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ACCELERATED CAVITATION RESEARCH

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ACCELERATED CAVITATION RESEARCH

By

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THE CAVITATION—pitting tests described in this article were made with an accelerated cavitation machine of the vibratory type. An attempt was made to solve some of the phenomena of cavitation by varying the amplitude of vibration, by varying the depth of submergence of the test specimen in the test liquid and by using alkalis, acids and oils for the test liquid. Other tests were made to determine the relative resistance to pitting of recently developed materials and techniques for applying these materials. Results showed that accelerated cavitation tests can be used to determine some of the mechanics of cavitation, as well as indicating that some of the newly developed materials may be suitable for use on hydraulic machinery under operating conditions where cavitation occurs.

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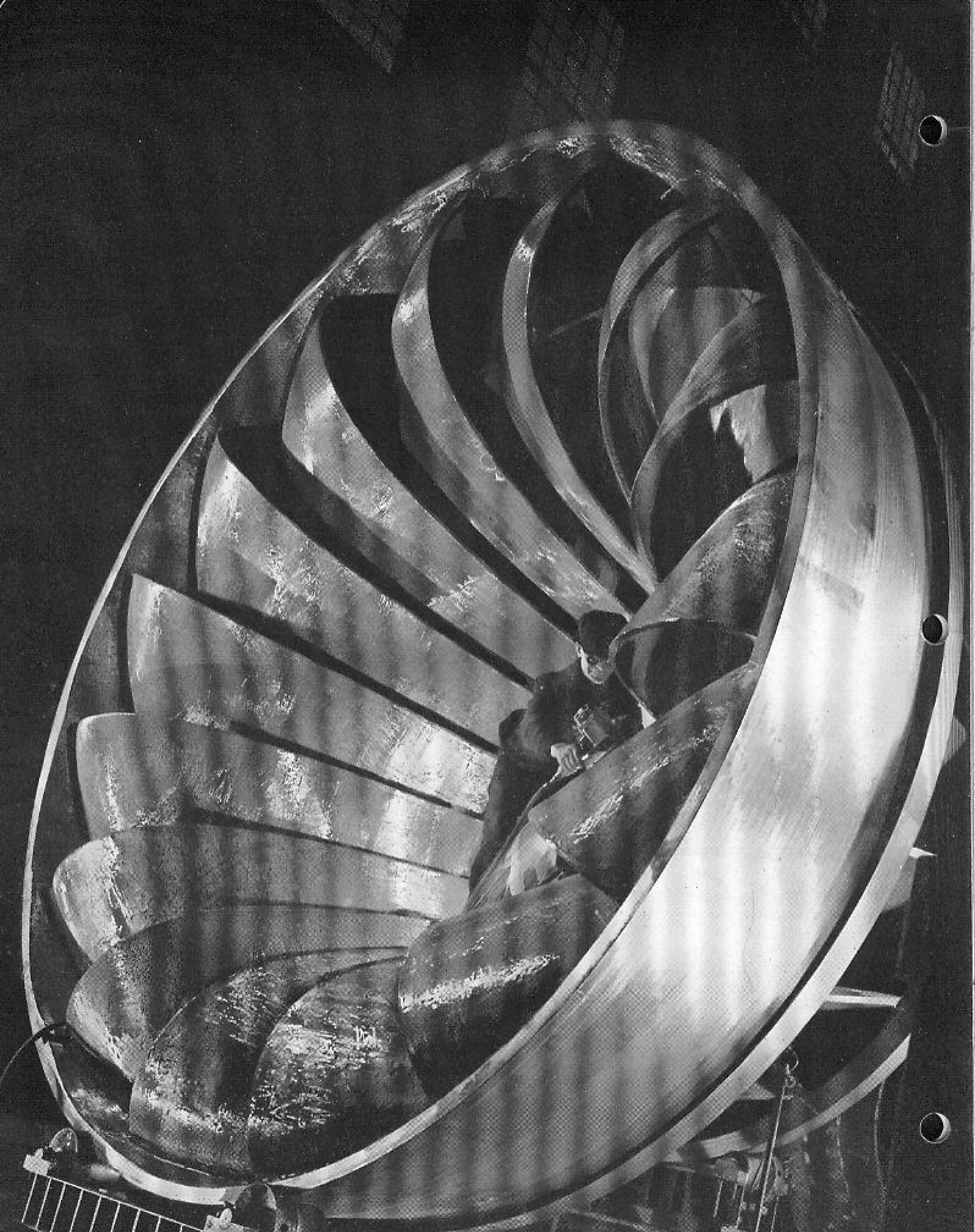

An accelerated cavitation machine of the vibratory type was constructed by the Research Laboratory of the Allis-Chalmers Mfg. Co. in 1948 and was placed in operation in September of that year. It has been in continous use ever since for making hundreds of tests on a large variety of materials to determine their relative resistance to cavitation and has also been used for making investigations of some of the phenomena of cavitation and pitting.

These tests supplement the accelerated cavitation tests made during the years 1934 to 1937 by J. M. Mousson (1)* and S. Logan Kerr (2) who tested about all the materials available at that time which were suited for use on hydraulic machinery. The development of new materials and new techniques for the application of materials since 1937, some of which have unusually high resistance to pitting or other advantages when used where cavitation occurs, indicated the necessity for continous research of this type and resulted in the construction of the accelerated cavitation machine described in this article.

History of Cavitation

The following is a brief history of cavitation and the problems which brought about the development of accelerated cavitation machines.

Cavitation as used throughout this article is defined as the formation of voids within a body of moving liquid (or around a body moving in liquid) when the particles of liquid fail to adhere to the boundaries of the passageway. This occurs when there is insufficient internal pressure to overcome the inertia of the particles and force them to take sufficiently curved paths along a boundary which has a change or variation in shape.

Cavitation affects the operation of hydraulic machinery in various ways. It can cause a loss of power and efficiency by increasing resistance to the flow. It can produce noise and vibration and it can produce pitting which is defined as the actual erosion of material subjected to cavitation.

The phenomenon of cavitation was anticipated as early as 1754 by Leonhard Euler (3) in his theory on hydraulic turbines when he noted that an insufficient pressure in a perfect liquid can cause a divergence between theory and experiment and can result in zero resistance.

Some of the practical aspects of cavitation were first noted in connection with ship propellers operating at high speeds. Sidney W. Barnaby and Mr. Thorncroft, in a paper presented to the Institution of Civil Engineers in London in 1895, mentioned the occurance of a new phenomenon during propellor trials of *HMS Daring* (4). They noted the formation of cavities in water which tended to become filled with water vapor. This condition was held responsible for waste of power and other difficulties. About the same time Chas. A. Parsons (5) verified this by tests on the *S S Turbina* where loss of power on the first steam turbine driven propellers was traced to cavitation.

The first recorded indication that cavitation produced erosion or pitting of materials was in an article published in 1907 by W. Wagenbach (6), in which he described how the Francis turbine runners of the Jaice hydroelectric works in Bosnia failed after a few weeks operation in 1890. The runners were so badly eroded by cavitation that they had to be replaced. After this there were numerous reports of pitting, both on hydraulic turbine runners and on ship propellers.

However, the wide variation in the resistance of different materials, to pitting is a phenomenon that was first discovered during the 1920's. It is probable that prior to this period some engineers may have suspected such variations but there is no record of any published information on actual comparative tests.

J. Ackert in his handbook published in 1926 (7), reported the relative resistance of cast iron, cast steel and bronze to to erosion or pitting.

In 1924 the Allis-Chalmers Mfg. Co. fastened 15 patch plates of various types of materials to the back sides of the buckets near the discharge edge on a cast iron Francis runner furnished for the Isle Malign Plant in Quebec. An inspection of this runner after three and one half years of operation showed that patch plates of stainless steel resisted pitting to a remarkable degree as compared to the cast iron in the runner and as compared to other materials used in the remainder of the patch plates. About this time similar experiments with various materials including stainless steel were being made on hydraulic turbine runners in a number of other power plants. However, it was soon realized that using different types of material in a hydraulic turbine and then waiting a number of years for an answer was not a very satisfactory method of determining the degree of resistance to pitting of these materials. The time interval was entirely too long, and there was no satisfactory method for comparing materials tried in one turbine with those tried in another.

Therefore, starting about 1932 several types of machines were developed which were capable of producing accelerated cavitation whereby the resistance of various metals to pitting could be determined accurately under laboratory control within a reasonable period of time (8).

The earlier machines used the principal of passing water at a high velocity through a restricted area, followed by a

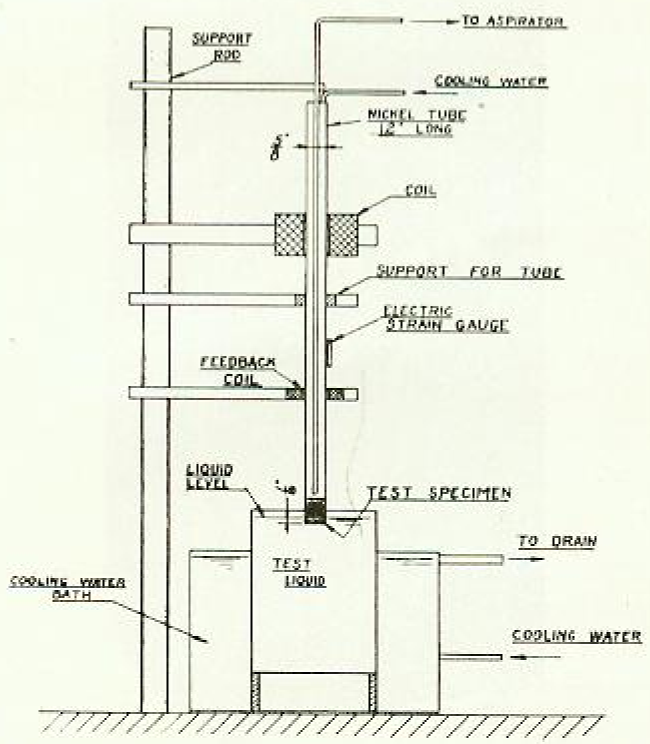

Fig. 1—Schematic layout of vibratory type accelerated cavitation machine.

*Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

sudden enlargement. This was known as the venturi tube type of machine.

In 1935, Dr. J. C. Hunsacker and Dr. H. Peters of Massachusetts Institute of Technology developed the vibratory method of accelerated cavitation. (9) (10) This is the method used for tests described in this article.

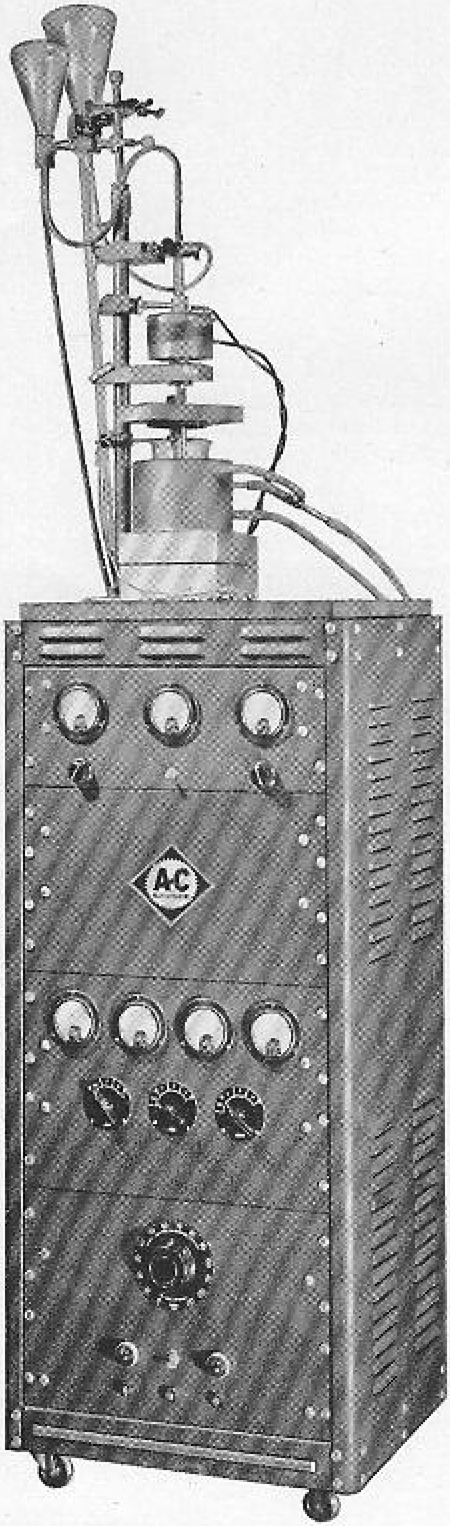

Fig. 2—Photograph of accelerated cavitation test machine.

