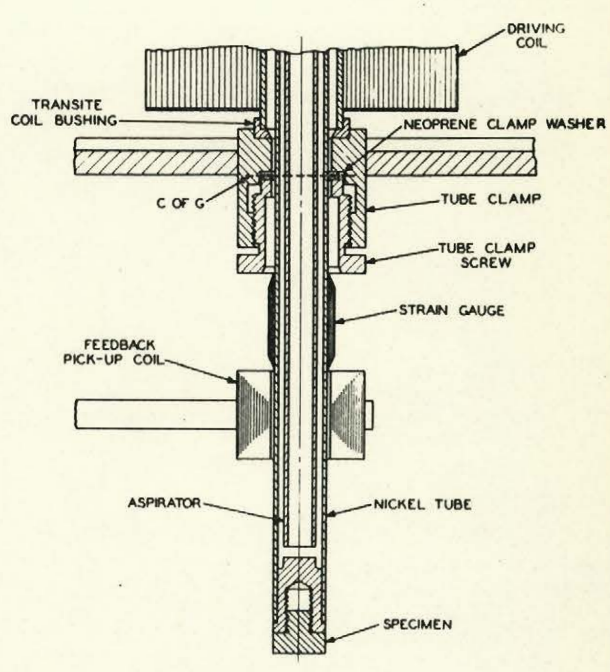

Fig. 4 Details of Transducer Suspension

different investigators, we propose that certain conditions of test be specified and accepted by the field as tentative standards. These conditions include the frequency of vibration, the amplitude of vibration, type of test liquid, temperature of test liquid, atmospheric pressure, depth of submergence, depth of test liquid, and the time of test.

The frequency of vibration is defined to be 6500 ± 50 (cps). This is approximately the resonant frequency of oscillation of a nickel tube 12 in. in length, bearing a mass load of about 37 grams, and with the assembly freely suspended at the center of gravity. The natural frequency can be adjusted by varying the tube length, tube weight, or bushing weight, with the specimen weight remaining within the tolerances given. A 12-in. nickel tube weighing 108 grams should have a resonant frequency of 6500 cps within 20 cycles when it is fitted with a 23.5-gram bushing and a 13.25-gram specimen and the total length is 12.625 in.

For still greater precision of frequency adjustment, a specimen

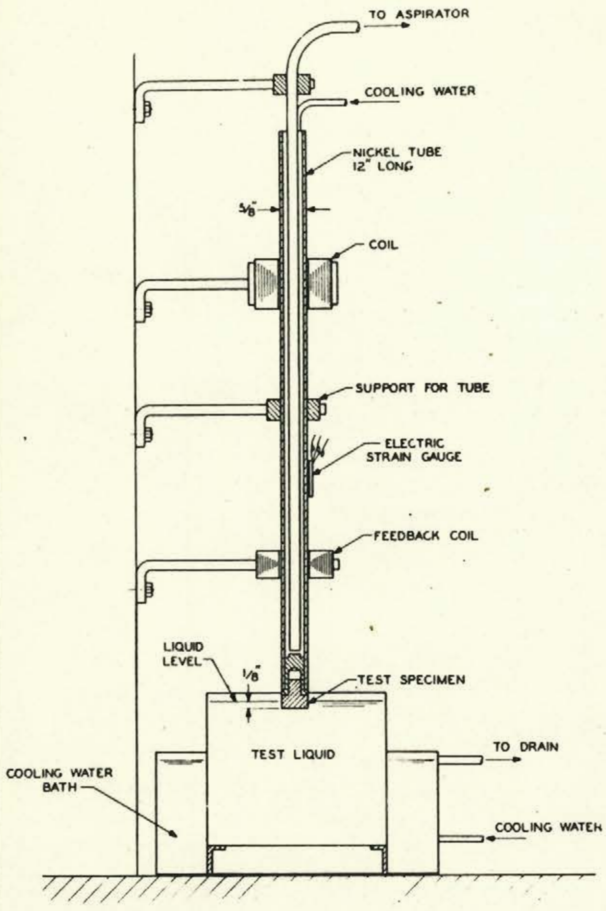

FIG. 5 SCHEMATIC LAYOUT OF VIBRATORY-TYPE, ACCELERATED-CAVITATION MACHINE

bushing may be fitted to a transducer tube longer than 12 in. and the natural frequency adjusted to 6500 cps by progressive decreases in the tube length.

