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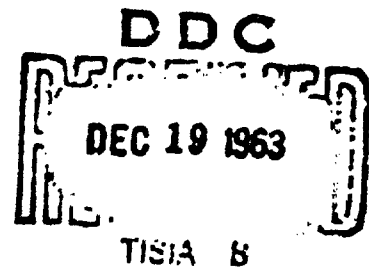
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HYDRONAUTICS, Incorporated

TECHNICAL REPORT 233-2

A COMPARATIVE EVALUATION
OF
CAVITATION DAMAGE TEST DEVICES

by

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TABLE OF CONTENTS

	Page
SUMMARY.....	1
INTRODUCTION	2
DEVICES UNDER CONSIDERATION.....	3
MAGNETOSTRICTION DEVICES.....	3
FLOW DEVICES	4
ROTATING DISK DEVICES	4
DEFINITION OF INTENSITY OF CAVITATION DAMAGE	4
ESTIMATION OF INTENSITIES OF VARIOUS DEVICES.....	7
COMPARISON OF INTENSITIES OF VARIOUS DEVICES.....	7
APPLICATION OF THESE CONCEPTS TO FIELD DEVICES.....	9
LIMITATIONS	10
CONCLUSIONS.....	12
REFERENCES	13
APPENDIX - SPECIMEN CALCULATION OF I FOR THE ASME STANDARD MAGNETOSTRICTION DEVICE	16

NOTATION

r	Radius of test specimens in Magnetostriction Device
a	Amplitude
f	Frequency
d	Depth of immersion of specimen
D	Diameter of the beaker
H	Depth of liquid in the beaker
V_o, p_o	Velocity and pressure in the free stream in flow devices
A	Chamber diameter of the Rotating Disk Device
B	Width of chamber
R	Radius of the disk
S	Gap between the Rotating Disk and the Stationary Wall
m	Reference radius of the disk
ω	Angular velocity of the disk
β	Angular velocity of the core
E_a	Energy absorbed by material
ΔV	Volume loss of material
S_e	Strain-energy of the material
P_a	Power absorbed by material
t	Testing time
A_e	Area of erosion
I	Intensity
i	Average depth of erosion

LIST OF FIGURES

- Figure 1 - Definition Sketch of the Magnetostriiction Device
- Figure 2 Basic Principles of Flow Devices
- Figure 3 - Rotating Disk Device
- Figure 4 .. Effect of Test Duration on Rate of Cavitation
Damage for 1100-F Aluminum
- Figure 5 - Effect of Test Duration on Rate of Cavitation
Damage for 304-L Stainless Steel
- Figure 6 - Four Zones of Cavitation Damage Rate

LIST OF TABLES

Table 1	-	Magnetostriction Devices
Table 2	-	Flow Devices
Table 3	-	Rotating Disk Devices
Table 4	-	Intensities of Various Devices

SUMMARY

A comparative evaluation of three types of test devices (Magnetostriction, flow and rotating disk) that are used for investigations of cavitation damage is accomplished by means of a rational definition of intensity of cavitation damage.

The intensity of cavitation damage is defined as the power absorbed per unit area of the damaged material surface. It is estimated by multiplying the average depth of erosion per unit time by the strain energy of the material.

As a result of this analysis a few interesting conclusions are reached. The intensity of cavitation damage of the A.S.M.E. Standard Magnetostriction Device is approximately one erg per second per square centimeter (i.e. 10^{-7} watts/cm²). Similarly the intensity of the rotating disk device used by Thiruvengadam is also one erg/sec/cm². The most intense laboratory device so far used is the rotating disk device of Rasmussen. The least intense device is the Venturi type flow device used by Hammitt.

These results contradict the popularly held view that the so-called "accelerated" damage devices are more intense than the rotating disk device. This leads to the conclusion that the cavitation damage produced by field devices may some times be as intense as that produced by the magnetostriction devices.

The limitations involved in this analysis are also discussed.

INTRODUCTION

Many investigations have been made to classify the relative resistance of materials to cavitation damage by conducting experiments in various devices such as (i) magnetostriction devices, (ii) flow devices and (iii) rotating disk devices. However, no attempt to correlate the results obtained from this variety of equipment has been successful. Consequently, there has been no method by which these results could be extrapolated to actual field devices except through qualitative experience. This situation results from the lack of a satisfactory definition of the intensity of cavitation damage.

The need for such a definition has been long felt. It can be seen from the following remarks by Knapp (1) that this goal appeared to be a formidable task. "However, at this point, the investigator finds himself on the brink of an abyss gazing out over completely unknown territory since no satisfactory method has been developed for measuring the absolute intensity of cavitation, either in the laboratory or in the field...Future work on the relative resistance of materials to damage should be correlated with studies of mechanics of damage. An important step would be the development of a definition of intensity of cavitation and some rational measure of it which could be used both in hydraulic machines and structures and in equipment employed for determining relative resistance."

The goal of the present investigations is precisely that described by Knapp and to some extent this goal has been achieved. A rational definition of the intensity of cavitation damage is

proposed and the concept has been successfully utilized to compare the magnitude of the intensities developed by various devices used in the laboratory. It seems that the proposed method can also be used for evaluating the intensities of field equipment. This would provide a rational and quantitative link between the various laboratory devices and field equipment.

DEVICES UNDER CONSIDERATION

The cavitation damage test equipment that is considered for comparative evaluation can be classified into three main groups:

- (i) Magnetostriction
- (ii) Flow
- (iii) Rotating Disk

The method adopted for evaluating this equipment can also be applied to other devices that are not included here.

MAGNETOSTRICTION DEVICES

The basic principle of this device is that a cylinder of radius r is oscillated along its longitudinal axis in a liquid with a double amplitude of $2a$ and frequency f (Figure 1a). The cylinder is immersed to a depth d below the liquid surface in a beaker of diameter D and depth H . The oscillation of the piston is accomplished by the magnetostriction effect experienced by certain ferromagnetic materials. Further details of construction and operation of magnetostriction devices may be found in References 2 and 3. The physical oscillation of the cylinder produces an alternating hydrodynamic pressure which causes the formation, growth and collapse of vapor bubbles on the face of the cylinder. The pictorial representation of how these bubbles are formed when a disk moves in the

liquid is shown in Figure 1b which is based on Reference 4. The erosion pattern also is very similar to this (Figure 1c). Table 1 shows the published details of magnetostriction devices used for cavitation damage tests.

