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HYDRONAUTICS, Incorporated

TECHNICAL REPORT 233-7

INTENSITY OF CAVITATION DAMAGE ENCOUNTERED IN FIELD INSTALLATIONS

By

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SUMMARY

A nomogram called "Cavitation Damage Intensity Estimator" is presented for estimating cavitation damage intensities of field installations. This simple approach is based on an earlier definition of cavitation damage intensity as the power absorbed per unit area of the eroded material. Using this estimator and the data published for field installations, the damage intensity is estimated for ships' appendages, ships' propellers, valves, Diesel engine cylinder liners, hydraulic turbine runners and pumps. These estimates show that the intensities for propellers and valves can be several orders of magnitude higher than that for laboratory test devices. A summarized analysis shows the field experience and laboratory experience in the proper perspective in terms of their intensities. The possible usefulness of various protection methods are projected for various intensity levels. The threshold intensity of cavitation damage is found to be proportional to the endurance limit of metals. These ideas are only preliminary in nature and further coordinated field and laboratory efforts are suggested in this direction.

INTRODUCTION

Ever since the discovery of the serious destruction of ships' propellers, hydraulic turbines and other major hydraulic structures due to cavitation damage, there have been several attempts to relate quantitatively the damage occurring in the field installations to that observed at the laboratory. These attempts were handicapped by the lack of an acceptable definition of intensity of damage which can be readily computed for field devices as well as for laboratory devices.

Furthermore, the field experiences were mostly reported in a qualitative manner rather than in specific quantities such as depth of erosion, area of erosion, physical and chemical properties of materials and liquids used, hydrodynamic characteristics of the device, time of operation, time during which the most serious damage occurred. The reason for the lack of quantitative information is the obvious difficulty in obtaining such data. In fact, such detailed information is not available even for the research devices used in the laboratory.

As a result of this situation, there has been a general impression among the various investigators that the intensity of cavitation damage (although no quantitative definition of the intensity of cavitation damage was available until recently) experienced in field installations is very low when compared to the laboratory test devices, e.g. magnetostriction oscillators. It is for this reason that tests conducted in such devices have been called "accelerated" tests. In addition, this reasoning led to the question of the suitability of the test method for screening materials for use in field installations operating under so called "real time" damage conditions.

In the past, several repair procedures and protection methods have been highly successful in some cases, while the same methods have failed badly in other situations. Perhaps this could have been explained or anticipated if there were some quantitative way of determining intensity ranges in which a given method proved to be successful. Furthermore, in certain cases, hydrodynamic redesign coupled with a superior material selection helped to reduce or completely eliminate cavitation damage. Such successes have gone unnoticed because of the lack of quantitative correlations between the remedy applied and output performance.

These considerations bring forth the necessity for a new approach toward quantifying the field experience rationally in terms of some acceptable and at the same time easily obtainable parameters and to compare them with laboratory experience. This would lead to an overall perspective of the problem of cavitation damage from the points of view of researchers, designers and operators. Such is the aim of this report.

DEFINITION OF INTENSITY OF CAVITATION DAMAGE

One of the approaches to the problem of cavitation damage is to define the intensity of cavitation damage in a rational manner and to compute its value for various field installations. Recently a reasonably successful definition of the intensity of cavitation damage has been proposed (1). According to this definition, the intensity is the power absorbed per unit area of the damaged material surface; it is given by

$$I = \frac{iS_e}{t} \qquad [1]$$

where

I is the intensity of cavitation damage,

$\bar{i}$ is the average depth of erosion,

S_e is the strain energy of the metal, and

t is the time.

Using this intensity parameter, sixteen laboratory devices were compared (1) and this attempt provided an overall assessment of the various devices used for research purposes.

FIELD INSTALLATIONS AFFECTED BY CAVITATION DAMAGE

It is the purpose of this report to estimate the intensity parameter for the field devices that have been plagued by cavitation damage in the past so that one can get a relative idea of how serious the cavitation damage problem is in relation to the various type of installations. The installations that have experienced serious cavitation damage may be listed as follows:

(1) Ship underwater appendages, hydrofoils, struts, rudders, hull, etc.,

(2) Ship propellers,

(3) Hydraulic turbines,

(4) Pumps,

(5) Valves, regulators, sluice gates,

(6) Diesel engine cylinder liners,

(7) Bearings,

(8) Civil engineering hydraulic structures such as baffle piers, stilling basins, spillways, intake structures, penstocks and tunnels,

(9) Underwater sound transmission and detection devices, and

(10) Nuclear and space technology equipment such as liquid metal handling equipments, cryogenic liquid handling equipments.