The amplitude of vibration is defined to be 0.00342 ± 0.00005 in., peak to peak. This particular amplitude is admittedly arbitrary, but it has been used in the majority of investigations since the inception of cavitation-resistance testing by the vibratory method. A decrease of the amplitude of vibration to 0.003 in. only decreases the assayable damage to the test specimen. An increase to 0.0035 in. or more does not make amplitude any more measurable and tends to decrease the present margin between the operating stresses and the fatigue limit of the transducer.

The test liquid is defined to be fresh distilled water. This medium is most readily duplicated and precludes secondary corrosion effects.

The test-liquid temperature is defined to be 76 F ± 1 deg F.

The atmospheric pressure, above the test liquid, is tentatively defined to be the prevailing barometric pressure. It is recognized that the total hydrostatic pressure involved in the cavitation index, applied to the vibratory method, is predominantly the pressure of the atmosphere above the test liquid and that variations in the atmospheric pressure are accompanied by variations in the cavitation attack on the specimen. However, this correlation has been quantified experimentally and a correction factor has been derived by which damage at any given pressure may be corrected to damage at a particular pressure. By this means, test results obtained at various barometric pressures can be compared at a fixed datum level.

The plane of the test surface of the specimen is to be submerged 0.125 in. below the quiescent surface of the test liquid. It has been found that, with amplitudes of vibration as small as 0.005 in., at this depth of submergence the oscillating specimen begins to draw air from above the liquid surface down the sides of the specimen to the cavitating test surface. The air flow is accompanied by a characteristic hissing sound which is quite noticeable. However, at the 0.00342-in. amplitude of oscillation, the streaming of air from the liquid surface to the lower test face of the specimen has not been detected. The practical reason for the slight immersion is to keep the interface between the specimen and holder bushing as far out of the liquid as possible.

It is specified that there should be 4.5 in. of test liquid beneath the test surface of the specimen. This may be stated otherwise, that there should be a distance of 4.5 in. from the sound-generating surface to the bottom of the test-liquid container, as measured along the extended axis of the transducer tube.

The definition of this distance as a condition of testing is a compromise between the ideal and the practical. Ideally, in evaluating the resistance of materials to cavitation damage independently of particular geometrics and operational parameters, the experimenter would perform the vibratory accelerated test in an infinite volume of the test liquid. The nearest approach to the ideal probably would be to move the apparatus in a boat to the deepest part of one of the Great Lakes, and there carry out the desired tests. However, in the laboratory, a small volume of test liquid must be contained in a vessel capable of absorbing only a part of the intense sound generated by the vibrating specimen. The reflected sound waves cause measurable cavitation damage and the geometry of the test-liquid container must be kept constant to avoid variations in results.

Experiment has shown that a test-liquid depth of 4.5 in., or approximately one half the wave length of 6.5 kc sound in water at 76 F temperature, offers a desirable compromise. With this depth, the test results have a small standard deviation. The effect of the sound field seems to be least at this depth, apparently as a result of the standing wave created in the liquid between specimen and container bottom.

The remaining condition is the duration of the accelerated test. This is specified to be 120 min divided into four test intervals of 30 min each. It is apparent that the specification of a test time is arbitrary. However, shorter test times of, say, 90 min limit observation of damage sustained by materials of higher resistance, while test times of more than 120 min do not especially increase the ease of measurement but do increase the test costs.

TEST PROCEDURES

The conditions of test as specified define the recommended parameter adjustments during the actual test. There also should be a standardization of procedures in preparing for and performing the test. The procedures recommended later have been established by experiments with an extensive variety of materials.