FLOW DEVICES

These devices utilize conventional hydrodynamic principles in producing cavitation either in venturi tubes or in the wake of body shapes or in the low pressure regions on the boundary of hydrodynamic shapes as shown in Figures 2a, 2b and 2c. Usually the test specimen is stationary and the liquid flows past the specimen. Apart from the geometry, the important parameters are velocity, pressure and size. The various equipments of this group with their basic geometrical shapes and essential parameters are shown in Table 2.

ROTATING DISK DEVICES

In this case, a circular disk is rotated in a standing mass of liquid contained in a chamber (Figure 3a). Any discontinuity such as a circular hole produces cavities collapsing downstream of the hole. When the disk rotates, there is a core of liquid rotating along with the disk and the velocity distribution would be as shown in Figure 3b. Table 3 gives the details of this type of equipment.

DEFINITION OF INTENSITY OF CAVITATION DAMAGE

The term intensity has long been used in a vague sense by many previous investigators. It was characterized by the following measurements:

- (i) Weight loss
- (ii) Volume loss
- (iii) Number of pits produced
- (iv) Loss of radioactive coating materials.

It was realized as early as 1935 by Schomb et al (19) that weight loss can be a misleading parameter characterizing intensity since the strength and density can vary independently. In spite of this fact, weight loss continues to be used for comparing various materials by many investigators even to date. Knapp (20) proposed the method of measuring the number of pits per unit time per unit area on a given material to represent the "intensity or damage potential" of a particular device. But this measure can only represent the rate and density with which the bubbles are collapsing and not the energy of collapse of the bubbles. The loss of radioactive coating materials is not generally favored because of its inherent procedural complexity and further it is only an indirect measure of weight loss. By far the best and simplest measure of the total energy absorbed by the material is the volume loss for a given material. However, the gross volume loss cannot represent the intensity because it would vary with size or area. Hence a rational definition of intensity can be formulated as a logical extension of this measure in the following manner.

It is generally accepted that a portion of the total bubble collapse energy is absorbed by the test material causing final fracture and volume loss. The energy absorbed by the material E_a is given by

$$E_a = \Delta V \cdot S_e \quad [1]$$

where ΔV is the volume loss and S_e is the strain energy which is defined as the energy absorbed per unit volume of the material up to complete fracture. Hence, the power absorbed by the material is given by

$$P_a = \frac{\Delta V \cdot S_e}{t} \quad [2]$$

where $\frac{\Delta V}{t}$ is the volume loss per unit time (rate). In order to take into consideration the effect of size of the system, the power absorbed per unit eroded area is defined as the intensity of damage of the device.

Then

$$I = \frac{P_a}{A_e} = \frac{\Delta V \cdot S_e}{A_e \cdot t} \quad [3]$$

$$I = \frac{i S_e}{t} \quad [4]$$

where I is the intensity of cavitation damage, A_e is the area of erosion and $i = \Delta V/A_e$ is the average depth of erosion.

The value of I can easily be computed if we know the average depth of erosion per unit time and the energy absorbed by the unit volume of the material up to fracture by this type of loading.

While the average depth of erosion per unit time can be accurately measured after a test on a material, the value of S_e is not precisely known at present. This difficulty was overcome by using the strain-energy (area of the stress-strain diagram) obtained from a simple tensile test as a first approximation (21) and this approach was favorably received by many. The same idea will be used for the present attempt also. The limitations of this approach are discussed later.

ESTIMATION OF INTENSITIES OF VARIOUS DEVICES

The value of the intensity of cavitation damage I for various devices was estimated as shown in the specimen calculation for the A.S.M.E. Standard Magnetostriction Device in the Appendix. Similarly the value of I for various other devices are computed from the published data using one of the five materials for which the strain energy values are known as given in Reference 21. At least one of these five materials has been used by each one of the investigators. Table 4 gives the value of the parameters used for computing the intensity of each equipment as published along with the values of intensity in watts per square centimeter. The reason why these five materials were specifically used for this analysis is because the strain-energy for other materials used by various investigators have not been published.

COMPARISON OF INTENSITIES OF VARIOUS DEVICES

Table 4 presents an interesting comparison of intensities of cavitation damage of sixteen devices for which quantitative data have been published in the literature. It so happens that the device No. 1 (A.S.M.E. Standard Magnetostriction Device) is not

only an arbitrarily defined standard device but it can also be considered as a unit intensity device since its intensity is about one erg per second per square centimeter (10^{-7} watts/cm²). It is a matter of coincidence that the intensity level of the rotating disk device (Device No. 16) used by Thiruvengadam (11) is also approximately 10^{-7} watts/cm². It can be seen from Table 4 that the most intense device so far used is the rotating disk device of Rasmussen (Device No. 14). This result shows that the so-called accelerated devices (magnetostriction devices) are not more intense than the rotating disk devices. Further it will be noted that the intensities of Device Nos. 8, 10, and 12 are just a tenth of the intensity of the A.S.M.E. Standard Magnetostriction Device (Device No. 1).

There is a general feeling that the intensities of actual field systems would be very much lower than the intensity of magnetostriction devices. For example Leith and McIlquaham (22) remark as follows: "Field experience in hydraulic turbines indicates that one year of design-load operation is comparable to the first 30 min. of the A.S.M.E. Standard test which gives a time scale of about 18,000:1." The present analysis shows that this contention may not be a general case applied to field devices. It is suggested that the term "accelerated device" may be replaced by the term "high or low intensity device."

The second interesting result that emerges from the present analysis is that the devices used by advocates of the chemical and electro-chemical damage mechanisms have possessed very low intensities. It is understandable why Petracchi (13) attributed no

weight loss to the mechanical part of the mechanism because the device used by him (Device No. 9) was one thousand times less intense than the standard A.S.M.E. device. Similarly, the device used by Wheeler (9) (Device No. 5) was 250 times less intense than the A.S.M.E. Standard Device.