Cavitation Machine

Figure 1 shows a schematic layout of the vibratory type of accelerated cavitation machine. Figure 2 is a photograph of the machine as built by the Allis-Chalmers Mfg. Co.

The apparatus follows the general description by S. Logan Kerr (2). It consists of a vacuum tube oscillator which produces an alternating magnetic field through the nickel tube. When the frequency of the magnetic field is the same as the natural longitudinal frequency of vibration of the nickel tube, the tube will vibrate at maximum amplitude in the longitudinal direction.

The test specimen Figure 3 is attached to the end of the tube and immersed in the test fluid to a depth of ⅛ in. Since the test fluid heats rapidly during a test run and since the rate of pitting varies considerably with the temperature of the fluid, the beaker containing the test fluid is set in a running water bath to maintain a constant temperature of 76 deg. plus or minus 1 deg.

Since the frequency and amplitude of vibration of the test specimen have considerable effect on the rate of pitting, provisions are made to control these quantities at all times. The frequency of course is determined by the length of the nickel tube. The vacuum tube oscillator circuit is tuned to the natural frequency of the nickel tube. All tests are made at a frequency of 6500 cycles per second this being the natural frequency of vibration of the nickel tube 12 in. long, with test button attached.

An electric strain gauge is attached to the nickel tube to measure the amplitude of longitudinal vibration. It is calibrated at frequent intervals by measuring the actual movement of the test specimen by means of a stroboscopic light and a microscope with micrometer scale. All tests are made with an amplitude of vibration of .0034 in. In this paper, the amplitude of vibration refers to the total travel of the test specimen. The criterion for rate of pitting is the loss of weight of the test specimen.

Method of Testing

As a check on the relative performance of the vibratory machine, it was decided to use a brass test specimen as a standard to be tested at frequent intervals. By comparing the rate of pitting of the various standard specimens, any serious deviation in the relative performance of the apparatus becomes apparent immediately.

At first cast bronze was used for this purpose. However, it was found that this material would pick up water and actually increase in weight during the first 30 minutes of testing. The standard test specimen was then changed to rolled brass, ASTM Specifications B-16-44, which gave satisfactory results.

However, since most materials, particularly cast materials have a tendency to pick up some moisture during the course of a 2 hour cavitation test, all of the test specimens are placed in boiling water for 30 minutes, before being tested and before being weighed.

All of the test specimens are carefully adjusted to the same weight within ½ gram. They are all weighed accurately to the nearest 1/10 milligram in a chemical balance scale. All specimens are weighed every 30 minutes during the test. It was found that the rate of loss of some of the metals increases for the first 60 to 90 minutes but after that period the loss approaches a fairly constant rate. The length of each test was therefore limited to 120 minutes. Figure 4 shows how the rate of loss of metal varied with

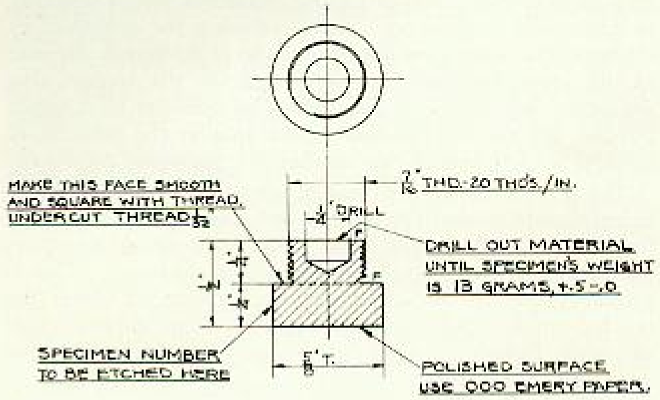

Fig. 3—Buttons used for test specimens in cavitation machine.

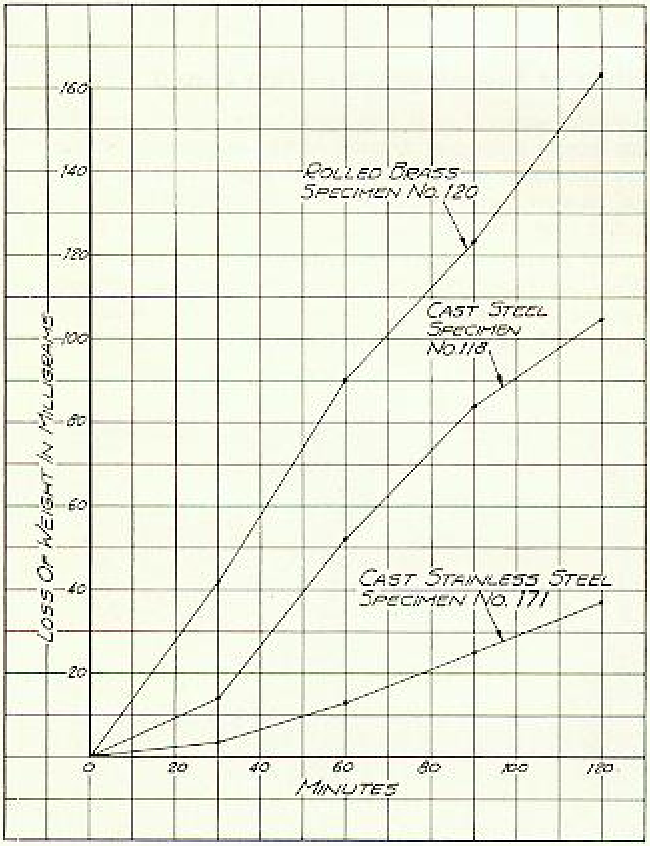

Fig. 4—Loss of weight of test specimens.

time. It was observed in several instances that a highly polished specimen had a slower rate of pitting during the first 60 minutes of testing than the same material with a dull finish. However, by the end of a 120 minute test the highly polished specimen would be pitting at the same rate as the duller specimen.

Effect of Amplitude of Vibration

An interesting series of tests was made on several materials to determine the effect on the rate of pitting by changing the amplitude of vibration of the test specimen. The construction of the accelerated cavitation machine made it possible to control the amplitude of vibration by controlling the power output of the vacuum tube oscillator. The amplitude was measured by means of the electric strain gauge fastened to the nickel tube. This strain gauge was calibrated at frequent intervals by means of a microscope micrometer. During these tests the frequency of vibration was the same as for all the tests described in this paper, namely 6,500 cycles per second.

Figure 5 shows how the amount of pitting decreased as the amplitude was decreased. There was very little difference in the rate of pitting between .0030 inches and .0035 inches amplitude. For this reason an amplitude of .0034 inches was selected for all the standard tests made on different materials to determine their relative resistance to pitting. Thus a slight variation in amplitude for different tests had very little effect on the relative rate of pitting of the test specimens.

The results of these tests indicate that a certain amplitude of vibration of the test specimen is needed to produce actual pitting, and that the magnitude of the amplitude required varies for different metals. The 18-8 rolled stainless steel type 302 required an amplitude of .0025 inches before pitting became appreciable. The cast steel specimen showed very little pitting below .0016 inches amplitude, and the brass specimen probably would have stopped pitting below .001 inches if the tests had been carried to such low values.

Apparently there is a difference in the minimum force required to produce pitting on different materials and changing the amplitude of vibration seems to change the forces that produce pitting. This experimental data corresponds to some of the field results, where cast iron or cast steel which pitted rapidly was replaced with stainless steel which did not pit at all under the same operating and cavitation conditions.

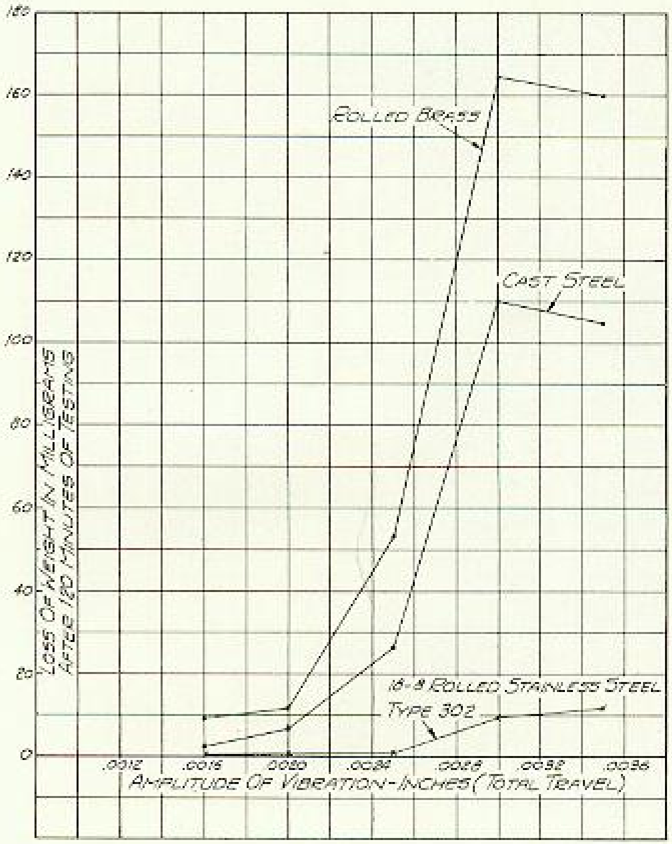

Fig. 5 — Effect of amplitude on vibration.

Just what the forces are that are created by the vibrating specimen and that produce pitting is still open to speculation. The maximum velocity of the test specimen when vibrating at 6,500 cycles per second, with an amplitude of .0034 inches is only 5.8 feet per second as computed from the sine wave formula

$$V = FA$$

Where V = Maximum Velocity
F = Frequency
A = Amplitude (full travel)

This velocity is much too low to produce any impact forces sufficient to cause pitting. However, the acceleration of the test specimen is quite high. At .0034 inches amplitude of vibration the maximum acceleration is 7,300 G's or about 235,000 ft. per second. It is possible that this high rate of acceleration is responsible for the forces that produce pitting.

The most logical explanation is the theory by R. T. Knapp and A. Hollander (11) that bubbles form in the cavitation region where the absolute pressure drops below the vapor pressure of the surrounding liquid. They actually demonstrated by high speed moving pictures that cavitation bubbles form in the liquid and then collapse at velocities up to 800 feet per second, depending upon the size of the bubble. These extremely high velocities of collapse produce pressures of approximately 50,000 pounds per square inch, but only over a microscopically small area.

Observation of the test specimens after having been tested at various amplitudes of vibration showed that the pitted area on the bottom of the button, and the depth of pitting decreased with a decrease in amplitude. One of the reasons why the depth of pitting decreases with a decrease in amplitude is apparent when observing the test fluid in stroboscopic light. As the amplitude is decreased the size of the vapor bubbles that form beneath the button also decrease. According to the theory of collapse of a vapor bubble, the smaller the bubble the smaller the velocity of collapse and therefore the smaller the pressures produced.