This classification is by no means complete. An attempt will be made to discuss some of the above cases for which some quantitative information is available.

CAVITATION DAMAGE INTENSITY ESTIMATOR

A nomogram (Figure 1) called cavitation damage intensity estimator has been prepared using Equation [1] with three aims in mind. It provides a visual idea of the range of intensities encountered in actual practice within the ranges of the depth of erosion, material used and time of operation. It also provides a quick and easy method of estimating the intensity of damage for a given installation. This would be particularly useful for operators. Lastly, the selection of better materials, if available, is easily made.

The procedure in using this estimator is as follows:

1. To determine the intensity of damage, if the depth of erosion, the strain energy of the material eroded and the duration of erosion are available, draw a straight line connecting

the depth of erosion and the strain energy of the material eroded. This line will intersect the second line from the left (the line without any scale). Join this point of intersection with the duration of erosion by means of another straight line which will intersect the intensity scale, thus giving the intensity of cavitation for this case.

2. To determine the depth of erosion after a given operating time on a given metal, if the intensity of the system is known, proceed as follows:

This procedure is the reverse of the previous operation, in which case one would draw a straight line connecting the duration of operation and the intensity so as to intersect the second line from the left. A straight line joining this point of intersection and the strain energy of the material would intersect depth of erosion scale, indicating the depth of erosion for these conditions.

3. To determine the strain energy of the material required to give a certain depth of erosion after a given duration of operation in a system of given intensity:

In this case, a straight line joining the intensity and the time of operation would intersect the second line from the left. Another straight line connecting this point of intersection and the depth of erosion would cut the strain energy scale at the required value.

4. Similarly one can find the duration of operation for a given system of known intensity, fabricated from a given material, if a criterion for the allowable depth of erosion is set.

This estimator should be a convenient design tool for engineers. The usage of the proper units as shown in the nomogram for each parameter would yield the intensity in watts per square meter. The following conversion would give the intensity in American engineering units

$$\text{Watt/Meter}^2 = 1.25 \times 10^{-4} \text{ H.P./Foot}^2.$$

INTENSITY ENCOUNTERED IN FIELD INSTALLATIONS

Ships' Hull and Appendages

It is known that ship hulls and other appendages may be seriously damaged by cavitation (2). However very little data are reported. For one case of a destroyer, the armor hull plates above the propeller were pierced by a hole of dimensions of about one square foot after the destroyer had operated for several hours at maximum speed (3). If we assume the thickness of the armor plate as one inch, the time as 10 hours and the strain energy as 50,000 psi, we would obtain the intensity from the intensity estimator (Figure 1) of approximately as 250 watts/meter^2. This intensity is amazingly high since it is 250 times that of the standard ASME magnetostriction device. One can easily conclude that no material can resist this intensity for a prolonged period of operation and this would form a clue in suggesting a change in the hydrodynamic design and operational limits.

Lichtman _et al_ (2) made a detailed survey of cavitation damage encountered in U. S. Navy vessels and attributed certain cavitation damage ratings. However no information as to the depth of erosion, material used and time of operation were given.

Ships' Propellers

Cavitation damage in some of the early designs of ship propellers was so serious that they had to be discarded after their maiden voyages. Neville (4) reported that for the case of the _Bremen_, the propeller blades were eroded up to 4 3/4 inches deep within two round trips across the Atlantic Ocean. Similarly several more instances may be cited from the literature. Actual data were collected for a few modern destroyers of the U. S. Navy which have experienced significant cavitation damage* (Table 1). The intensities ranged from 10^{-1} watt/meter^2 to 250 watts/meter^2 as compared to one watt/meter^2 for the ASME magnetostriction apparatus. In one case (DDG-15), the ship cruised at 20 knots for 20 hours and its intensity was of the order of 40 watts/meter^2, whereas for the other propellers, the exact duration of cavitation damage is not known. However, the number of hours of operation and the corresponding speed ranges were available in some cases. It is most likely that the major portion of damage occurred at speeds higher than 30 knots.

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* These data were kindly furnished by Mr. J. Hill of U. S. Bureau of Ships, Department of the Navy (5).