In the past two decades considerable work has been done on the effect of the air content of a liquid on the incidence of cavitation and the cavitation attack on hydraulic materials. Although the quantization is still a subject of controversy, it seems that the air content of a cavitating liquid tends to exert a passivating influence on cavitation attack. In the vibratory test, a convenient means of stabilizing the air content of the test liquid has been to subject the liquid to the intense sound field generated by a dummy specimen prior to the timed test. This method yields consistently reproducible test results, dependent on the length of the pretest treatment. Other investigators, variously, have treated the test liquid with pretest boiling, or have ignored the effects of air content. The differences between damage measured in the several cases are not extreme and are restricted to the first 30-min interval of test.

However, since the effects are not universally agreed upon, it is of advantage to remove the question from the test. As a tentative standard procedure, we specify that the test liquid be boiled for 15 min prior to the test proper.

While the test water is being prepared, the specimen must be readied for testing. It has been found that cavitation attack tends to localize damage at surface imperfections on the face of the test specimen. A perceptible scratch within the area of most intense attack often becomes a disproportionately large pit during the vibratory test.

It is recognized that it is not possible to bring the test surface of all types of material to a mirror-polish superfinish. However, the test surfaces of different specimens can easily be made equal in average finish, thus supplying a common reference level.

The test surface of the specimen should be polished to a roughness of approximately 3 microinches root-mean-square, using triple-zero (000) emery paper.

The physical and chemical peculiarities of many materials tested by the vibratory method create an error in damage evaluation. If the test material is uniformly porous, during the test the specimen may absorb a considerable amount of the test liquid, which is driven deep into the material by the nearly 8000 gravities peak acceleration. At the end of the first test interval, such a specimen may reveal an actual increase in mass, despite visibly extensive damage and material loss. Attempts to remove the absorbed liquid by the application of high heat may heighten the rate of oxidation of some materials. Removal of the liquid by chemical drying or slow heating adds much to the over-all time required to complete the resistance test.

A further effect has been seen in the case of metals which have a higher affinity for oxygen. While the specimen is being vibrated in the test, the material may oxidize heavily on surfaces and at grain boundaries in contact with the test liquid. If the material is somewhat porous, the oxygen gained by chemical combination during the test becomes a noticeable factor.

By experimental trial, a pretest treatment was found by which materials could be brought to a condition sufficiently stable that spurious physical and chemical effects would not detract from the precision of damage measurements. The test specimen is to be preoxidized by boiling in a sample of the test liquid for about 15 min, prior to the test. When the specimen is removed from the boiling liquid, it should be placed immediately in a second sample of cool test liquid and allowed to soak long enough for the specimen to return to the ambient temperature. When cool the specimen should be removed from the liquid, and dried carefully on all exterior surfaces with a lintless tissue wetted with CP reagent acetone. As soon as the surface moisture is removed the specimen should be weighed and quickly placed in the transducer for the test.

At the end of each 30-min test interval the specimen should be removed from the transducer, surface-dried with CP reagent acetone on a lintless tissue, and weighed at once. As soon as it is weighed the specimen should be returned to the vibrator and the test continued.

All weight measurements should be made to the nearest 0.1 milligram.

Summary

To summarize: The magnetostrictive type of vibratory apparatus, which has a water-cooled centrally supported pure nickel tube as a transducer, is recommended by the committee for accelerated cavitation-resistance testing. A test specimen having a flat circular surface $^5/_8$-in. diam is suggested. The test liquid should be contained in a cylindrical flat-bottomed pyrex glass vessel approximately $3^1/_2$-in. diam and the container placed in a thermally regulated heat-exchange bath for control of the test-liquid temperature.