The reason for the decrease in pitted area with a decrease in amplitude is also apparent from observation of the test fluid under stroboscopic light. As the amplitude decreases the area covered by vapor bubbles also decreases. This is probably due to the lower vacuums produced under the test button at lower amplitudes, and therefore the formation of vapor bubbles over a large area is prevented by the surrounding pressure.

Further tests are being made in an attempt to determine what forces are being produced under the vibrating test specimen, or what is actually taking place that produces the pitting.

Effect of Submergence in Test Liquid

Another series of tests was made to determine the effect on the rate of pitting of various depths of submergence of the test specimen in the fluid. Tests were made on brass and on 18-8 cast stainless steel at various depths of submergence from ⅛ in. to 2 in.

The results of these tests are shown in figures 6 and 7. With the rolled brass specimen the material removed increased 25% with an increase of submergence from ⅛ in. to 2 in. With the 18-8 cast stainless steel specimen the material

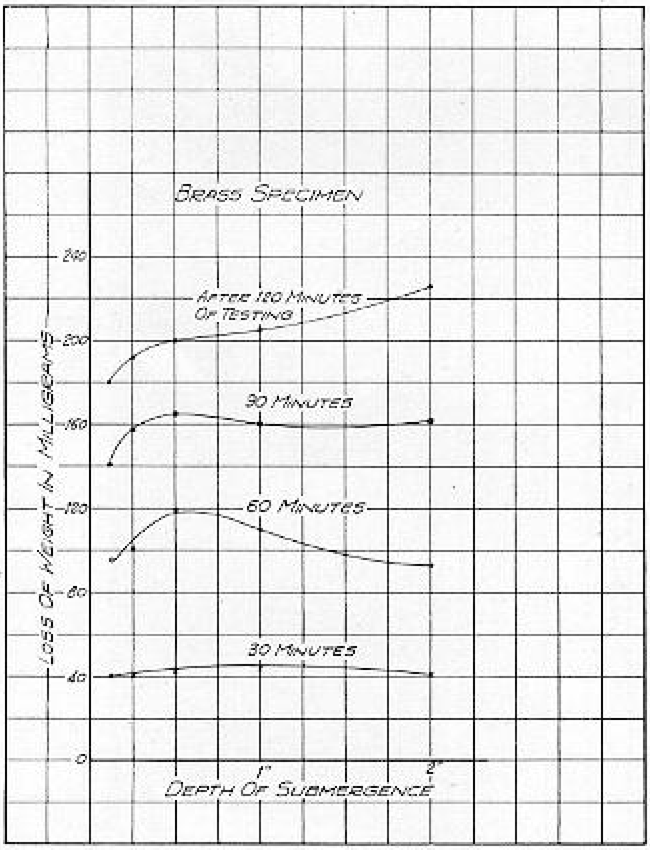

Fig. 6—Cavitation tests to determine effect of submergence on brass specimen.

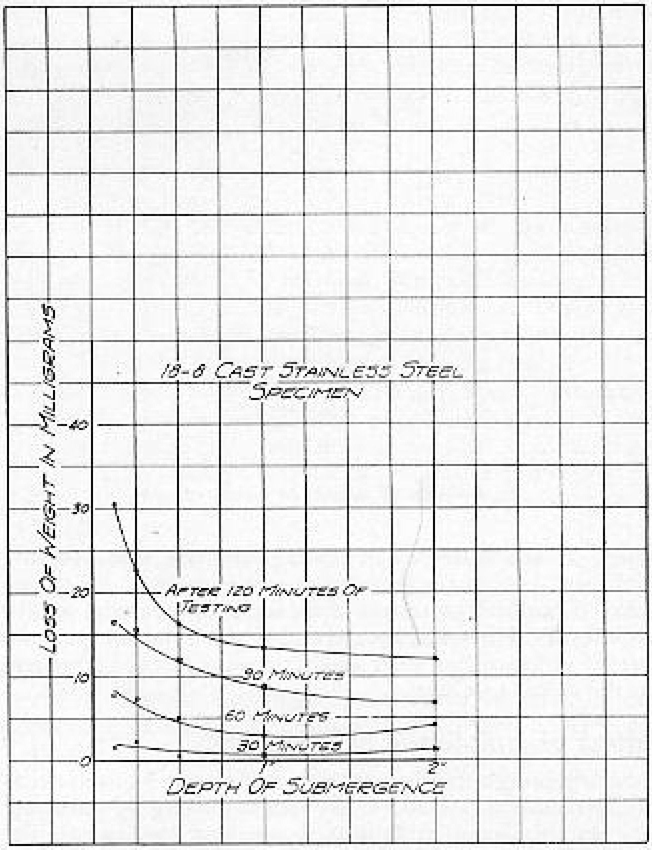

Fig. 7—Cavitation tests to determine effect of submergence on stainless steel specimens.

removed decreased 60% with an increase of submergence from ⅛ in. to 2 in.

On both the brass and the stainless steel the area of the pitted surface on the specimens increased with an increase in submergence. However, on the brass the depth of pitting remained about the same for all depths of submergence while on the stainless steel the depth of pitting decreased as the submergence was increased. Figure 8 is a photograph showing the pitting of brass and stainless steel at ⅛ in. submergence and at 2 in. submergence.

The reason why only the central portion of the specimen is erroded or pitted is not quite clear. As the test specimen vibrates, vapor bubbles form near the center of the bottom of the button and flow downward to the bottom of the container in a continuous stream. Figure 9 shows this action with a test specimen vibrated in oil. Air bubbles are also visible in the liquid. Apparently air is being drawn down along the side of the test button from the surface of the liquid. This air flows underneath the button to prevent formation of the vapor bubbles at the outer edges. As the depth of submergence of the test specimen is increased, the quantity of air drawn from the surface decreases, thereby permitting the formation of larger pitted areas on the test specimen. This flow of air is not visible on any of the photographs, but close observation with stroboscopic light indicates that air is actually being drawn from the surface of the liquid to the bottom of the vibrating test specimen.

The reason why the brass specimens pitted to the same depth at all depths of submergence and why the pitting on stainless steel decreased with an increase of depth, cannot be explained readily. It might be expected that pitting would decrease with increased submergency because with increased pressure, the formation of vapor bubbles decreases. It is possible that the severity of cavitation actually did decrease with an increase in submergence, but that the brass specimen was so susceptible to cavitation, that it was not very sensitive to a change in the cavitation forces, whereas the stainless steel was probably close to the borderline between pitting and not pitting and was therefore sensitive to any slight differences in the cavitation forces such as would occur due to an increase in the depth of submergence. This is similar to what occurred when the amplitude of vibration was decreased as shown in figure 5.

Effect of Different Test Liquids

One of the most interesting series of tests was made using different test liquids. Most of the standard tests to determine the relative resistance of different materials to pitting have been made in distilled water. S. Logan Kerr made some tests using salt water (2) which showed very little difference in the rate of pitting as compared to fresh water.

The present series of tests used liquids such as sulphuric acid, hydrochloric acid, oils and water treated with a chromate inhibitor. The materials tested were brass, stainless steel, cast steel and special cast irons.

Table 1 lists the results of tests on various cast irons when tested in distilled water and in water treated with chromate (Na3 Cr04.) The chromate solutions were alkaline, having a PH number of 8.6.

The purpose of these tests was to determine whether addition of an inhibitor such as chromate to water would reduce pitting. With the exception of the heat treated low

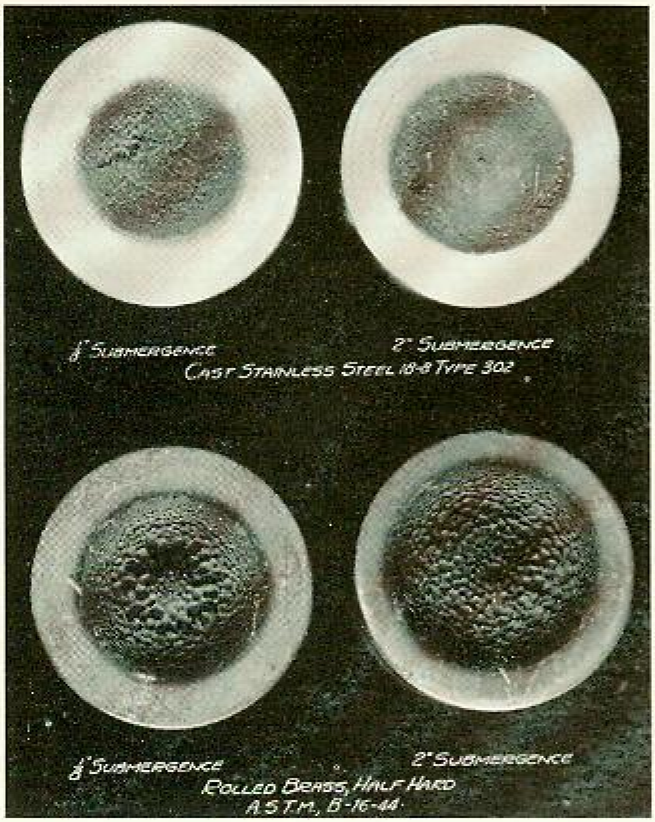

Fig. 8—Photograph of brass and stainless steel at ⅛ in. and 2 in. submergence.

Fig. 9—Photograph of specimen vibrating in oil.

Table 1 — EFFECT ON INHIBITOR IN TEST LIQUID ON RESISTANCE TO PITTING

MATERIAL	TEST LIQUID	Total loss in MG in 120 min.
Low Alloy Gray Iron, as cast—Rockwell A55	Water (distilled)	68
Low Alloy Gray Iron, as cast—Rockwell A55	0.2% Chromate ($Na_2 CrO_4$) 99.8% Water PH = 8.6	67
Low Alloy Gray Iron, as cast—Rockwell A55	0.4% Chromate ($Na_2 CrO_4$) 99.6% Water PH = 8.6	67
Low Alloy Gray Iron, Heat Treated—Rockwell A71	Water (distilled)	59
Low Alloy Gray Iron, Heat Treated—Rockwell A71	0.2% Chromate ($Na_2 CrO_4$) 99.8% Water PH = 8.6	36
Low Alloy Gray Iron, Heat Treated—Rockwell A71	0.4% Chromate ($Na_2 CrO_4$) 99.6% Water PH = 8.6	31
Type 1 Ni-Resist—Rockwell A43	Water (distilled)	136
Type 1 Ni-Resist—Rockwell A43	0.2% Chromate ($Na_2 CrO_4$) 99.8% Water PH = 8.6	115
Type 1 Ni-Resist—Rockwell A43	0.4% Chromate ($Na_2 CrO_4$) 99.6% Water PH = 8.6	122
Type 2 Ni-Resist—Rockwell A35	Water (distilled)	166
Type 2 Ni-Resist—Rockwell A35	0.2% Chromate ($Na_2 CrO_4$) 99.8% Water PH = 8.6	166
Tipe 2 Ni-Resist—Rockwell A35	0.4% Chromate ($Na_2 CrO_4$) 99.6% Water PH = 8.6	181
Type 3 Ni-Resist—Rockwell A42	Water (distilled)	133
Type 3 Ni-Resist—Rockwell A42	0.2% Chromate ($Na_2 CrO_4$) 99.8% Water PH = 8.6	130
Type 3 Ni-Resist—Rockwell A42	0.4% Chromate ($Na_2 CrO_4$) 99.6% Water PH = 8.6	115

alloy cast iron, none of the test results indicated that addition of chromate increased the resistance to pitting any appreciable amount.

However, since the Brinell hardness was determined for all of the test specimens it was noted that the loss of metal of the various materials after 120 minutes of testing varied with hardness. This is shown in figure 10 and despite the fact that this curve represents cast iron with various chemical compositions, there is a definite relation between hardness and resistance to pitting.