Valves

The present survey shows that very serious damage may occur in valves controlling liquid flow. Borland and Stiles (6) reported that a 316 stainless steel needle valve failed in 10 minutes of operation. The maximum intensity for this case has been estimated to be as much as 3000 watts/meter^2. Table 2 shows the details and intensities for a few more cases.

Diesel Engine Cylinder Liners

Another case where cavitation damage seems to be important is the Diesel engine cylinder liners (12,13,14). As shown in Table 3, the damage intensity in certain specific cases can be as much as one watt/meter^2.

Hydraulic Turbines and Pumps

Almost parallel with the detection of cavitation damage in ship propellers, damage was also discovered in hydraulic turbines and pumps. However, it is much more difficult to extract quantitative data for turbines and pumps except for some early cases of severe erosion. In recent literature, the damage is described only qualitatively. Despite this limitation, some quantities have been estimated from photographs and other descriptions as shown in Table 4. In two cases for pumps, quantitative information was available and are included in Table 5. Both cases are examples of liquid metal handling pumps.

Since the operational times are total hours of operation and since cavitation damage occurs most likely during a part of this time, the intensities estimated in this report would, in the Author's opinion, generally be lower than the actual intensities by a factor of at least ten.

<u>Other Devices</u>

Similar estimates of the intensity of damage could be made for any machine which has experienced cavitation damage. Since there is not much information available for other devices, no estimates are presented herein. However, this kind of estimation of intensity would form a guide for selecting suitable protection methods based on the experience with other devices.

LIMITATIONS

What has been presented in this report is only a preliminary step toward more rational approaches that are to come by a co-ordinated effort in the laboratory as well as in the field. Because of the approximate nature of the data available, the whole analysis is necessarily approximate. The intensities estimated herein would vary depending up on the depth of erosion. In most cases the maximum depth of erosion is reported and it would indicate the maximum intensity. This aspect is unavoidable unless more detailed observations are reported in the future.

Again, the property of the material characterising its energy absorbing capacity is not available accurately. Even the use of the strain energy (as given by the area of the stress-strain diagram from a simple tensile test) may not be justified for strain-rate sensitive materials. However, the strain energy seems to be adequate at least for the most common metals which do not exhibit strain rate sensitivity (22,23). It should not be very difficult to replace the static strain energy property for any other property that represents the fracturing process during cavitation damage which may come to light as a result of future investigations. One approach is to obtain dynamic stress-strain data and to use the dynamic strain energy for strain-rate sensitive materials (24). In the case of corrosive environments, an equivalent strain energy which takes into account the reduction in mechanical properties as well as the increase in loss of material due to corrosion may have to be used.

In fact, it would be very easy to define the intensity of one of the laboratory devices (e.g. Standard ASME Magnetostriction Device) as unity and determine the equivalent strain energy in any environment for any given metal based on the depth of erosion and time. This would take into account directly the strain rate effects also.

The third important parameter is the time during which the erosion took place. This is very difficult to determine, particularly for field installations. Since the operating hydrodynamic parameters would be varying over a period of time and since the output intensity of damage as estimated in this report would also be varying along with input hydrodynamic parameters, the intensities reported herein are essentially approximate in most cases. However this kind of analysis brings forth the possibility of a quantitative approach for future guidance along with some a priori conclusions.

The intensities of the case histories reported herein apply only to specific cases where significant cavitation has occurred and should not be generalized, at this stage, for the purposes of design.

SOME REMARKS ON THE RANGE OF INTENSITIES FOR THE POSSIBLE APPLICATION OF KNOWN PROTECTION METHODS

It is interesting to compare the intensity ranges for each of the field installations considered in this report with the intensities of the laboratory test devices reported in Reference 1. As pointed out earlier in this report, the damage intensities of certain valves have been estimated to be as much as 3000 watts/meter^2 and certain propeller damage intensities as great as 250 watts/meter^2 compared to one watt/meter^2 of the ASME Standard magnetostriction apparatus and of the Indian Institute of Science rotating disk apparatus. As more and more data become available, a statistical distribution of the occurrence of intensities for each type of installation will be possible.