The flow device (Device No. 13) used by Hammitt (17) is the least intense device with which any author has claimed to have obtained weight loss in laboratory tests. It is about 30,000 times less intense than the A.S.M.E. Standard Device. It seems that the single event pitting concept is a result of investigators with such a low intensity device.

APPLICATION OF THESE CONCEPTS TO FIELD DEVICES

The intensity of cavitation damage as defined herein is independent of the type of the system and hence it can be usefully applied to field flow systems for selecting the material that would sufficiently withstand the damage intensity of the system. For example, the intensity of damage of a propeller of a ship or the runner of a hydraulic turbine could be estimated by analyzing the log book for a given operating time. From this value, the material that could sufficiently withstand this intensity could be specified for the future designs. In other words, the intensity of that component could be rated in relation to the test devices that have been used for the basic investigations.

The fact that the intensity of the rotating disk devices is comparable to the magnetostriction devices (or is of greater order of magnitude as in the case of Device Number 14) suggests that there is no reason to believe that the intensity of the field

devices should necessarily be very low. In fact the flow situation in the rotating disk device is not very abnormal when compared with any rotating component of a turbo-machine and if it can produce such a high intensity of damage, then such intensities are also possible in the field devices. It would be highly desirable to make an estimate of the intensity range of the field devices from the available operational data so that one of the sixteen laboratory devices considered herein could be selected as the most representative of the field systems based on their intensities as the criteria.

LIMITATIONS

One of the serious limitations in the testing procedure adopted by all the investigations so far is the superposition of the third uncontrolled variable - namely the test duration. Although some investigators had known that the rate of damage was time dependent, no one has previously conducted systematic investigations to establish the relationship between the rate of damage and the testing time, thereby eliminating the interacting influence of testing time.

Figure 4 shows the variation of rate of volume loss as a function of the cumulative testing time for 1100-F Aluminum keeping all the other test conditions constant. It can be seen that the rate of damage increases with time in the early stages of testing, then decreases with time and finally reaches a steady rate independent of test duration. Figure 5 shows the same relationship for 304-L Stainless Steel. Analysis of these figures shows that

there exist four zones of damage with respect to testing time as shown in Figure 6. They are:

- Zone 1 - Incubation Zone
- Zone 2 - Accumulation Zone
- Zone 3 - Attenuation Zone
- Zone 4 - Steady State Zone

The time required for each zone depends upon the physical properties of the material for a given set of test parameters. However, such detailed analysis is not possible for most of the devices considered here because the testing time was arbitrarily selected for each one of the investigations and only the cumulative loss after this testing time has been published by most of them. To this extent, the present estimate of the intensities are inaccurate.

A further limitation to this analysis is in obtaining the proper value of the strain-energy of the materials tested. The value of strain-energy (even the value that could be obtained from a simple tensile test) is not given for the specific materials used by various investigators. At least one among the five materials that seemed to exhibit a correlation with cavitation damage loss (21) has been used by each of these investigators. Only these five materials have been used in these analyses (with the exception of lead for Device No. 10 since no other material was used in that investigation) for all the devices. This involves the assumption that the strain-energy of the materials as published in Reference 21 was the same for the materials used by the various authors. While this may not be objectionable as a first-approximation, there

are still two aspects that need serious consideration: (1) The effect of rate of strain on the strain-energy of the material (2) The relationship between the fracture energy obtained from a simple tensile test and the energy absorbing capacity of the material from the overlapping dynamic indentations of the bubble collapse. Nevertheless, it is believed that this analysis brings out the necessary quantitative approach for future investigations.

CONCLUSIONS

1. The term intensity of cavitation damage has been defined as the power per unit area of the material tested. It is the product of the average depth of erosion per unit time and the strain-energy of the material. It has the dimensions of power per unit area and this definition is independent of the test device.
2. According to this analysis, the most intense device is the Device No. 14 used by Rasmussen (15). The least intense device is the Device No. 13 used by Hammitt (17). The A.S.M.E. standard device (Device No. 1) is not merely an arbitrarily set standard device but coincidentally, it seems to be a unit (1 erg/sec/cm^2) device also.
3. This analysis suggests that the order of magnitude of the intensity of field devices need not necessarily be low. They can be as high as the laboratory values or even greater.
4. For low intensity devices (such as Device Nos. 5 and 9) used by Wheeler and Petracchi the environmental effects such as corrosion play an important role.
5. The present concept of intensity can be utilized easily to obtain quantitative guidance for future field installations.

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APPENDIX

SPECIMEN CALCULATION OF I FOR THE
A.S.M.E. STANDARD MAGNETOSTRICTION DEVICE

Diameter of the Specimen = 5/8 inch. The area of erosion was taken to be 0.8 times the area of the specimen since the bubble cloud occupied only that much area (see Figures 1b and 1c and also Reference 4).

Weight loss due to cavitation damage on commercial Brass for a testing period of 120 min:

According to Kerr (5)	= 156 mgs.
According to Rheingans (3)	= 155 mgs.
According to Leith (23)	= 140 mgs.
Average value	= 150 mgs.

The density of Brass was taken as 8.5 gms/cm³.