Table 2 lists the results of tests on half hard rolled brass bar stock using various solutions of sulphuric and hydrochloric acid and also oils. The first group of tests seemed to indicate that the greater the concentration of sulphuric acid the greater the resistance to cavitation. In the second series however, where both the water and the acid solutions were wetted to give approximately the surface tensions of the oils used, there seemed to be very little difference in the resistance to pitting between distilled water and various concentrations of acid. The biggest variation was found when oil was used as the test liquid. The results showed that there was a marked drop in loss of weight of the test specimen when vibrated in either mineral seal oil or transformer oil. A test was also made mixing the mineral seal oil with chloroform to increase the specific gravity and decrease the viscosity, bringing these values closer to that for water. This mixture showed an increase in the loss of weight of the test specimen.

Table 3 lists the results of tests on cast stainless steel, type 302. Again the acid solutions showed no marked increase or decrease but the test in the seal oil showed a big decrease in pitting.

Table 4 lists the results of tests on cast steel. These tests indicate a definite increase in loss of weight with the acid

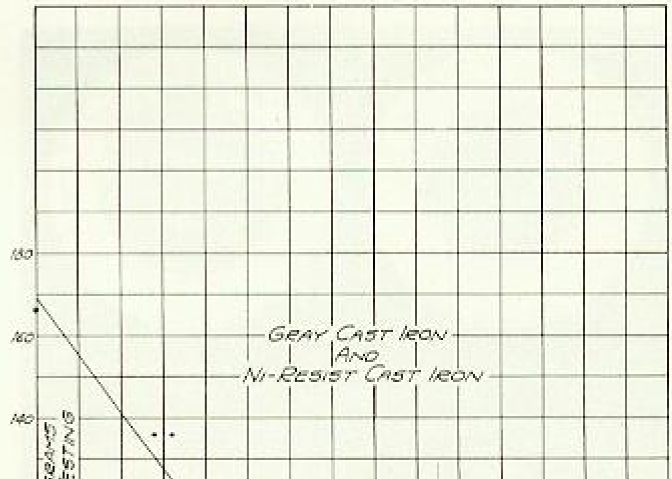

Fig. 10—Effect of hardness of cast iron on resistance to pitting.

Table 2 — **ROLLED BRASS BAR STOCK, ASTM, B-16-44, HALF HARD**

Cu. 60%, Zn. 27% PB. 3%, 90 Brinell

Test Liquid	PROPERTIES OF LIQUID		Total loss in MG in 120 min.
	Vapor Pressure ft H_2O	Surface Tension dynes/-cm.	
Water (distilled)	1.1	76.5	190
5% H_2SO_4, 95% H_2O	.8	76.1	174
25% H_2SO_4 75% H_2O	.7	71.2	154
50% H_2SO_4, 50% H_2O	.3	65.5	77
Water (wetted to reduce surface tension)	1.1	34.6	145
25% H_2SO_4, 75% H_2O (wetted)	.7	32.0	166
5% HCL, 95% H_2O (wetted)	....	49.1	156
25% HCL, 75% H_2O (wetted)	....	41.0	164
MINERAL SEAL OIL	....	32.3	1.2
MINERAL SEAL OIL & CHLOROFORM	....	31.5	39
TRANSFORMER OIL Spec. N-2698, Sun Oil Co. T-92304-6199 Sun X 2587	....	34.7	4.7
ETHYL ALCOHOL	2.6	21.7	17.7
CARBON TETRACHLORIDE	5.1	....	18.7
CHLOROFORM	9.0	26.7	18.0
ACETONE	10.2	23.3	12.3
TURPENTINE	0.2	27.1	4.6

Table 3 — **CAST STEEL, FED. SPEC. QQ-S-681 b CLASS 2 MED.**

Test Liquid	PROPERTIES OF LIQUID		Total loss in MG in 120 min.
	Vapor Pressure ft H_2O	Surface Tension dynes/-cm.	
Water	1.1	76.5	104.4
25% H_2SO_4, 75% H_2O (wetted)	.7	32.0	155.5
25% HCL, 75% H_2O (wetted)	....	41.0	146.0
MINERAL SEAL OIL & CHLOROFORM	....	31.5	6.9
ETHYL ALCOHOL	2.6	21.7	6.6
CARBON TETRACHLORIDE	5.1	....	1.6
CHLOROFORM	9.0	26.7	2.0
ACETONE	10.2	23.3	1.3
TURPENTINE	0.2	27.1	0.6

solutions. However, the acid solutions have a corrosive effect on cast steel and can cause an appreciable loss of weight due to corrosion alone, during the two hour test period. This static loss of weight of the test specimens in the acid solutions is shown in table 5. The brass and stainless steel loss due to corrosion is neglibible. However, when the static loss due to corrosion for cast steel is subtracted from the loss of weight of the test specimens, as determined during the cavitation tests, there again is an indication that the acid solutions do not effect the resistance to pitting.

The general conclusion from all of these tests is that acid solutions do not change the cavitation forces, and there is some evidence that the greater the acid concentration the smaller the amount of pitting. On the other hand when the test specimens are vibrated in oil, alchohol and other liquids the weight loss is greatly reduced. The explanation for this phenomena probably lies in the correlation between the rate of pitting, and the vapor pressure, and surface tension of the liquid. Plotting the rate of pitting against the vapor pressure with liquids of approximately equal surface tension showed a definite relationship. This is similar to the relationship Mosson (1) and Nowotny (13) found in their tests when changing the temperature of the water. Figure 11.

The experiments by Mousson were confined to the lower temperatures and vapor pressures, whereas Nowotny covered the entire range of temperature from freezing to boiling. The increase in rate of pitting with increase in temperature at the lower temperatures and the reduction in rate of pitting with higher temperatures as found by Nowotny seem to indicate that the vapor point, and the outside pressure are determining factors. This is indicated by the conditions of stability of the vapor bubbles whose

Table 4 — **CAST STAINLESS STEEL, TYPE 302 18% Cr, 8% Ni, 0.11% C.**

Test Liquid	PROPERTIES OF LIQUID		Total loss in MG in 120 min.
	Vapor Pressure ft H_2O	Surface Tension dynes/-cm.	
Water (distilled)	1.1	76.5	35
25% H_2SO_4, 75% H_2O (wetted)	.7	32.0	25
25% HCL, 75% H_2O (wetted)	....	41.0	48
MINERAL SEAL OIL & CHLOROFORM	....	31.5	2.1

Table 5 — **LOSS OF WEIGHT OF TEST SPECIMENS DUE TO CORROSION WHEN IMMERSED STATICALLY IN TEST LIQUID FOR 120 MINUTES**

MATERIAL	TEST LIQUID	Loss of Weight in MG in 120 min.
Rolled Brass, ASTM, B-16-44—Half Hard	25% H_2SO_4, 75% H_2O	0.3
	50% H_2SO_4, 50% H_2O	2.2
Cast Stainless Steel—Type 302	25% H_2SO_4, 75% H_2O	6.5
	25% HCL, 75% H_2O	5.2
Cast Steel—QQ-S-681b, Class 2 Medium	25% H_2SO_4, 75% H_2O	51.8
	25% HCL, 75% H_2O	67.3

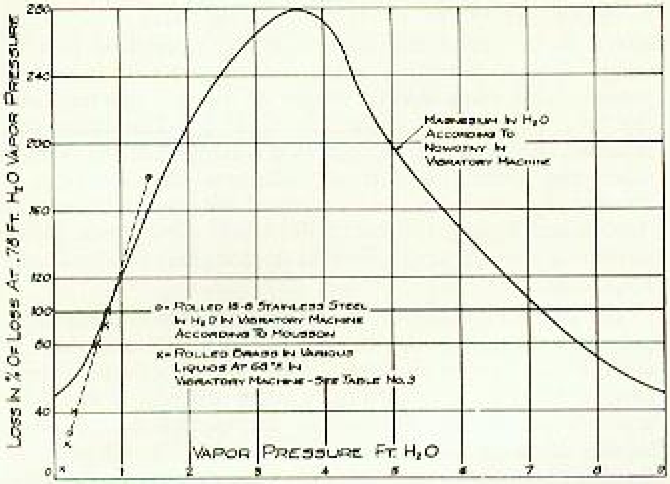

Fig. 11—Relation between vapor pressure and rate of pitting as measured by loss of metal in test specimen.

collapse produce the mechanical forces that cause pitting erosion. For equilibrium of a vapor bubble we have

$$P_i = P_e - \frac{2S}{r}$$

Where: P_i = internal pressure
P_e = external pressure
s = surface tension of the liquid
r = radius of the bubble

For boiling liquid the internal pressure is equal to the vapor pressure which is equal to the external pressure (where the liquid is boiled in an open container the external pressure is equal to the atmospheric pressure) or $P_i = P_v = P_e$ where P_v = vapor pressure). Under this condition the bubble continues to grow (r approaches infinity) and finally explodes. Since there is no possibility for the bubbles to collapse, the destructive forces are absent. Therefore, with the stability of the bubbles decreasing with decreasing pressure differences ($P_e - P_v$) and on the other hand with an increase in the number of bubbles and their collapse with increasing vapor pressure (increasing temperature) the relation between temperature and rate of pitting is indicated. Nowotny demonstrated this by making tests on aluminum test specimens in various alcohols and benzines, the boiling points of which were between 68 deg. and 136 deg. C. He found that at the boiling point, $P_e = P_v$, the test samples were not damaged regardless of the liquid used.

Nowotny also demonstrated that by keeping the liquid at constant room temperature, which was equivalent to keeping the vapor pressure constant, but changing the external pressure P_e, the limiting condition $P_e - P_v$ in general governed the rate of erosion. For high external pressures where the differential pressure $P_e - P_v$ was large, the test specimens were badly eroded. For low external pressures where the pressure differentials were small, $P_e - P_v = O$, no damage was visible.

As a further check, tests were made with the water at 100° C (boiling) but with an external pressure Pe of 2 atmospheres. This again produced pitting of the test specimen, which was quite natural since $P_e - P_v$ was greater than zero.

All these tests indicate defnitely that the destruction by cavitation does not depend merely on water hammer but depends upon bubble formation because with the vibratory machine, the liquid impact does not change with a change in external pressures P_e. The tests also indicate the reason for the various rates of pitting when using different liquids with different vapor pressures, as shown in tables 2, 3 and 4.

All of this adds to our knowledge of the Mechanics of Cavitation and shows that there is a definite similarity between the cavitation produced by Mousson with a Venturi type of machine and the cavitation produced with the vibratory machine used by the Author.

The tests with various liquids as shown in tables 2, 3 and 4 also seem to show that the surface tension of the liquid has an important influence on the degree of pitting. The greater the surface tension S the greater the damage. This is indicated by the nature of the bubble mechanism. The capillary energy of the bubble, $E = 4\pi (r_0)^2 S$, which released during the collapse of the bubble is a measure of the attack of each individual bubble. r_0 denotes the radius of the bubble before collapse. However, further investigations along these lines are necessary before a relationship between surface tension and rate of pitting can be definitely established.

Pitting Resistance of Various Materials

Tables 6 to 19 list practically all of the materials tested in the accelerated cavitation machine. These materials were tested at a depth of immersion of ⅛ in. in distilled water at 6500 cycles per second with a total travel amplitude of .0034 inches.

Cast and Rolled Stainless Steels

Table 6 lists tests on a number of cast stainless steels, which indicate quite a variation in resistance to pitting. Even cast stainless steels of the same type but cast in different foundries show considerable variation in their resistance to pitting. For example cast stainless steel type 302, which contains 18% chrome and 8% nickel showed losses of 12, 22 and 35 milligrams as furnished by 3 different foundries. This is a maximum variation of 300% in the resistance to pitting. Some of these variations may be due to the materials being cast for various purposes. Other causes for variations are the carbon content of the steel, where the specifications for a particular type permit a wide variation in carbon. The heat treatment of the casting and the hardness of the material also effect its resistance to pitting.