Threshold Cavitation Damage Intensity for Metals

A few experiments were conducted using the HYDRONAUTICS Magnetostriction Apparatus to determine the threshold cavitation damage intensity for six metals. The experimental apparatus described in earlier reports (22,23) consists essentially of a magnetostriction transducer, an oscillator, an amplifier, a power supply, a voice coil and an oscilloscope. A specimen of the metal to be tested is vibrated in a liquid at a frequency of 14 kcs. The displacement amplitude can be controlled precisely. Using this apparatus, the intensity of cavitation damage was determined as a function of the displacement amplitude using different metals as shown in Figure 2 (22). This figure shows that the cavitation damage intensity is proportional to the square of the displacement amplitude.

It has been found that there is a minimum displacement amplitude for each metal below which there will be no cavitation damage for a prolonged duration. This minimum amplitude is called the threshold amplitude and the intensity of cavitation damage at this amplitude is called the threshold intensity of cavitation damage. The threshold intensity of cavitation damage for six metals was experimentally determined by arbitrarily setting the test duration as 20 hours since at this time interval nearly a billion cycles will be accumulated for this test frequency. The results of these experiments are shown in Table 6 along with the endurance limit of these metals at a billion cycles using the same apparatus as reported in Reference 23. Figure 3 shows that there is a good correlation between the threshold intensity of cavitation damage and the endurance limit at one billion cycles except for the case of SAE 1020 mild steel. This is due to the corrosive interaction. The only explanation available at present as to why this corrosion effect did not lower the endurance limit at the same rate, is that corrosion products are continuously removed during cavitation while they are not readily removed during fatigue tests. This could be significant for tests involving corrodable materials such as steel.

Some Remarks on Protection Methods

From the above experiments, it is clear that the level of threshold intensities for various metals are of the order of 10^{-1} watt/meter^2 at the most. Elimination of cavitation damage by substituting one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selection coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 watt/meter^2. However, if the intensity levels are higher than these values, then the above protection methods may not work. In such cases, hydrodynamic redesign, air injection and specifying limits for operation are the alternate remedial possibilities. These considerations are pictorially represented in Figure 4. Further field and laboratory investigations are needed to confirm these ideas.

CONCLUSIONS

The following conclusions are reached from these investigations:

1. The intensity of cavitation damage experienced in ship's propellers and valves can be several orders of magnitude greater than that of the laboratory test devices currently being used. The intensities encountered in other installations also can be as much as that of the experimental equipments. A more thorough systematic reporting of the field experience in the future would greatly enhance the understanding of this problem. A nomogram called the "cavitation damage intensity estimator" is presented in order to aid this effort of field observations.

2. The present analysis shows the range of applicability for the various protection methods in relation to the intensity of cavitation damage. Experiments on the threshold intensity of cavitation damage for metals show that the threshold intensity is proportional to the endurance limit of these metals. Based on this result one can conclude that the maximum threshold for metals is most probably of the order of 10^{-1} watt/meter^2.

3. These investigations have brought to light the necessity of learning more about the relationships between the hydrodynamic parameters controlling the input intensity and the output intensity so far discussed in this report. This knowledge would be useful in controlling the intensity of cavitation damage within the range wherein the structures can be made resistant by proper materials selection and auxiliary protection methods.

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TABLE 1

Intensity of Cavitation Damage on Some Ship's Propellers

Designation	Ship Velocity (Knots)	Time of Operation (Hours)	Maximum Depth of Erosion (Inches)	Material Used	Strain Energy (psi)	Intensity $\frac{\text{watts}}{(\text{meter})^2}$	Location of Damage	Area of Damage	Remarks
Bremen		500 - (2 round trips across Atlantic	4-3/4"	Al-Bronze (Assumed)	16,500	8			Metal not given.
DDG-15	20	20	7/8	Mn Bronze	18,000	36			
DD-779 Douglas H. Fox	>30	5-1/4	3/16	Superston	22,600	40	6" from hub	6" x 1-1/2"	All four blades showed similar damage
	25-30	120	3/16			2			
	0-25	2105	3/16			10^{-1}	9" from hub	7" x 1/2"	
DD-78 Massey	25-30	~ 100	1/2	Mn Bronze	18,000	5			
DD-806 Higbee	15-20	~ 150	1/2	Mn Bronze	18,000	3	Suction side, 12"-18" from leading edge	18" x 3"	3000 miles traveled
DD-888 Stickell	< 25	2013	1/4	Mn Bronze	18,000	10^{-1}		5" x 2-1/2"	Port side more pitted than Starboard
	25-30	53	1/4			4			
	> 30	6	1/4			37			
DD-876 Rogers	< 25	529	3/16	Superston	22,600	4×10^{-1}			Damage on all four blades
	25-30	10	3/16			20			
	> 30	8	3/16			26			
	> 30	128	3/16			2	Pressure side	4" x 2"	Test run
DD-838 Small	< 25	1935	1/2	Superston	22,600	3×10^{-1}			
	25-30	139	1/2			4			Starboard - less damage
	> 30	25	1/2			22			
DD-851 Rupertus	< 25	1289	1/8	Superston	22,600	10^{-1}	3" from leading edge		
	25-30	42	1/8			3			
	> 30	8	1/8			17			
DD-875 Truber	< 25	1220	3/4	Stainless Steel	35,000	10^{-1}	6" from trailing edge; 6" from hub		On all blades
	25-30	12	3/4			110			
	> 30	6	3/4			220			
DD-836 McKenzie	> 25	1458	1/8	NALAB Bronze	17,000	10^{-1}			Scattered pits over 50% at 6" radius from hub
	25-30	26	1/8			4			
	> 30	10	1/8			10			