The following test conditions are suggested as tentative standards for vibratory, accelerated-cavitation testing:

Test frequency of 6500 $\pm$ 50 cps.
Test amplitude of 0.00342 $\pm$ 0.00005 in.
Test liquid, fresh distilled water.
Test liquid temperature of 76 F $\pm$1 deg F.
Test pressure, the prevailing barometric pressure, with the test results to be corrected to a reference pressure.
Submergence of test specimen of 0.125 in.
Test-liquid depth of 4.5 in. below the test specimen.
Test time of 120 min divided into four equal intervals.

The following procedures are suggested as tentative standards for vibratory resistance tests:

The distilled water should be prepared for test by boiling for 15 min to reduce the air content to a minimum.

A root-mean-square roughness of three microinches should be obtained on the flat circular test surface of the specimen, using triple-zero emery paper.

The specimen should be stabilized in state of oxidation and water content by the following sequence: Boil for 15 min in distilled water, soak to ambient temperature in distilled water, and surface-dry with CP reagent acetone immediately before each weighing and testing.

The specimen should be taken from the vibratory apparatus at the end of each 30-min interval of testing, surface-dried, and weighed. All weights should be taken to the nearest $^1/_{10}$ milligram.

18. APPENDIX III

CAVITATION AND NUCLEATE BOILING

The formation of the first vapour bubble during cavitation and nucleate boiling was studied during 1958, when Dr. T. D. Patten of Edinburgh University was a Visiting Research Fellow at McGill University. A special test button with an imbedded heater was made, so that cavitation or nucleate boiling could be studied separately or simultaneously. A standard flat test surface was tested first, and then conical and spherical test surfaces were tested.

However, the formation of the first vapour bubble at given temperature and pressure conditions was not reproducible, and no definite correlation could be established between the pressure gradient required in cavitation and the temperature gradient required in nucleate boiling.

Future research is anticipated specifically related to electrode steam generators, where severe attack occurs on the electrode tip during arcing conditions at minimum electrode immersion. Submerged water spouts are directed on the tips of the electrodes to prevent the accumulation of steam bubbles and, hence, cavitation and nucleate boiling occur simultaneously.

19. APPENDIX IV

1) A.S.M.E. paper 59-A52

   "Some Corrosion Effects in Accelerated Cavitation Damage"

   by W. C. Leith and A. Lloyd Thompson.

2) Discussion by Dr. M. S. Plesset

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3) Reply by W. C. Leith

19. APPENDIX IV (Cont'd.)

Discussion of Paper No. 59-A-52, "Some Corrosion Effects in Accelerated Cavitation Damage" by W. C. Leith and A. Lloyd Thompson.

The authors have ascribed the star-shaped bubble pattern to the presence of radial vibrations of the test specimen. In the experiments which I have reported, the star-shaped pattern did not appear to have this origin. My observations showed that this pattern was not connected with the diameter or thickness of the specimen. I also found a random element in the number of rays in the star pattern. It must be admitted that the apparatus used by Leith and Thompson is different from mine so that their interpretation of the mechanism of the star formation may be correct. This point is of some importance since these star bubble patterns are associated with lines of deep erosion of the test specimen. My experience has been that the formation of uneven cavitation damage is a source of inaccuracy in damage data. Such damage patterns make reproducible data difficult to obtain.

In the authors' discussion of the effect of metal properties they attach significance to the so-called incubation time. This time is considered by the authors to be a period during which there is no loss of weight. I believe that it is incorrect to describe the "incubation period" as a period in which there is no loss of weight. In our experiments we observe a weight loss immediately following exposure to cavitation. The initial rate of weight loss is less than that found after some exposure. The small initial rate increases

19. APPENDIX IV (Cont'd.)

with exposure until a characteristic constant rate is obtained. The smaller initial rates of weight loss require greater accuracy for their observation. When the characteristic constant rate of weight loss is obtained, further damage can eventually lead again to a nonlinear region of weight loss. This excessive damage is often a cause of inaccuracy in measurements.

A question may be raised regarding the data presented on cathodic protection. Figure 8 of the paper shows a greater weight loss when anodic currents were applied to the specimen. The authors do not state whether these weight losses for the anodic case were corrected for loss of material due to anodic current flow alone. Unless such a correction is made this curve is meaningless.