Table 7 lists the results of tests on 12%, 13% and 14% chrome cast steels with varying Brinell hardness. Figure 12 show the loss in milligrams during a two hour test in the accelerated cavitation machine plotted against Brinell hardness, where both the 12% and 13% chrome steel test specimens were taken from the same castings, and the variation in Brinell hardness was obtained entirely by changing the heat treatment of the two materials. These tests show the large effect that hardness of a material has on its resistance to pitting.

The large variations in resistance to pitting of the different cast stainless steel indicate the necessity for constant checks on such material when used in hydraulic machinery to assure that the desired resistance to pitting is being obtained.

Table 6 — CAST STAINLESS STEEL

Specimen No.	Cr %	Ni %	C. %	Heat Treatment	Type	Furnished by	Brinell Hardness	Total loss in MG in 120 min.
	MATERIAL							
159	18	8	0.12	As Cast	302	Midvale	...	12
103	18	8	0.12	As Cast	302	Midvale	...	13
137	27	10	0.26	As Cast	312	....	...	13
234	28	8	0.31	As Cast	...	American Brake Shoe	229	13
231	19	8	0.12	2050° F ½ Hr.	...	American Brake Shoe	156	17
228	19	9	0.06	2050° F 1 Hr.	...	American Brake Shoe	156	19
230	18	9	0.07	2000° F ½ Hr.	...	American Brake Shoe	136	19
229	18	9	0.04	2000° F ½ Hr.	...	American Brake Shoe	146	22
106	18	8	0.10	As Cast	302	Boney Floyd	...	22
107	17	12	0.10	....	316	....	...	24
233	18	14	0.08	2050° F 1 Hr.	...	American Brake Shoe	149	28
139	21	10	0.11	As Cast	307	....	...	31
168	18	8	0.11	As Cast	304	Allegheny Ludlum	...	33
167	18	8	0.11	As Cast	302	Allegheny Ludlum	...	35
232	18	10	0.07	2050° F ½ Hr.	...	American Brake Shoe	170	47
169	....	....	....	As Cast	327	Allegheny Ludlum	...	53

Table 7 — CAST CHROME STAINLESS STEEL

Specimen No.	Material	Cast by	Brinell Hardness	Total loss in MG in 120 min.
182	12.0% Chrome..............	Ohio Steel..................	302	20
108	12.0% Chrome, 0.10% C.......	....	...	22
196	13.0% Chrome..............	Allegheny Ludlum...........	306	25
207	13.1% Chrome..............	Ohio Steel..................	269	29
208	14.3% Chrome..............	Ohio Steel..................	269	34
212	14.0% Chrome..............	Ohio Steel..................	269	34
171	13.0% Chrome, 0.12% C.......	Allegheny Ludlum...........	...	38
213	14.1% Chrome..............	Ohio Steel..................	223	46
205	13.4% Chrome..............	Onio Steel..................	223	47
194	13.0% Chrome..............	Allegheny Ludlum...........	235	49
209	14.3% Chrome..............	Ohio Steel..................	223	49
210	14.1% Chrome..............	Ohio Steel..................	187	50
195	13.0% Chrome..............	Allegheny Ludlum...........	241	51
181	12.0% Chrome..............	Ohio Steel..................	225	54
193	13.0% Chrome..............	Allegheny Ludlum...........	229	57
170	13.0% Chrome, 0.12% C.......	Allegheny Ludlum...........	...	59
206	13.2% Chrome..............	Ohio Steel..................	187	64
192	13.0% Chrome..............	Allegheny Ludlum...........	207	70
180	12.0% Chrome..............	Ohio Steel..................	167	141

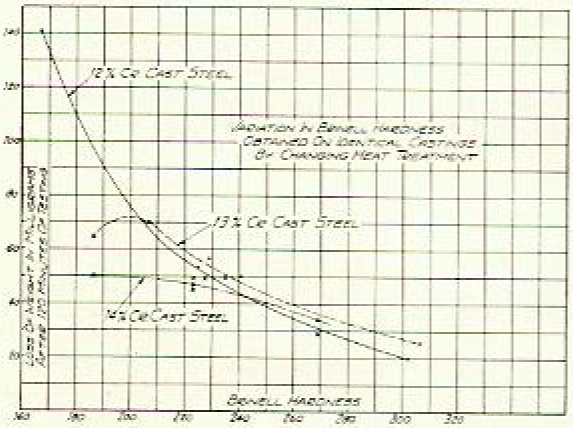

Fig. 12—Effect of Brinell hardness of cast chrome.

Table 8 — ROLLED ANNEALED STAINLESS STEELS

Specimen No.	Material	Total loss in MG in 120 min.
105	18% Cr., 8% Ni, 0.12% C., Type 302..........	8.0
157	18% Cr., 8% Ni, 0.12% C., Type 302..........	32

Table 8 lists the results of tests on rolled annealed stainless steel. The wide variation in resistance to pitting of the two rolled stainless steels of the same type is another reason for the necessity for making careful accelerated cavitation tests on all materials of this type before using them for the purpose of resisting pitting.

Welded Steels

Table 9 lists the results of tests on various welded materials. These tests also show a wide variation in resistance to pitting depending upon the type of material used.

Table 9 — **WELDED MATERIALS**

Specimen No.	Material	Brinell Hardness	Total loss in MG in 120 min.
248	Lincoln Abrasoweld	320	2.5
249	Arcos Chromend (16% Cr—7% Ni)	275	8.5
136	16% Cr, 7% Ni	...	9.4
250	Crucible steel—Rezistal WH	177	11
135	19% Cr, 9% Ni—Cb	...	13
252	Smith Co.—Smithway (18% Cr, 8% Ni)	137	23
251	Smith Co.—Smithway 159 (25% Cr, 20% Ni)	133	25
15	Lincoln A5	...	27
16	Stelco 604	...	27
254	Lincoln Stainweld D (25% Cr, 20% Ni)	145	27
256	Victor (G.E. Co.) W2310	136	29
258	Victor (G.E. Co.) W-23-8	134	31
257	Victor (G.E. Co.) W2310 Cb	142	32
134	19% Cr, 9% Ni—Cb	...	36
132	25% Cr, 12% Ni—Cb	...	36
14	130x INCO Monel	...	37
255	Crucible steel—Rezistal KA2S (19% Cr, 9% Ni)	134	37
245	Arcos Chromend K (19% Cr, 9% Ni)	130	38
247	Lincoln Stainweld A-7 (18% Cr, 8% Ni)	140	40
246	Lincoln Stainweld A5-Cb (18% Cr, 8% Ni)	133	41
133	25% Cr, 12% Ni—Cb and 19% Cr, 9% Ni—Cb	...	41
17	Lincoln Aerisweld AE-124K	...	55
253	International Nickel, Monel 140-x	116	89

Table 10 — **WELDED STAINLESS STEEL ON 12% CHROME STEEL**

Specimen No.	Material	Brinell Hardness	Total loss in MG in 120 min.
	Effect of Preheat on Base Metal		
188	18% Cr, 8% Ni on 12% Cr. Cast Steel Preheated to 600° F.	186	7.6
186	18% Cr, 8% Ni on 12% Cr. Cast Steel—No Preheat	195	7.8
187	18% Cr, 8% Ni, on 12% Cr. Cast Steel Preheated to 400° F.	195	8.0
184	12% Cr, on 12% Cr. Cast Steel Preheated to 400° F.	360	13
185	12% Cr, on 12% Cr. Cast Steel Preheat-600° F.	352	14
183	12% Cr, on 12% Cr. Cast Steel—No Preheat	347	16.8

Some of these materials such as Lincoln Abrasoweld showed a very high resistance to pitting. However, the Abrasoweld has such a high Brinell hardness that it is nearly impossible to grind or machine and its use is therefore quite limited. The tests indicated that the 16% chrome 7% nickel stainless steel also had very high resistance to pitting. This material can be ground and machined without too much difficulty.

Table 10 shows the results of tests on welded stainless steels when welded to 12% chrome either preheated or not preheated. These tests show that preheating of the base metal has very little effect on the resistance to pitting of the welded deposit.

In recent years there has been some difference of opinion among engineers as to the type of stainless steel welding rod to be used in prewelding or repairing hydraulic machinery for protection against the effects of pitting (erosion) due to cavitation. The most important differences have

Table 11 — **WELDED STAINLESS STEEL**

Specimen No.	MATERIAL: 1st Layer of Weld	MATERIAL: 2nd or Final Layer of Weld	Brinell Hardness	Total loss in MG in 120 min.
		1st SERIES		
203	17% Cr, 7% Ni, Type 301	...	308	10
201	18% Cr, 8% Ni, Type 308	...	160	23
198	25% Cr, 12% Ni, Type 309	...	145	26
204	17% Cr, 7% Ni, Type 301	17% Cr, 7% Ni, Type 301	255	6
199	25% Cr, 12% Ni, Type 309	18% Cr, 8% Ni, Type 308	145	31
202	18% Cr, 8% Ni, Type 308	18% Cr, 8% Ni, Type 308	151	33
200	25% Cr, 12% Ni, Type 309	17% Cr, 7% Ni, Type 301	175	35
		2nd SERIES		
237	17% Cr, 7% Ni, Type 301	17% Cr, 7% Ni, Type 301	196	7.2
241	17% Cr, 7% Ni, 1% Cb.	17% Cr, 7% Ni, 1% Cb.	355	11
236	18% Cr, 8% Ni, Type 308	17% Cr, 7% Ni, Type 301	167	14
235	18% Cr, 8% Ni, Type 308	18% Cr, 8% Ni, Type 308	166	19
242	17% Cr, 7% Ni, Type 301	18% Cr, 8% Ni, Type 308	161	19
238	25% Cr, 12% Ni, Type 309	18% Cr, 8% Ni, Type 308	166	20
240	18% Cr, 8% Ni, 1% Cb.	18% Cr, 8% Ni, 1% Cb.	185	23
239	25% Cr, 12% Ni, 1% Cb.	18% Cr, 8% Ni, 1% Cb.	168	27

Table 12 — CHEMICAL ANALYSIS OF TEST SPECIMENS

Speci-men No.	WELD ROD MATERIAL		Chromium	Nickel	Total Carbon
	1st Layer of Weld	2nd Layer of Weld (final layer)			
203	17% Cr, 7% Ni, Type 301	....	12.48	4.90	.09
201	18% Cr, 8% Ni, Type 308	....	16.45	7.80	.10
198	25% Cr, 12% Ni, Type 309	....	16.90	11.20	.12
204	17% Cr, 7% Ni, Type 301	17% Cr, 7% Ni, Type 301	15.80	6.50	.05
199	25% Cr, 12% Ni, Type 309	18% Cr, 8% Ni, Tipe 308	19.85	10.30	.06
202	18% Cr, 8% Ni, Type 308	18% Cr, 8% Ni, Type 308	19.56	9.70	.07
200	25% Cr, 12% Ni, Type 309	17% Cr, 7% Ni, Type 301	17.12	7.80	.10

Cast steel used for base metal.

been concerned with the composition of the welding rod, the number of layers of weld to be used, the amount of dilution of the weld deposit with the base metal and the effect of the presence of columbium in the weld rod.

To answer these questions, two series of tests (specimens 198 to 204, and specimens 235 to 242) were made on various combinations of stainless steel weld deposits. The results of these tests are shown in Table 11.

Since the investigation was primarily concerned with the prewelding and repair of hydraulic turbine runners, cast steel was selected for the base metal in the preparation of the test specimens.