TABLE 2

Intensity of Cavitation Damage on Valves*

Type	Hydraulic Details	Time of Operation	Depth of Erosion	Material	Strain Energy (psi)	Intensity watts/m^2	Reference
6" Cast Iron Test Valve	200 psig → 0 psig	3 or 4 wks.	Say 1/2"	Cast Iron	10,000	5×10^{-1}	8
Feed Water Bypass regulator.	2800-300 psi 600 fps 2" x 3/4"	6 to 9 hrs.	1/2 to 1"	316 St. Steel.	40,000	200	9
Control Valve	——	Few hrs. Assume 10 hrs.	Say 1/2"	18-8 St. Steel with harder overlay	35,000	100	6
Control Valve	2000 psi pressure difference	10 min.	1/4"	316 St. Steel	40,000	3000	6
Needle Valve	145 ft. head 72" diameter	1 min.	1/2"	Steel	15,000	5×10^{-1}	10
Needle Valve	52" conduit	One flood. Assume 1 wk.	1-1/4"	Steel	15,000	6	10
Sluice Gate	10'x9-1/2' size Discharge of ≅ 5000 cu. secs.	1500 hrs.	3/4"	Steel	15,000	3×10^{-1}	11
Sluice Gate		75 hrs.	1/4"	Steel	15,000	2	11

* These are some specific cases where cavitation damage data are available.

TABLE 3

Intensity of Cavitation Damage on Diesel Engine Cylinder Liners *

Horsepower	Time of Operation	Material Used	Maximum Depth inches	Strain Energy	Intensity	Reference
	300 hours	Cast Iron	1/2	10,000	1	12
River Barge Diesel Engine	3 weeks	not given Assumed Cast Iron	1/16	10,000	10^{-1}	13
	900 hours	Cast Iron	5/16	10,000	10^{-1}	13
	one year	Cast Iron	3	10,000	10^{-1}	13
	1000 hours	Cast Iron	1/10	10,000	5×10^{-2}	14

* These are some specific cases where cavitation damage data are available.

TABLE 4

Intensity of Cavitation Damage on Hydraulic Turbines*

Type	Time of Operation	Depth of Erosion	Material Used	Strain Energy	Intensity	Reference
Francis Turbine	3 years	"So Badly" Assume 1"	Cast Steel	15,000	3×10^{-2}	15
Francis Turbine	4 years	"Hole Through" Assume 1"	Cast Steel	15,000	2×10^{-2}	16
Francis Turbine	3 years	1/64"	Bronze	18,000	10^{-3}	16
Francis Turbine	"Few Weeks" say 10 wks.	1"	Bronze	18,000	5×10^{-1}	17
Kaplan Turbine	4 years	3"	Not Given Assume Bronze	18,000	10^{-1}	18
Pelton Wheel	Two weeks	2"	—	20,000	7	19

* These are some specific cases where cavitation damage data are available.

TABLE 5

Intensity of Cavitation Damage on Pumps *

Detail	Liquid Pumped	Time of Operation	Depth of Erosion inches	Material Used	Strain Energy	Intensity	Reference
Liquid Potassium Pump	Liquid Potassium	300 hrs.	50×10^{-3}	Stainless Steel	Assume 15,000	10^{-1}	20
Sodium and Salt Fused Pump	Liquid Sodium at $1200^{\circ}F$	2500	0.34	Inconel	Assume 18,000	10^{-1}	21

* These are some specific cases where cavitation damage data are available.