The strain-energy of commercial Brass was taken to be 880 kgms/cm² from Reference 21. Using these values the intensity was computed as follows:

$$\begin{aligned}
 I &= \frac{150 \times 10^{-3} \times 880 \times 10^3}{120 \times 60 \times 1.6 \times 8.5} \frac{\text{ergs}}{\text{sec. cm}^2} \\
 &= 1.3 \frac{\text{ergs}}{\text{sec. cm}^2} \\
 &\approx 1 \frac{\text{erg}}{\text{sec. cm}^2} \quad \text{or} \quad 10^{-7} \frac{\text{watts}}{\text{cm}^2}
 \end{aligned}$$

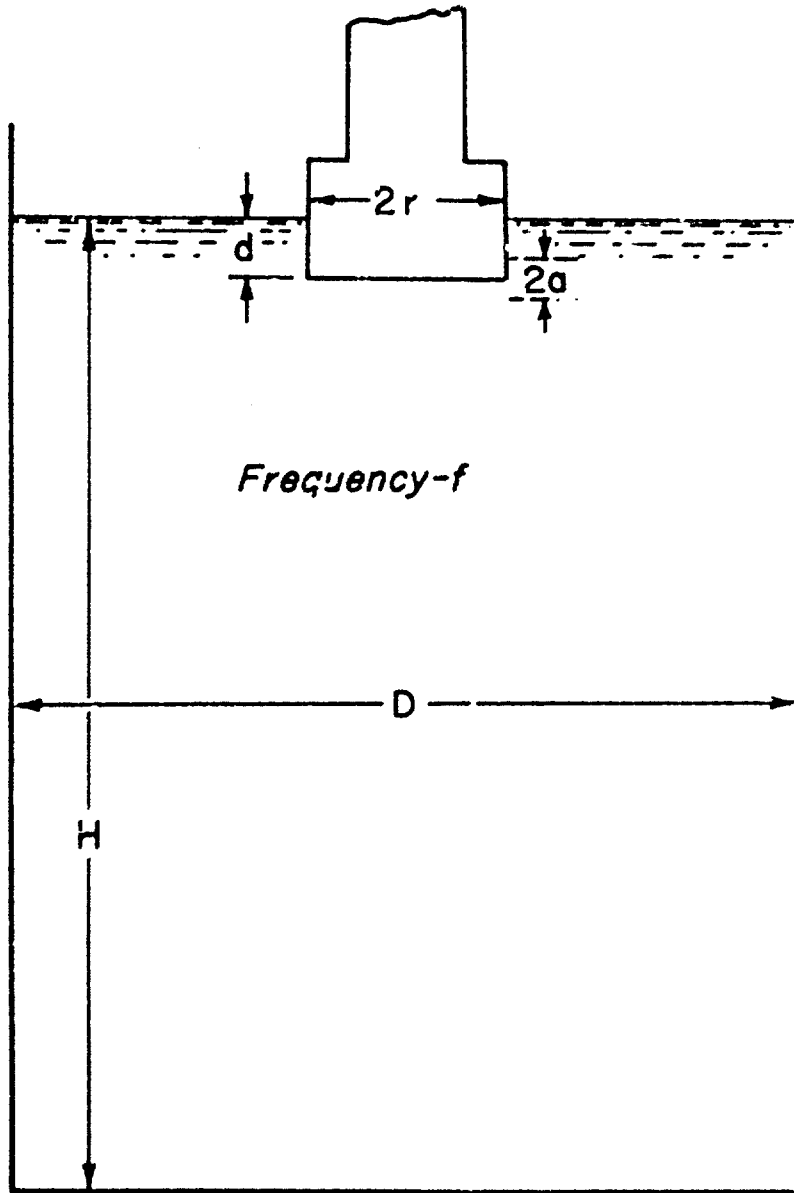


Figure 1.a.-Definition Sketch of the Magnetostriction Device

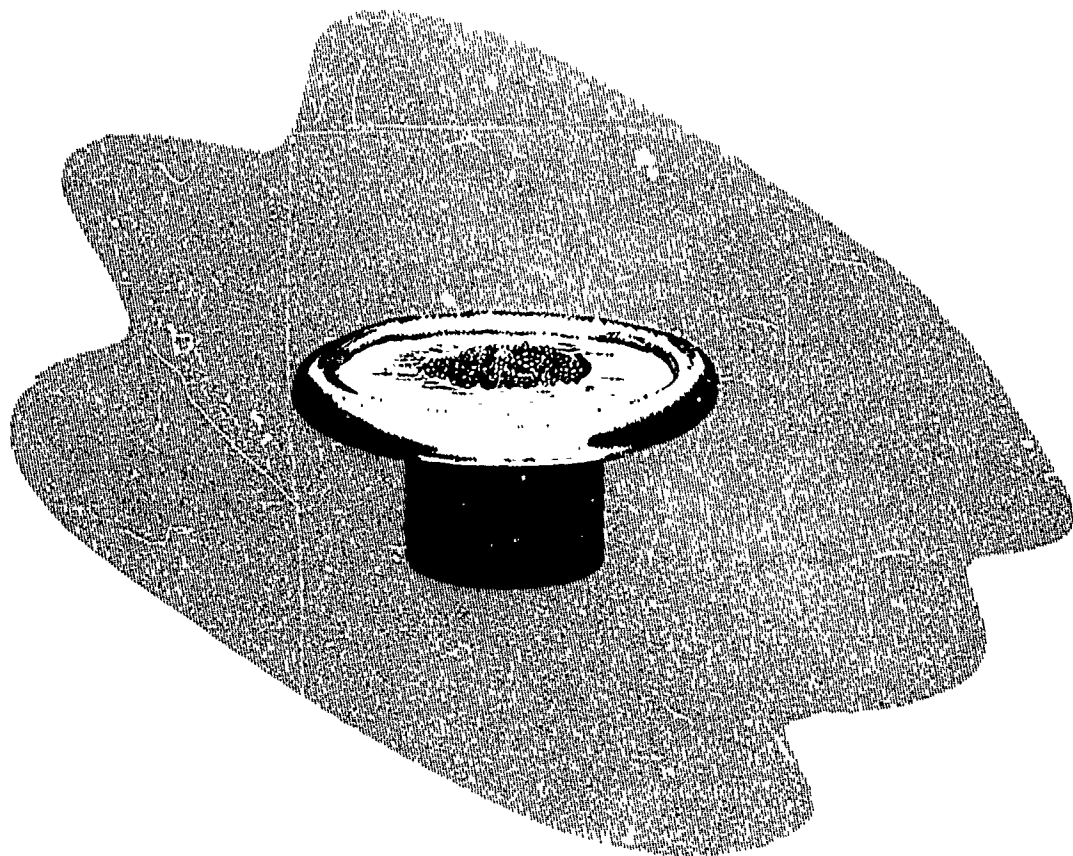


FIGURE 1.b - PICTURE OF FORMATION OF CAVITATION BUBBLES
(REFERENCE 4)