These tests specimens were made by applying the stainless steel weld deposits to bars 10 in. long by 2½ in. wide by 1 in. thick, cast separately with steel conforming to Federal Specifications QQ-S-681-b, Class 2, medium, which is commonly used for hydraulic turbine runner castings.

Six types of standard commercial stainless steel weld rods as purchased from the Arcos Corporation, 1500 So. 50th St., Philadelphia, Pa. were used as follows:

Type 301, grade, 17% Cr, 7% Ni
Type 308, grade, 18% Cr, 8% Ni
Type 309, grade, 25% Cr, 12% Ni
Special, grade, 17% Cr, 7% Ni, 1% Cb
Special, grade, 18% Cr, 8% Ni, 1% Cb
Special, grade, 25% Cr, 12% Ni, 1% Cb

The chromium and nickel percentages refer to the commercial weld rod designation and do not refer to the chemical analysis of the weld deposit.

After the test specimens were welded, they were ground to a smooth finish. The Brinell hardness of each specimen was then determined. For the first series of tests, standard bend tests were made on each of the test specimens, and a chemical analysis was made of chips taken from the uppermost weld deposit of each specimen.

The results of the accelerated cavitation tests on the 1st series of specimens show that two layers of type 301 stainless steel welds have considerably greater resistance to pitting than any of the other combinations of welds. These tests also show that two layers of weld give greater resistance to pitting than one layer.

Table 12, shows the chemical analysis of the uppermost layer of the weld deposit on the test specimens of the 1st series of tests. This table shows that there is considerable dilution of the weld deposit when placed upon the base metal. Another interesting observation is that the weld deposit with an actual content of 16% chrome and 6½% nickel has the highest resistance to pitting. Welds with chrome and nickel contents above and below these figures seem to be more susceptible to cavitation. This is in general accordance with the test results obtained by J. M. Mousson (1) as well as with test results on various welded materials as listed in table 9.

The bend tests made on the welded bars of the 1st series of specimens indicated that the use of only one layer of type 301 weld deposit resulted in lower bend angles, and therefore lower ductility than with one layer of either type 308 or type 309. The bend tests also indicated that two layers of weld regardless of the combination, resulted in definitely higher bend angles and therefore greater ductility than 1 layer of any type of weld deposit. The bend angles obtained with two layers of weld indicated satisfactory ductility considering the fact that the weld is a protective coating and not subject to high stresses.

Since there was considerable variation in the resistance to pitting of the various weld combinations in this 1st series of tests, it was decided to conduct a second series of tests, using various combinations of welds, as well as making tests on stainless steel deposits made with weld rods containing from 0.8 to 1.0% columbium.

The first series of tests had indicated that two layers of weld had a higher resistance to pitting, and had greater ductility than one layer. Also from the practical standpoint, two layers of weld deposit are always desirable for prewelding and repairs so as to insure a thorough coverage of the surface being prewelded or repaired. Therefore, all test specimens in the second series of tests had two layers of weld.

The results of the accelerated cavitation tests on this second series of specimens 235 to 242 are shown in table 11. The 2nd series again indicates that two layers of 17% Cr, 7% Ni, type 301 stainless steel weld have a greater resistance to pitting than any other combination of weld deposits. The addition of columbium did not increase the resistance to pitting of any of the types of weld rods tested. Nor was there any indication that the addition of columbium made the welding process easier. In fact the the presence of columbium sometimes makes welding with stainless steel rod quite difficult. Columbium also seems to have the effect of greatly increasing the hardness of the 17% Cr, 7% Ni, weld deposit as shown in table 11. This makes it difficult to machine and grind.

Although two layers of 17% Cr, 7% Ni, type 301 stainless steel weld show a very high resistance to pitting, it has several undesirable characteristics when welded directly to a mild carbon steel base. The stainless steel weld has a tendency to dilute with the carbon steel until it is no longer austenitic. It thus may form a boundary layer of martensite steel between the base metal and the weld which is extremely hard and brittle. If subjected to high stresses,

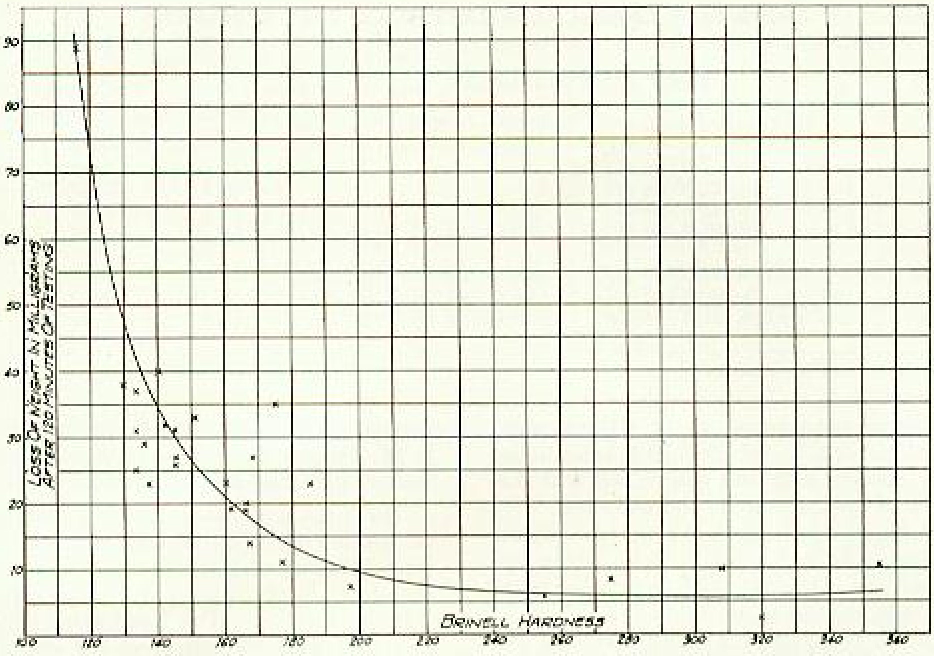

Fig. 13—Effect of hardness of various welded materials on resistance to pitting.

cracks may develop in the martensite boundary layer and spread into both the welded surface and the base material.

However, further tests and experimental data will be required before definite conclusions can be made regarding such characteristics.

Welds with higher chrome and nickel contents have less tendency to form such a martensite boundary layer. 25% Cr, 12% Ni, stainless steel weld as a first layer should eliminate the possibility of a martensite boundary layer, if proper welding technique is used. However, the use of 25% Cr, 12% Ni, as a first layer and 17% Cr, 7% Ni, as a second layer does not have the high resistance to pitting that two layers of 17% Cr, 7% Ni have. It is possible that by using 25% Cr, 12% Ni for a first layer and then using two layers of 17% Cr, 7% Ni, a higher resistance will be obtained. Tests along these lines are now being made.

The conclusions that can be made based on the two series of tests are as follows:

1. Two layers of weld give better protection and have greater resistance to pitting than one layer of weld deposit.
2. The use of 25% Cr, 12% Ni, type 309 stainless steel as a first layer of weld tends to reduce the resistance to pitting of the weld deposits.
3. The addition of columbium to the weld rods has no beneficial effects as far as resistance to pitting is concerned.
4. Two layers of 17% Cr, 7% Ni, type 301 stainless steel weld gives the greatest resistance to pitting.
5. If the weld will be subjected to high stresses, 25% Cr, 12% Ni type 309 stainless steel should be used as a first layer so as to prevent the formation of a martensite boundary subject to the formation of cracks.

Based upon these conclusions it is recommended that two layers of 17% Cr, 7% Ni, type 301 stainless steel weld rods be used for pre-welding and repairing all hydraulic turbine machinery subject to strong pitting due to cavitation, where the welds and the base materials are not subject to high stresses. Where high stresses exist, it is recommended that 25% Cr, 12% Ni, type 309 stainless steel be used for a first layer. The use of weld rods containing columbium is not recommended.

It is interesting to note that for all the welded materials listed in tables 9, 10 and 11, there is a definite relationship between resistance to pitting and hardness, even though a wide variety of materials was used. This is shown in figure 13. For a Brinell hardness between 130 and 180 there is apparently quite a variation in the resistance to pitting depending upon the type of material used. However, the general trend seems to be the harder material, the greater the resistance to pitting. There also seems to be a definite upper limit in this respect. In other words any increase in Brinell hardness beyond 200 to 240 does not materially increase the resistance to pitting.

Table 13 — SPRAYED STAINLESS STEELS

Specimen No.	Material	Total loss in MG in 120 min.
12	Metco Metcaloy No. 2	72
11	Metco Metcaloy No. 1	98
112	18% Cr, 8% Ni, Type 302	187
116	13% Cr, Type 420	192
179	Metcaloy No. 2	216

Table 14 — CAST STEELS

Specimen No.	Material	Total loss in MG in 120 min.
178	Fed. Spec. QQ-S-681 b Class 2 Medium	88
158	Fed. Spec. QQ-S-681 b Class 2 Medium	104
118	Fed. Spec. QQ-S-681 b Class 2 Medium	105

Table 15 — **BRONZES**

Specimen No.	Material	Total loss in MG in 120 min.
	AMPCO ROLLED BRONZES *(Furnished by Ampco Co.)*	
111	Ampco No. 18 (extruded) Brinell 190.........	12
	AMPCO CAST BRONZES *(Furnished by Ampco Co.)*	
160	Ampco No. 20 Brinell 235..................	5.8
161	Ampco No. 21 Brinell 285..................	6.2
162	Ampco No. 22 Brinell 340..................	9.5
125	Ampcoloy 46 Brinell 190...................	9.9
124	Ampco No. 18 Brinell 170..................	12
121	Ampcoloy A3 Brinell 130...................	22
	WELDED AMPCO BRONZES *(Furnished by Ampco Co.)*	
163	Ampcotrode 200 on SAE 1010 steel, Brinell 220	3.2
164	Ampcotrode 250 on SAE 1010 steel, Brinell 260	5.3
126	Ampcotrode 160 on SAE 1010 steel, Brinell 185	5.2
127	Ampcotrode 160 on Ampco 18, Brinell 185...	5.9
165	Ampcotrode 300 on SAE 1010 steel, Brinell 320	9.5
128	Ampcotrode 160 on Ampcoloy 46, Brinell 180.	20
123	Ampcotrode 10 on SAE 1010 steel, Brinell 140	24
122	Ampcotrode 10 on Ampcoloy A3, Brinell 140..	31

Sprayed Stainless Steels

Table 13 lists the tests on various sprayed stainless steels. These tests indicate that although some of the sprayed stainless materials had a resistance about equal to cast steel, others pitted very rapidly. These differences are probably largely due to the method of application of the sprayed metal which accounts for the variance in field reports as to their effectiveness. Quite a number of the test specimens had to be scrapped before the two hour test period was completed because the sprayed metal would separate from the base. The high acceleration (about 7,300 G's) of the vibratory test is a severe test on the adhesion of the metal.