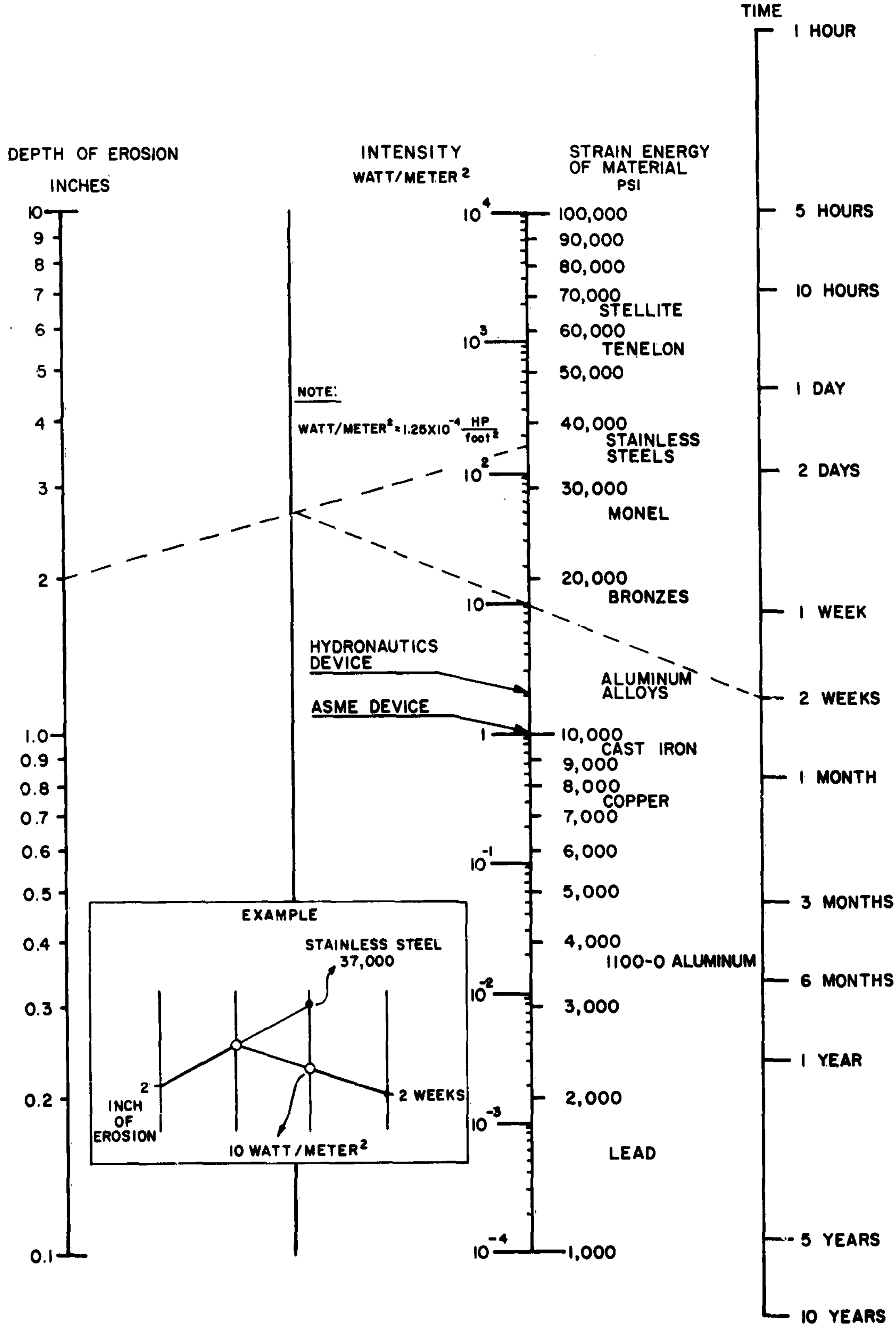
TABLE 6

Threshold Intensity of Cavitation Damage for Six Metals

Metal	Threshold Amplitude cm x 10^3	Threshold Intensity $\left(\frac{\text{Watts}}{\text{Meter}^2} \times 10^2\right)$	High Frequency Endurance Limit* at 10^9 Cycles psi
316 Stainless Steel	0.54	2.50	42,000
Monel	0.54	2.50	47,000
2024 Aluminum	0.37	0.84	18,000
1020 SAE Mild Steel	0.44	1.20	38,000
Tobin Bronze	0.50	1.51	24,000
1100-F Aluminum	0.30	0.58	12,000

* Values obtained from Reference 23.