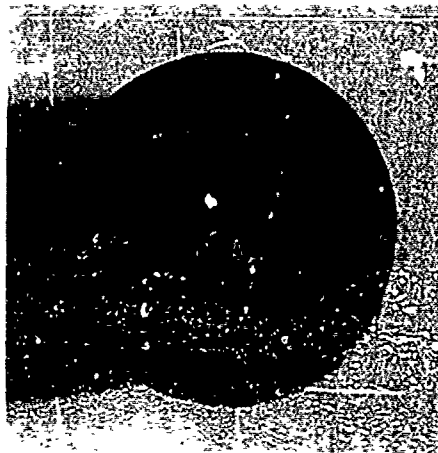
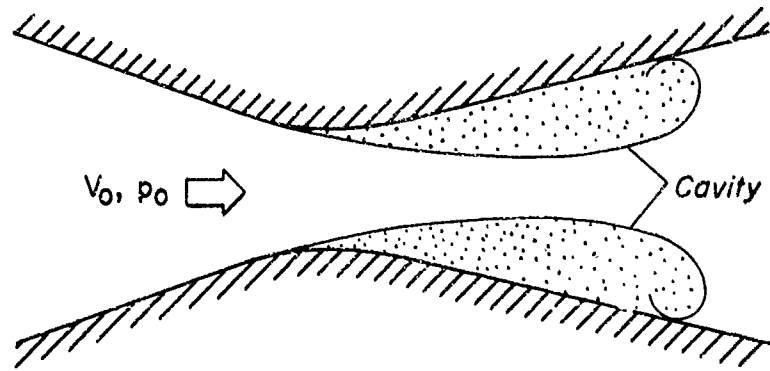
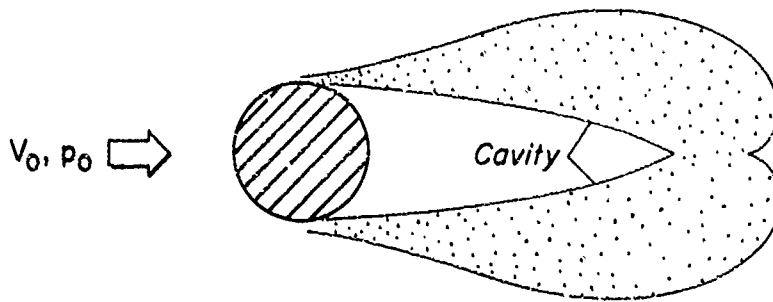


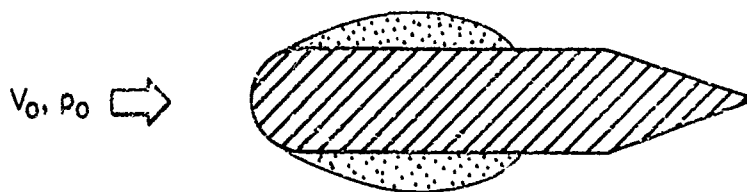
Figure 1.c.-Photograph of the Damaged Specimen