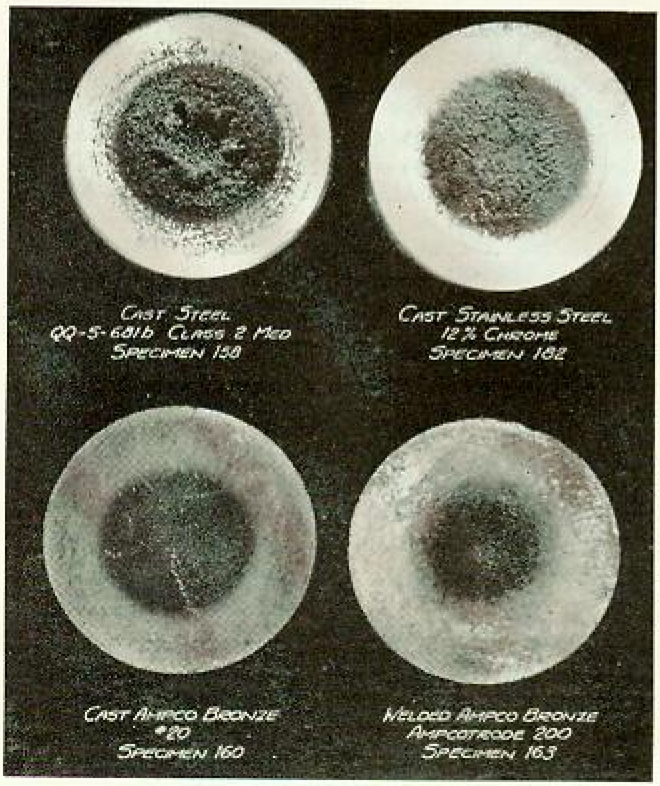

Fig. 14—Photograph of cast and welded Ampoc bronze.

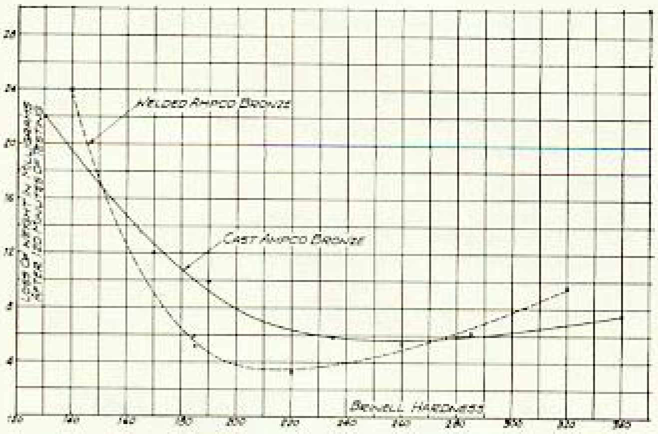

Fig. 15—Effect of hardness of Ampco bronzes on resistance to pitting.

If the sprayed material is carefully applied it seems to have about the same resistance to pitting as cast steel, but considerably less resistance than a properly welded stainless steel. In general the application of sprayed metal is cheaper than welding with mild or stainless steel, and it sometimes proves to be a satisfactory means of repair where pitting is not very severe, and where speed of application and low initial costs are a factor.

Cast Steels

Table 14 lists the results of tests on the cast steel most commonly used for hydraulic turbine runners. The tests on three castings from three different foundries do not show any appreciable variation.

AMPCO Bronzes

Table 15 lists an interesting series of tests on Ampco bronzes. Ampco is the trade name for a bronze with an aluminum content varying from 10% to approximately 14%. The Brinell hardness increases as the aluminum content increases. The results of the tests on the cast bronzes show that some of them have twice the resistance to pitting compared to the best stainless steel castings. The welded bronzes also show a remarkable resistance to pitting. Figure 14 shows photographs of cast and welded Ampco bronze test specimens. Figure 15 shows how the resistance to pitting of these materials varies with hardness. This curve shows that while the resistance to pitting increases with hardness there is a maximum point beyond which resistance to pitting decreases with increased hardness. This same trend can be noticed for welded materials of all types shown in Figure 13. The maximum hardness for best resistance to pitting seems to be about the same for both groups of materials.

Unfortunately there is very little information as to how these bronzes either cast or welded stand up under field conditions, which is really the final criterion. In one instance bronze patch plates were alternated with ordinary bronze on the back sides of the blades of a hydraulic turbine runner. After a period of operation the ordinary bronze patch plates had pitted to a considerable extent, while the Ampco bronze showed very little signs of pitting. Several Ampco bronze runners have been manufactured and

Table 16 — **WELDED COLMONOY**

Specimen No.	Material	Total loss in MG in 120 min.
	(Colmonoy furnished by Wall Colmonoy Co.)	
148	Colmonoy WER-100 Arc welded	6.0
145	Colmonoy No. 6 Arc welded	8.4
129	Colmonoy—2 layers gas welded	19
130	Colmonoy—1 layer gas welded	23
147	Colmonoy No. 5 arc welded	23
146	Colmonoy No. 4 arc welded	29

Table 17 — **COLMONOY SPRAYED AND THEN FUSED TO BASE**

Specimen No.	Material	Total loss in MG in 120 min.
144	Colmonoy No. 6	8.0
156	Colmonoy No. 6	9.5
143	Colmonoy No. 5	16
141	Colmonoy No. 4	30
151	Colmonoy, Sweat-on-Paste, Arc Application	30
150	Colmonoy, Sweat-on-Paste, QXI-ACETYLENE APPLICATION	34

are now in operation, but the period of operation has not been long enough to determine their resistance to pitting under field conditions.

Certainly the tests of the Ampco bronzes in the accelerated cavitation machine warrant experimenting with this material in field installations.

Colmonoy

Table 16 lists tests made on welded Colmonoy. The tests show that some types of welded Colmonoy have a high resistance to pitting.

Table 17 lists Colmonoy sprayed onto a base and then fused on at a temperature of 1850 deg. F. These tests show that some of these materials also have a high resistance to pitting.

Colmonoy is a trade name for a material consisting primarily of iron, nickel, chromium, borium, silicon and carbon. Before applying Colmonoy as a spray, the base metal is thoroughly grit blasted. The Colmonoy is then sprayed uniformly over the grit blasted area to a thickness of approximately .060 in. The sprayed area is then heated with an oxy-acetylene flame or in a heat treating furnace to a temperature of 1850 deg. F. Colmonoy has the property of becoming very plastic at this temperature thereby fusing itself to a grit blasted area.

Table 18 — **THIOKOL RUBBER**

Specimen No.	Material	Total loss in MG in 120 min.
Navy	*(Furnished by U. S. Navy)*	
No. 2	Flame sprayed on stainless steel	26
No. 4	Flame sprayed on stainless steel weld inlay	28
No. 10	Flame sprayed on manganese bronze	30
No. 8	Flame sprayed on mild welded steel	31
No. 6	Flame sprayed on mild steel	33

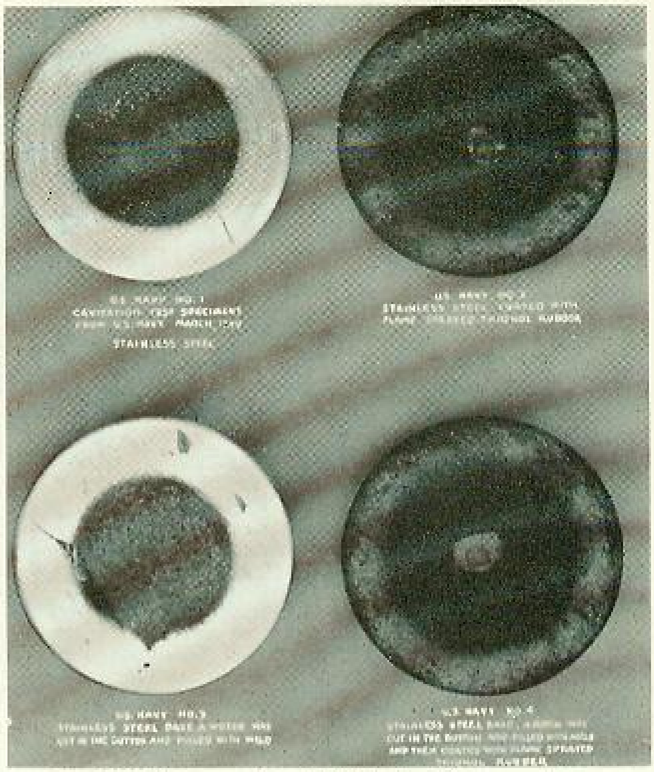

Fig. 16—Photograph of Thiokol rubber specimens.

The author knows of no field tests on this material but based on the results in the accelerated cavitation machine, it merits consideration. One advantage is the ease of application, whereby the material is sprayed on and then fused with a torch or in an oven. However, the fusing process presents the problem of possible distortion of the base metal. The cost of the Colmonoy material may also be a detriment to its general use to prevent pitting.

Several test buttons were prepared by spraying Colmonoy to a base, but eliminating the fusing process. It was impossible to obtain any pitting data on these specimens because the sprayed material separated from the base during the vibration tests.

Thiokol Rubber

Table 18 lists tests made on Thiokol rubber sprayed on various materials used for a base. The test specimens were prepared by the U. S. Navy. The loss of weight of the test specimens is not a very satisfactory means for determining the relative resistance of rubber because of its low specific gravity compared to metal. However, visual inspection of the test specimens indicated that the rubber overlay gave considerable resistance to pitting. Figure 16 shows a photograph of several of the rubber overlays after two hours testing in the accelerated cavitation testing machine. These photographs show how the center of the rubber overlay is eroded down to the base metal. The composition of the base metal apparently has very little influence on the resistance of the rubber to pitting, as is indicated in table 18.

The U. S. Navy has used this rubber overlay with considerable success on propeller shafts, rudders and struts of navy vessels where pitting was being encountered.

Table 19 — **MISCELLANEOUS MATERIALS**

Specimen No.	Material	Brinell Hardness	Total loss in MG in 120 min.
Special	Stellite, Haynes No. 6, Rolled	410	0.6
217	Vascaloy—Ramet, Tangtung-G	640	1.6
216	Ohio Die	601	2.5
214	Nestro	668	4.6
215	Vasco Supreme	657	6.2
166	Nitraloy—Holcomb No. 218	...	14
Navy No. 9	Manganese Bronze	...	80
Navy No. 7	Welded Mild Steel	...	97
Navy No. 5	Mild Steel	...	107
119	Brass, 70% Co, 30% Zn	...	156
120	Rolled Brass B-16-44 Half Hard Bar Stock used for Standard Check of Cavitation Machine Cu. 60%, Zn, 27% Pb. 3%	90	162

One of the important features of the successful use of rubber overlays is proper application. The U. S. Navy sand blasts the base metal to obtain a clean surface. The metal is heated to a temperature somewhat above the surrounding air temperature. The rubber is then sprayed on with a gun using the powder and gun developed by the Schori Process Corporation.

The results of the tests in the accelerated cavitation machine and the results obtained by the Navy under actual operating conditions, indicate that it might be desirable to investigate the performance of this rubber when used for hydraulic machinery parts subject to pitting.

Miscellaneous Materials

Table 19 lists some miscellaneous materials tested in the accelerated cavitation machine. This table shows that Stellite has by far the greatest resistance to pitting of all of the materials tested, which agrees with the results obtained in other accelerated cavitation machines.

The Stellite used in the present test was a rolled material consisting of 55% cobalt, 33% chrome, and 6% tungsten with a Brinell hardness of about 410. The Stellite was braised to the base metal with silver solder. Stellite can be obtained as a casting and can also be applied by welding. Its disadvantage for ordinary hydraulic machinery is its high cost, and the difficulty of machining and grinding it because of its extreme hardness. However, it has been used successfully for steam turbine blading where the erosion problems are somewhat similar to pitting in hydraulic turbines.

The other materials (specimens 217, 214 and 215) which show such a high resistance to pitting are all special alloy tool steels with a hardness which makes them unsuited for ordinary hydraulic turbine parts. They have their place however for special applications.

Conclusions

The tests on variation in amplitude of vibration, on variation in depth of submergence and with various liquids, answered some of the questions regarding the phenomena of cavitation. Although these tests were not always conclusive, they indicated the type of additional investigations that should be made.