In their consideration of temperature effects on cavitation damage the authors have found a result which has already been reported by A. S. Bebchuk, Soviet Physics-Acoustics, vol. 3, P. 97, 1957 and vol. 3, p. 395, 1957.

It appears further in the authors' consideration of temperature and pressure effects that the authors have attempted to consider these separately. From a fundamental point of view this approach is very likely not possible. There is certainly an important effect in cavitation damage of the amount of dissolved gas, and this amount is related both to temperature and pressure.

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19. APPENDIX IV (Cont'd.)

Reply to Dr. M. S. Plesset

Dr. Plesset's discussion emphasizes the divergence of opinion that exists between investigators who study different aspects of the same phenomenon. His most recent paper, 59-A-170, which is contained in the Appendix V, describes a novel experimental procedure to study the effect of cathodic protection in cavitation damage. There is some doubt as to the accuracy and reproducibility of his amplitude indication, since a displacement pick-up coil has been replaced by the more accurate strain gauge indication in the commercial cavitation machine as sold by Allis-Chalmers.

Dr. Plesset's apparatus has a solid exponential horn transducer operating at a frequency of 14,200 cps with an amplitude of .0020 inches, while the standardized A. S. M. E. apparatus has a nickel tube transducer operating at a frequency of 6,500 cps with an amplitude of .0034 inches. It would be interesting if Dr. Plesset could correlate his test results to the standardized A. S. M. E. test.

Dr. Plesset has proposed that a rimmed test button will eliminate the star-shaped damage pattern by reducing the radial flow. Following this proposal, standard flat buttons and rimmed buttons of rolled aluminum with the same surface roughness were tested. The Plesset rimmed button has a similar damage pattern as shown in Figure 18, but the total weight loss for a rimmed button is about 10% less than for a

19. APPENDIX IV (Cont'd)

flat button, as shown in Figure 19. These buttons were tested with the A. S. M. E. standard procedure, and the weight loss curves are definitely in the characteristic linear region, where accuracy and reproducibility are easily attained. It is suggested that the modulus of elasticity of the test button may have some influence on the damage pattern, since a soft metal with a low modulus such as cast aluminum, shows a distinct star-shaped damage pattern, while a harder metal with a higher modulus such as cast aluminum bronze, shows a more uniform damage pattern as shown in Figure 20.

As stated on Page 2 in the paper, 59-A52, the incubation period is found for rolled metals only, and the surface roughness for standard buttons is about 3 microinches. It is encouraging to note that Figure 29 in Dr. Plesset's paper, 59-A-170, shows an incubation period for stainless 17/7 steel.

The larger weight loss with an anodic current as shown in Figure 8 has been corrected for the static corrosion loss, and this data agrees with the published works of Beeching.(21).

The general effects of temperature were reported first by Kerr in 1937, but Figure 10 refers to the specific case of a diesel engine. The separate curves of temperature and pressure may not satisfy Dr. Plesset's fundamental point of view, but they can be adjusted separately both in the laboratory and the engine, to show the desired relative effects.

19. APPENDIX IV (Cont'd.)

A cavitation parameter of water for temperature has been established empirically which combines the effects of vapour pressure, viscosity and surface tension, as shown in Figure 21. This cavitation parameter is extremely useful for cavitation problems in water cooling systems.

The literature on cavitation contains many conflicting observations on the effects of dissolved air, and it is certainly an important effect. However, a complete series of temperature and pressure curves show relative effects, which include the amount of dissolved air.