a. Venturi Type



b. In the Wake of a Cylinder



c. Over a Body of Revolution

Figure 2-Basic Principles of Flow Devices

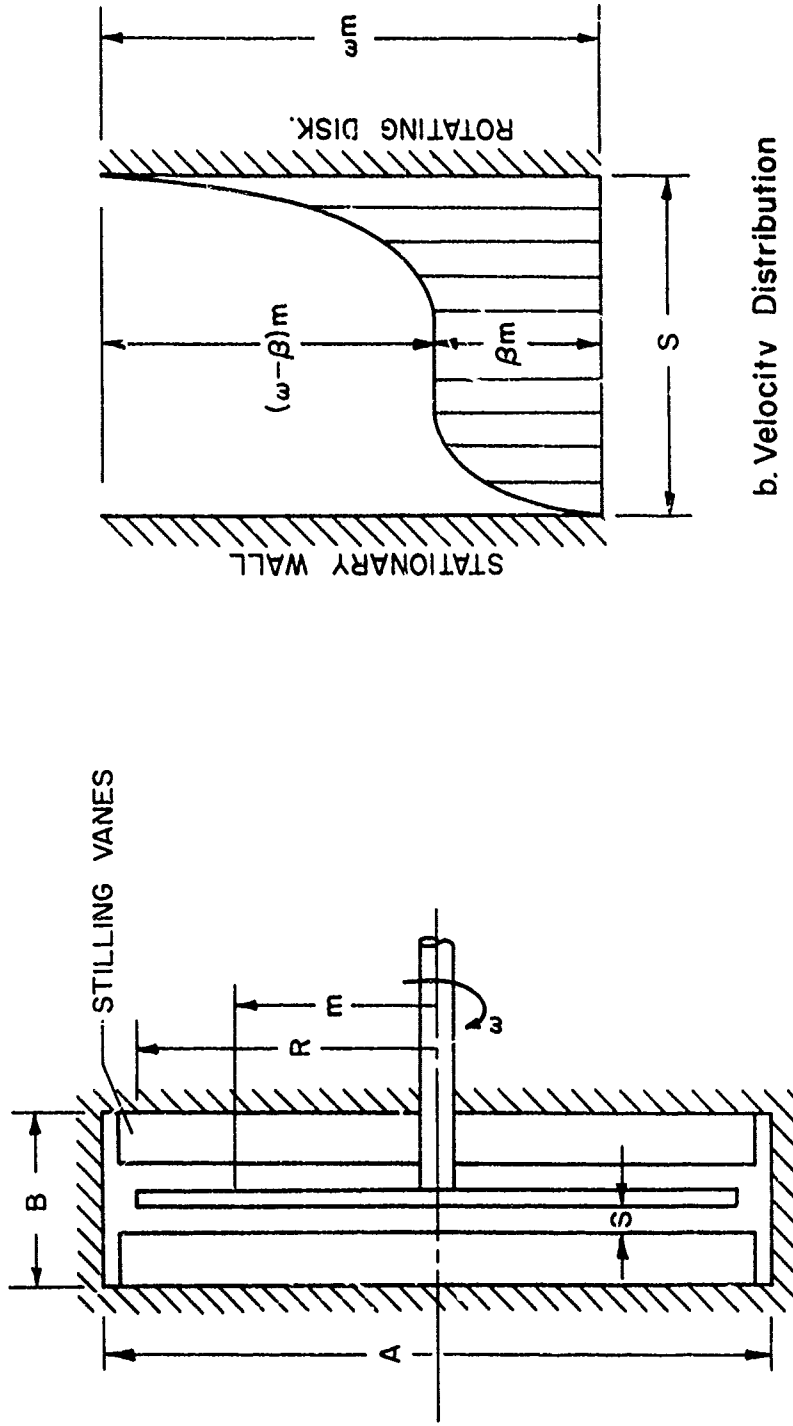


Figure 3 - Rotating Disk Device

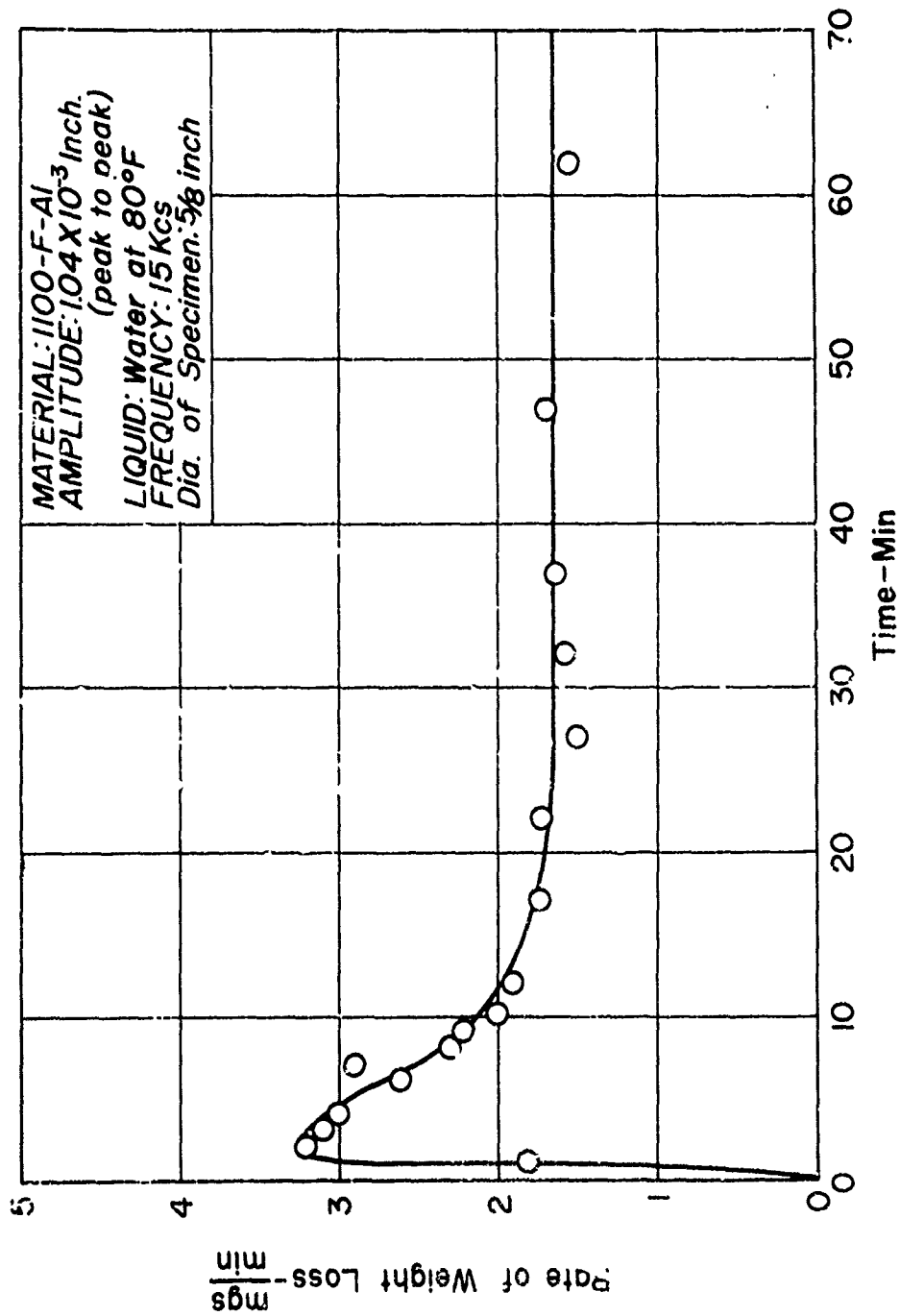


Figure 4 - Effect of Test Duration on Rate of Cavitation Damage