The standard accelerated cavitation tests were made mostly on standard trade materials to determine the qualities of materials readily available to the industry. These tests showed the following:

1. That new materials such as the Ampco bronzes, Colmonoy and Thikol rubber are constantly being developed which might be suitable for hydraulic machinery and might have a distinct advantage over the materials now in use.
2. That the practical application of the materials, such as number of layers to be used when making repairs by welding or when prewelding, influences the resistance to pitting whereas preheating the base metal has very little effect on the resistance.
3. That hardness has a definite effect on resistance to pitting regardless of the material being used.
4. That it is important to make constant accelerated cavitation tests on the special materials, particularly stainless steels, to insure obtaining the desired resistance to pitting.

The results of all of the tests showed that the accelerated cavitation machine is a very useful machine to:

1. Make further investigations on the phenomena of cavitation.
2. Test new materials and new techniques of application of materials for their relative resistance to pitting.
3. Test samples of all special materials to determine their resistance to pitting to avoid the wide variation of these qualities when the materials are obtained from different sources.

Although items 2 and 3 constitute practically a full time test program for an accelerated cavitation machine, any suggestions as to how it can be used for advancing the knowledge of the mechanics and phenomena of cavitation and pitting are welcomed.

Acknowledgments

All of these accelerated cavitation tests were made possible through funds provided by the Allis-Chalmers Manufacturing Company. The Research Laboratory of this Company built the cavitation machine and kept it in operation. The tests were made under the direction of the Hydraulic Department.

The Ampco bronze test specimens were provided by the Ampco Metal Company, Milwaukee, Wisconsin.

The Colmonoy specimens were furnished by the Wall Colmonoy Corporation, Detroit, Michigan.

Cast stainless steel specimens were provided by Allegheny Ludlum Steel Corp., Brackenridge, Pennsylvania, Ohio Steel Foundry Company, Lima, Ohio and Midvale Co., Midvale, Pennsylvania.

The Thiokol rubber specimens were supplied by the Material Laboratory, New York Naval Shipyard, Naval Base Station, Brooklyn, New York.

The Cast iron specimens for the tests with the chromate inhibitor were supplied by the International Nickel Company, New York, New York.

The author is indebted to those companies for making the facilities available for the tests, for furnishing test specimens and for permission to publish the test results.

Discussions

When this article was presented at the annual meeting of the A.S.M.E., November 29, 1949, a number of discussions were presented. Some of these discussions are reprinted below.

W. R. MacMammee*—Another source of damage to hydraulic equipment which frequently combines with cavitation is erosion. This is usually not serious as long as

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clear water is used, but when water at high velocities also carries in suspension hard material, such as sand, damage can be very rapid and severe.

Such conditions are not uncommon in South America, where the volcanic nature of much of the country, plus a rainy season of heavy and prolonged rainfall, combine to carry off large quantities of very finely divided solids of an abrasive nature.

The writer's company and the Braden Copper Company have been engaged in a program of materials testing to evaluate both standard and new materials under cavitation and erosive conditions.

The test program was carried out at the Pangal Plant of the Braden Copper Company, in Chile, where the nature of the water flow varies from clear water in the dry season to water heavily laden with silt in the rainy season.

By subjecting samples of various materials to a high-velocity jet of clear water, the resulting damage could be considered due to cavitation. During the rainy season, when turbid water was used, the rate of removal of test material was five to ten times as great, and was no doubt due to erosion by the sand particles.

A jet of water ½ in. diam. under 650 psi pressure was directed against the test specimen. The angle between the jet and the test specimen was 15 deg. A hole ¼ in. diam. was purposely placed in each specimen at the point of impingement to produce severe cavitation. Two spots on the specimen downstream form the hole were typical of the patterns produced by cavitation in the clear-water tests. When tests were made with turbid water, the damaged area usually showed a smooth, though irregular surface, quite different from the characteristic pockmarks of cavitation.

For metals, the time of exposure to the jet varied from a few hours for the soft steels to 20 days for the hardest alloys.

As might be expected, the hard, strong materials were most resistant to erosion as well as to cavitation. The Colmonoy alloys, mentioned by the author, were outstanding in their excellent resistance to erosion. In general, materials showing good resistance to cavitation in the clear-water tests also performed well under erosive conditions with turbid water.

It was noted, however, that 18-8 stainless steel, which resisted cavitation far better than mild steel, performed but little better when erosion was combined with cavitation. It may be that the ability of 18-8 to work-harden was an important factor in this result. The repeated blows sustained under cavitation conditions may produce local work-hardening to a much greater degree than the cutting action of sand particles in the water.

The straight chromium steels of about 14 percent chromium, heat-treated, were especially good in resisting erosion.

As tested here, rubber proved completely disappointing. Two samples, consisting of ⅛ in. rubber, vulcanized to steel plate under factory conditions, were tested with clear water only. Each failed in less than one min. Each time a strong odor of burned rubber was noticeable, and bits of rubber in the pit had the appearance of being charred. It appears that impingement of the jet produced sufficient working of the rubber to cause destructive internal heating.

One unexpected variable developed in these tests when it was discovered that the rate of pitting and erosion varied with barometric pressure, low pressure definitely accelerating removal of material.

B. G. Rightmire*—The experiments on the effect of amplitude, depth of immersion, and kind of liquid raise a number of interesting questions that the author has discussed qualitatively. In particular, he has suggested that air drawn in from the free surface reduces the damaged area more and more as the depth of immersion decreases. This explanation appears unlikely to the writer, for two reasons: a) The air bubbles that appear initially under the vibrating specimen do not continue to form after dissolved gas has been partially removed, as by an extended period of vibration. b) At small depths of immersion the free surface of the liquid near the vibrator is slightly elevated, indicating a mean pressure at the rim of the specimen *greater* than that at the same depth in the distant liquid.

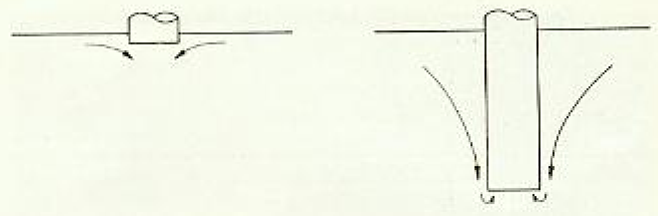

Fig. 17—Flow of liquid below test specimen according to Rightmire.

In the writer's opinion, the flow set up by the vibrator suffices to explain the observed effects of depth of immersion. This flow can be visualized by imagining the vibrating member to be replaced by a pipe that alternately injects and removes liquid. When removing liquid, the pipe acts approximately like a point sink; that is, the flow tends to be radially inward toward the open end of the pipe. On the other hand, when the pipe discharges liquid, a jet is formed, separated by a surface of discontinuity of velocity from the surrounding liquid. The rapid alternation of these two tendencies results in a general circulatory flow exhibiting a high outward velocity along the normal to the vibrating surface and a low return velocity along the walls of the container, in accordance with the requirements of continuity.

If the depth of immersion is small compared with the diameter of the vibrating member (⅛-in. immersion), the velocity field of this circulation will be as shown in Figure 17a. Figure 17b shows the velocity field if the depth is large compared with the diameter (2-in. immersion). The chief difference between these two fields is at the rim of the specimen, where the tendency for separation when the specimen moves upward is obviously greater in Figure 17b. One would thus expect the damaged area to be greater, the larger the depth of immersion.

Further tests along these fundamental lines can be planned and analyzed more effectively if the independent variables that are suspected to be of greatest importance are listed and a dimensional analysis made. Thus, one may assume here that, for a given air content and a given material, the independent variables are as follows:

A the amplitude of vibration, in.

f the frequency of vibration, cps.

R the density of the liquid, lb $sec^2/in.^4$

$p - p_v$ the difference between the pressure at the specimen and the vapor pressure of the liquid, $lb/in.^2$

v the kinematic viscosity of the liquid, $in.^2/sec.$

d the diameter of the specimen, in.

h the depth of immersion, in.

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The dependent variable may be conveniently taken as the volume loss of the material at the end of a given period of vibration, V. A dimensional analysis shows that one possible arrangement of the variable is

$$\frac{V}{A^3} = \text{function of} \left(\frac{P - P_V}{Pf^2 A^2}, \frac{f A^2}{V}, \frac{d}{A}, \frac{h}{A} \right)$$

Two series of tests probing the effect of the first two dimensionless variables (cavitation number and Reynolds number) were made several years ago at M. I. T. It is hoped that the results will soon be released for publication.

Wilhelm Spannhake†—The consistent tests and their most interesting and practically important results remind the writer of a series of experiments which he initiated at the Technical University of Karlsruhe, Baden, Germany, in 1939. They have been carried through by Dr. Hans Nowotny and were published in 1942. (13) These tests gave similar results for the curves showing the relationship between the loss of weight and the time of exposure of the material to the cavitation attack. However, Nowotny found that the loss of weight distinctly began after a certain "time of incubation," during which no loss of weight could be measured. For instance, with some sort of steel he found that during this incubation time, the material suffered about 6×10^6 hits of collapsing bubbles. He belives that during this time the material changes its properties, especially under the influence of heat created by the numerous blows concentrated on very small areas. He came to the conclusion that it is difficult to establish a general connection between the resistance against cavitation damage and the purely mechanical properties of materials as they are found at room temperature. By the same reason he finds that those high static pressures, which many authors believe to be necessary for an explanation of the cavitation damage, and which they failed to measure by experiments, are actually not necessary.

Nowotny went still further in analyzing the details of the details of the destruction. He applied a very sensitive x-ray method, taking pictures not only of the various samples of material before and after cavitation, but also of the particles broken out of the sample and fished out of the liquid. In this way he found that not only the grain structure was destroyed, but that even the single grains were broken. The grains fished out of the liquid showed a distinct reduction in size.

These few details out of Nowotny's article have been given in order to demonstrate that the vibratory method is fit not only for practical purposes, but also for a very thorough basic investigation in order to establish a consistent theory of the particular form of wear and tear inherent in the cavitation phenomenon. It might be possible that by means of such a theory we may sometime succeed in "constructing" that material which has the strongest resistance against the cavitation damage.

On the other hand, the writer would recommend not to abandon the other methods of creating cavitation such as that in Venturi tubes or around specially shaped bodies. It is still important to compare the effects of different kinds of cavitation.

At the same time Nowotny made his experiments, the writer succeeded in creating in a high-power Venturi tube with a velocity of 250 fps in the throat, the same primary effects such as discoloring, and the like, after an exposure of the best steel for only 30 sec.

The scientists of both hydrodynamics and metallurgy should combine their efforts to clear this phenomenon of cavitation which has obtained so great an importance since high speeds are being applied more and more in so many fields of modern technique.

Any contribution out of the laboratories of the industry such as the author's should be highly appreciated.

A. J. Stepanoff*—It seems natural that the sample buttons are pitted more in the middle than at the edges because water near edges is nearer the free surface and hence is more mobile than near the center of the button.

An interpretation of the air cloud below the sample on Figure 9 is as follows: As a result of local pressure drop below the sample some air is liberated into the vapor filled cavity. This air is not reabsorbed when the cavity collapses. I cannot visualize the mechanism of air drawing against the force of buoyancy.

I do not believe that an increase of submergence of two inches would have an appreciable effect on the recoil forces during the collapsing of cavity, as two inches are too small in comparison with atmospheric pressure of 34 feet.

I can easily see why loss of metal may increase with a greater submergence. The increase would probably be mostly near the edges because particles of water become less mobile with more submergence. Then decrease of metal loss with increased submergence would require a different hypothesis.

I was interested to notice the effect of hardness on the resistance to pitting because in his earlier report Hunsaker was not able to detect such relationship.

I understand that physical dimensions of oil molecules are greater than those of water since cavitation damage to metal may be on the intermolecular scale—bouncing of oil molecules against the metal may be less destructive than that of water molecules. Penetration of metal by oil in this process is probably less than that of water. Poulter (14) has shown that metal particles can be torn off by liquid penetrating into and escaping from the pores of the metal under successive pressure waves.

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