FIGURE 1-
CAVITATION DAMAGE INTENSITY ESTIMATOR



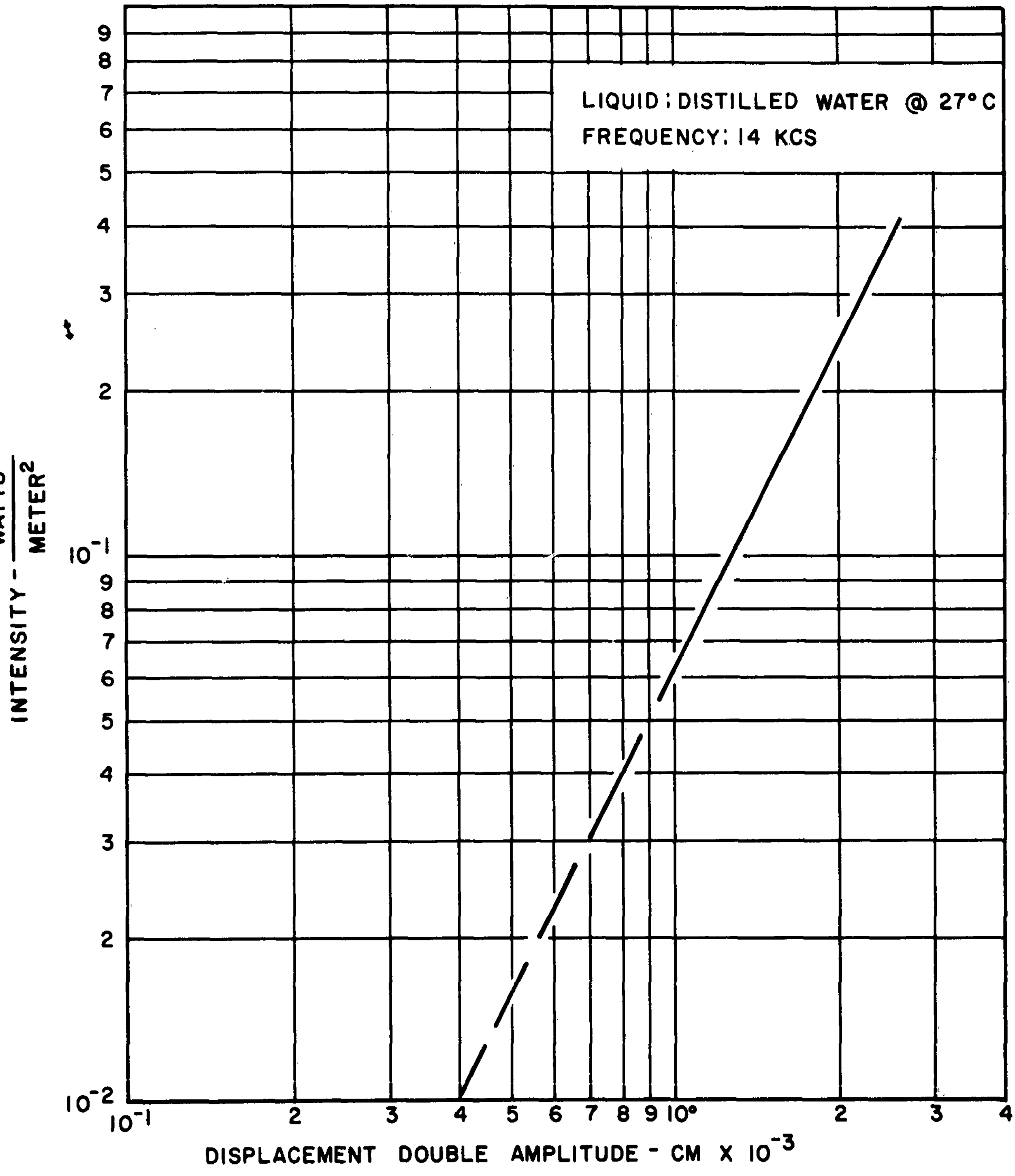


FIGURE 2 - EFFECT OF DISPLACEMENT AMPLITUDE ON CAVITATION DAMAGE INTENSITY [THIRUVENGADAM AND WARING (22)]