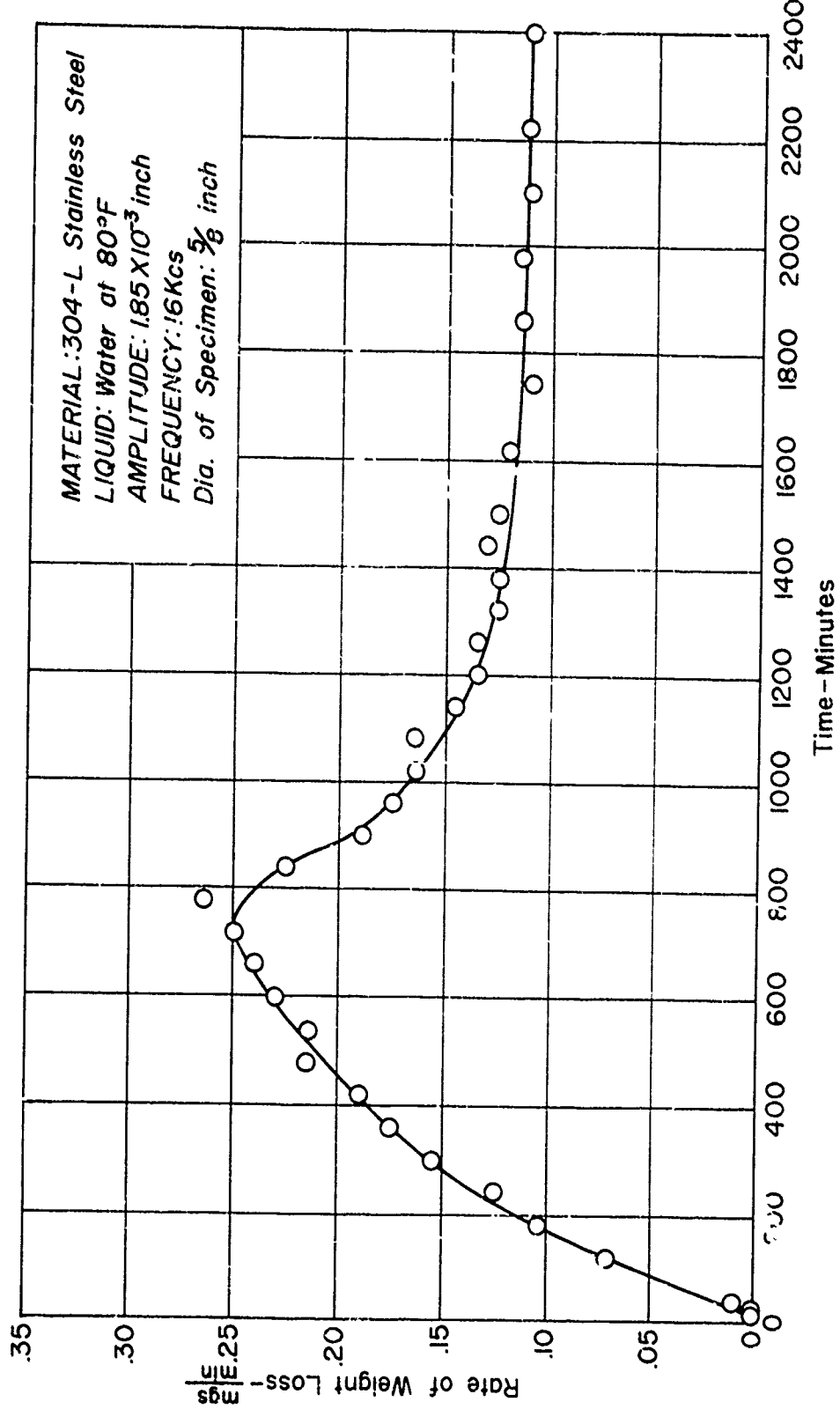


Figure 5 - Effect of Test Duration on Rate of Cavitation Damage for 304-L Stainless Steel

304-L Stainless Steel

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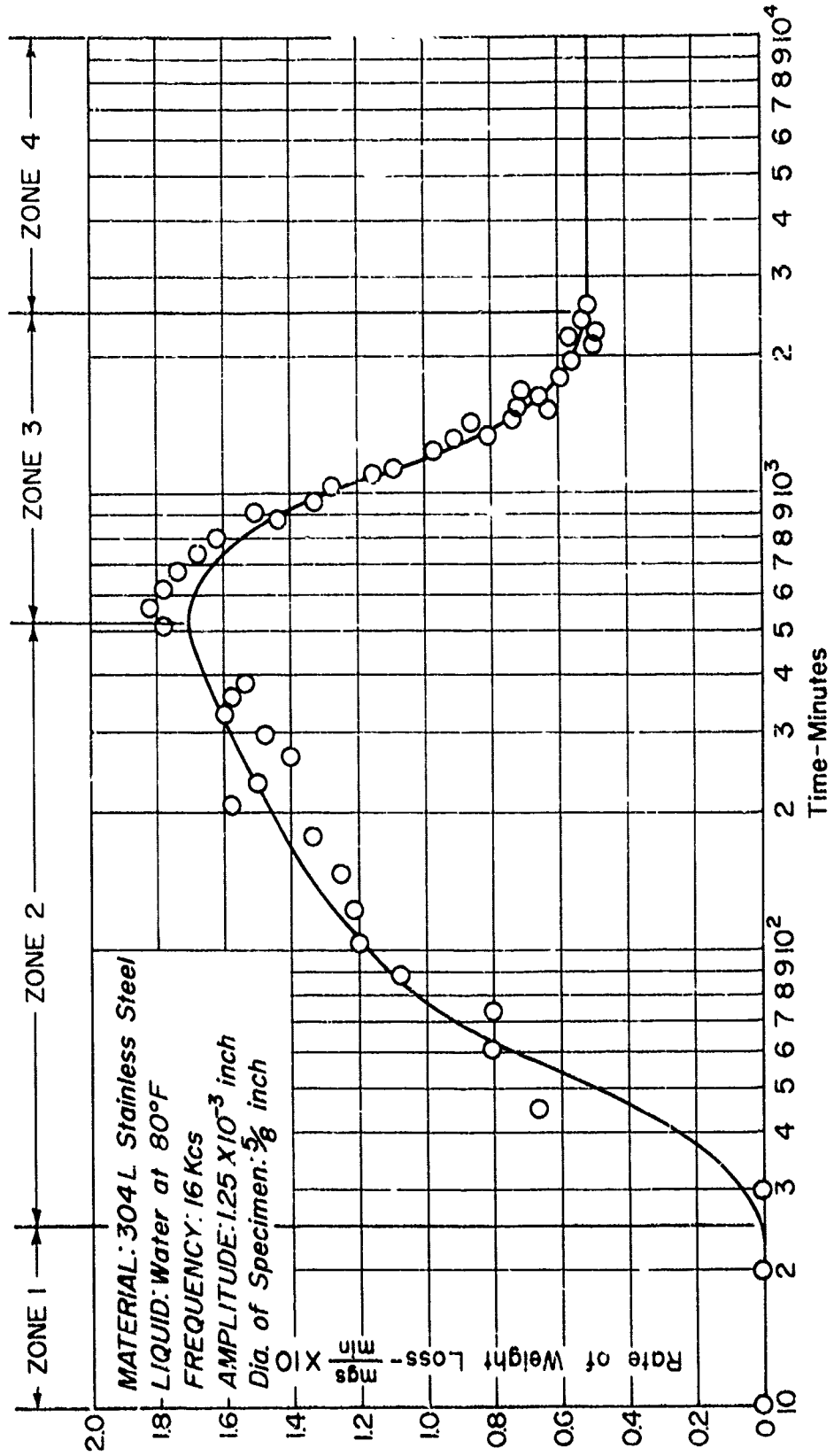