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WCL/fh. -

ROLLED ALUMINUM

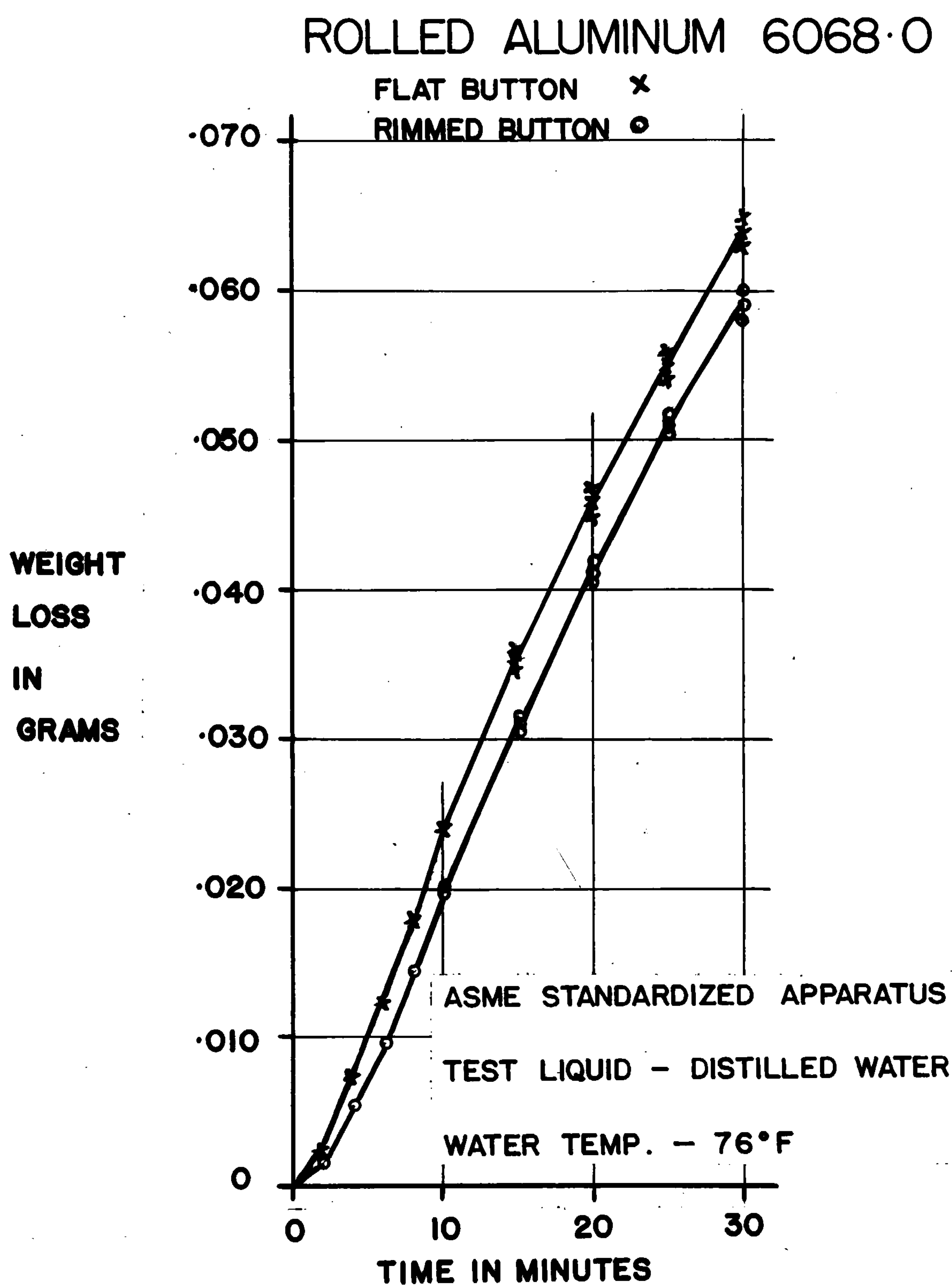
ASME STANDARD FLAT BUTTON

ROLLED ALUMINUM

PLESSET RIMMED BUTTON

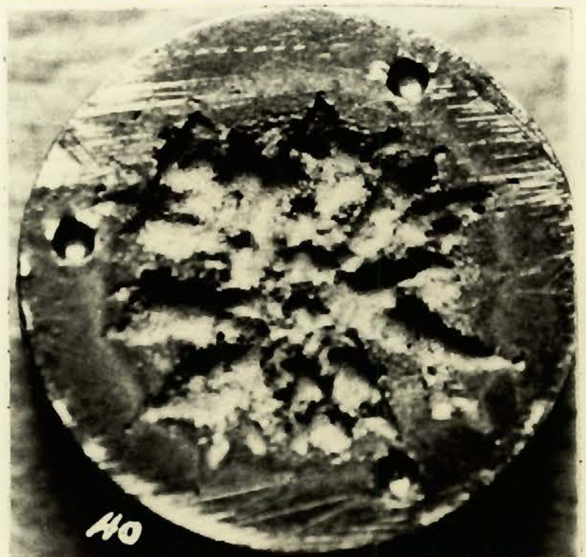
EFFECT OF A PLESSET RIMMED BUTTON

FIGURE 18



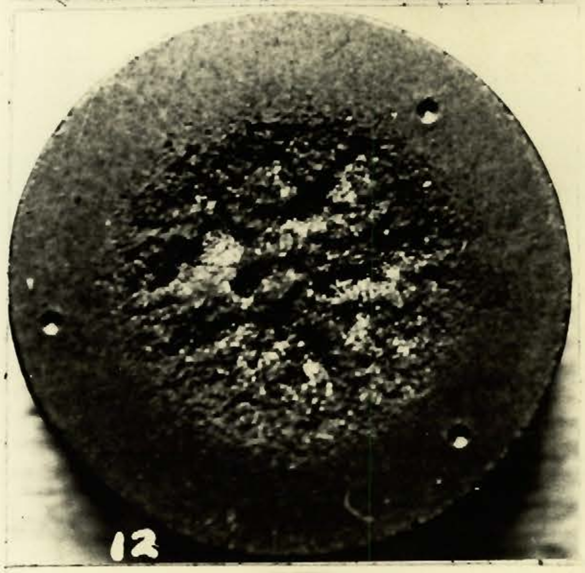
CHARACTERISTIC WEIGHT LOSS CURVES

FIGURE 19



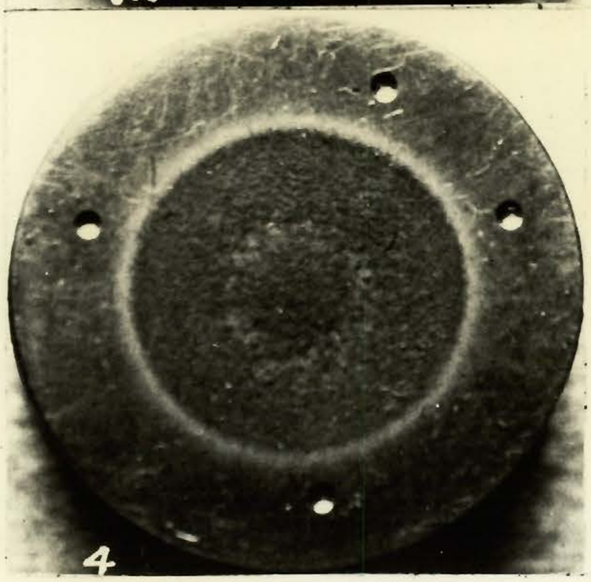
CAST ALUMINUM

MODULUS $E = 10 \times 10^6$ PSI



CAST IRON

MODULUS $E = 16 \times 10^6$ PSI



CAST ALUMINUM BRONZE

MODULUS $E = 22 \times 10^6$ PSI

EFFECT OF MODULUS
OF ELASTICITY

FIGURE 20

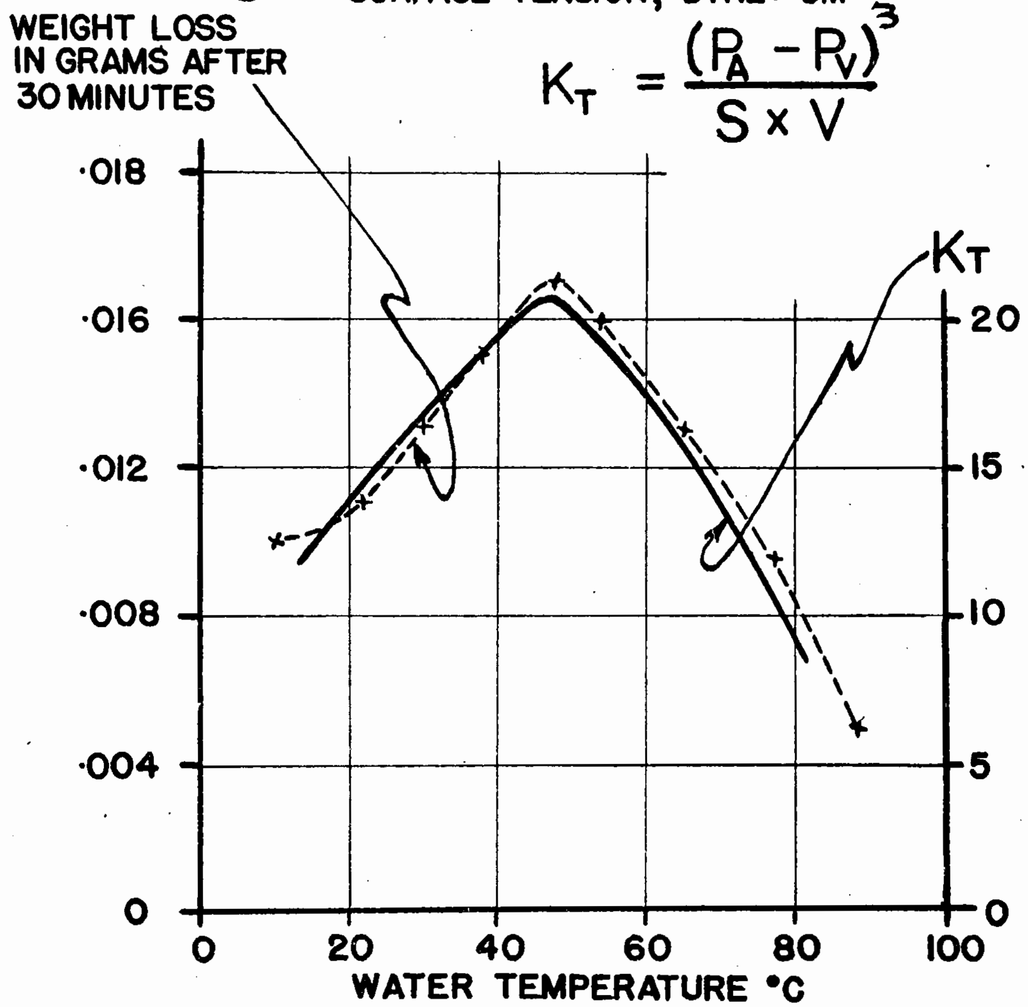
P_A = ATMOSPHERIC PRESSURE, MM

P_V = VAPOUR PRESSURE, MM

V = VISCOSITY, CENTIPOISES

S = SURFACE TENSION, DYNE / CM

$$K_T = \frac{(P_A - P_V)^3}{S \times V}$$



CAVITATION PARAMETER K_T OF WATER FOR TEMPERATURE

FIGURE 21

20. APPENDIX V

A. S. M. E. paper 59-A-170

" On Cathodic Protection in Cavitation Damage"

by M. S. Plesset.

SPECIFICATIONS OF THE PLESSET CAVITATION APPARATUS

1. Solid steel exponential horn transducer
2. Frequency - 14,200 cps
3. Amplitude - ,020 inches
4. Rimmed test button
5. Amplitude indication - displacement pick-up coil