Figure 6-Four Zones of Cavitation Damage Rate

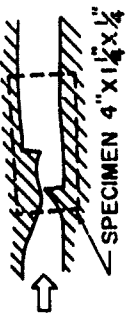


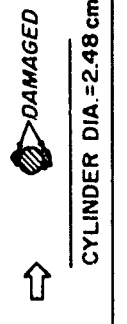

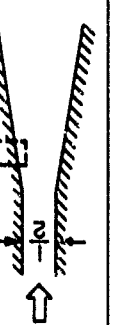
Figure 6-Four Zones of Cavitation Damage Rate

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TABLE 1
Magnetostriction Devices

Serial Number	Device Number	Reference Number	Frequency cps	Amplitude 2a	Diameter of Specimen 2r	Depth of Immersion d	Depth of Liquid in Beaker H	Liquid and temperature
1	1	(5)	6590	-	5/8 inch	1/4 inch	-	Water @ 20°C
2	1	(3)	6500	3.4 x 10 ⁻³ inch	5/8 inch	1/8 inch	-	Water @ 76°F
3	1	(2)	6500	3.4 x 10 ⁻³ inch	5/8 inch	1/8 inch	4.5 inch	Water @ 76°F
4	2	(6)	9000	0.05 m.m.	-	1 m.m.	-	Water
5	3	(7)	9000	-	5/8 inch	-	-	Water @ 20°C
6	4	(8)	8000	0.09 m.m.	-	6 m.m.	-	Water @ 25°C
7	5	(9)	8000	0.03 m.m.	1 cm	-	-	Water
8	6	(10)	14200	2.0 x 10 ⁻³ inch	5/8 inch	3/32 inch	-	3% NaCl Soln.
9	7	(11)	15000	2.0 x 10 ⁻³ inch	5/8 inch	1/8 inch	3.0 inch	Water @ 80°F

TABLE 2 - FLOW DEVICES

SERIAL NO.	DEVICE NO.	REF. NO.	BASIC GEOMETRY and TYPICAL DIMENSIONS	VELOCITY	PRESSURE	LIQUID and TEMPERATURE	TYPICAL TEST DURATION
1	8	(12)	 SPECIMEN 4" X 1 1/4" X 1/4"	265 fps at Throat	480 psi at Main Pipe	Water at 20°C	16 Hours
2	9	(13)	 SPECIMEN 2cm X 2cm	40 fps (estimated value at throat)	22 psi at Main Pipe	Water	20 Hours
3	10	(14)	 CYLINDER DIA. = 12 mm.	25 mps at Throat	75 psi	Water	5 Hours
4	11	(15)	 CYLINDER DIA. = 2.48 cm	9 mps	—	Water at 14-16°C	24 Hours
5	12	(16)	 CYLINDER DIA. = 1"	100 fps	100 psi	Water at 80°F	15 Hours
6	13	(17)	 SPECIMEN 3/4" X .06"	65 fps	35 psi	Water	150 Hours

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TABLE 3
Rotating Disk Devices

Serial No.	Device No.	Reference No.	Chamber Size		Disk Size		Gap S	Hole Dia.	RPM	Maximum um	Pressure	Liquid
			A	B	2R	b						
1	14	(15)	35 cm	35 cm	25 cm	1/2 cm	1 cm	1.5 cm	2500	25 mps	Atmo-spheric	Water at 12 - 18° C
2	15	(18)	13 in.	9 in.	12 in.	1/8 in.	5/8 in.	3/8 in.	3200	150 fps	15 psig	Water at 60 - 110°F
3	16	(16)	18 in.	9 in.	13 in.	1/8 in.	5/8 in.	3/8 in.	2800	154 fps	15 psig	Water at 70 - 90°F

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TABLE 4
Intensities of Various Devices

Device No.	Reference Number	Material	Strain Energy kgm/cm ²	Density gms/cm ³	Weight Loss mgs	Time seconds	Area of Erosion cm ²	Average Depth of erosion cm x 10 ³	Intensity $\frac{\text{watts}}{\text{cm}^2} \times 10^7$
1	2,3,5	Commercial Brass	380	8.5	150	120 x 60	1.6	11.00	1
2	6	1100-0-Aluminum	80	2.7	1.5	10 x 60	1.6	0.11	.05
3	7	Commercial Brass	880	8.5	31.1	90 x 60	1.6	2.3	.4
4	8	Commercial Brass	650	8.5	3.5	90 x 60	0.5	7.9	1
5	9	Mild Steel	230	7.9	0.8	120 x 60	0.5	.13	.004
6	10	Copper	700	8.3	80	30 x 60	1.5	6	2.5
7	11	1100-0-Aluminum	80	2.7	1.5	60	1.6	1.5	2
8	12	18-8 Cr.St. Steel	2750	7.8	11.3 x 7.8	16x60x60	7	1.7	.1
9	13	Commercial Brass	880	8.5	4.0	20x60x60	4	.12	.001
10	14	Lead	20	13		60 x 60		18	.1
11	15	Commercial Brass	880	8.5	1.0	60 x 60	1.0	.12	.03
12	16	1100-0-Aluminum	80	2.7	4.0	60	20	.07	.1
13	17	304 St. Steel	2750	7.8		150x60x60		.006	.00003
14	15	1100-0-Aluminum	80	2.7	250	30 x 60	1.0	96	4
15	18	1100-0-Aluminum	80	2.7	220	3.5x60x60	1.5	54	.34
16	16	1100-0-Aluminum	80	2.7	2.5	60	1.5	0.62	1

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