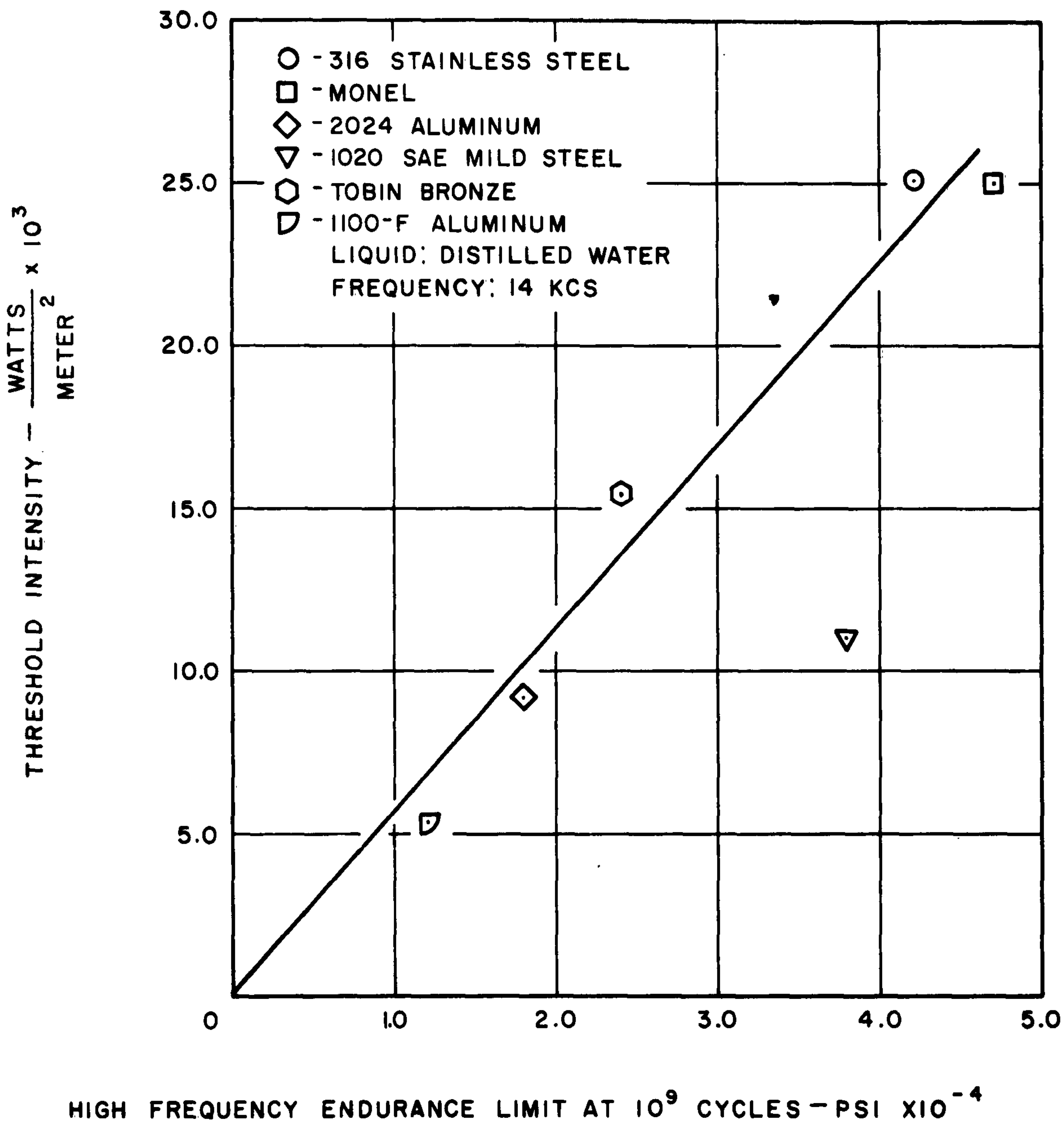


FIGURE 3 – THRESHOLD INTENSITY OF CAVITATION DAMAGE AS A FUNCTION OF HIGH FREQUENCY ENDURANCE LIMIT OF METALS

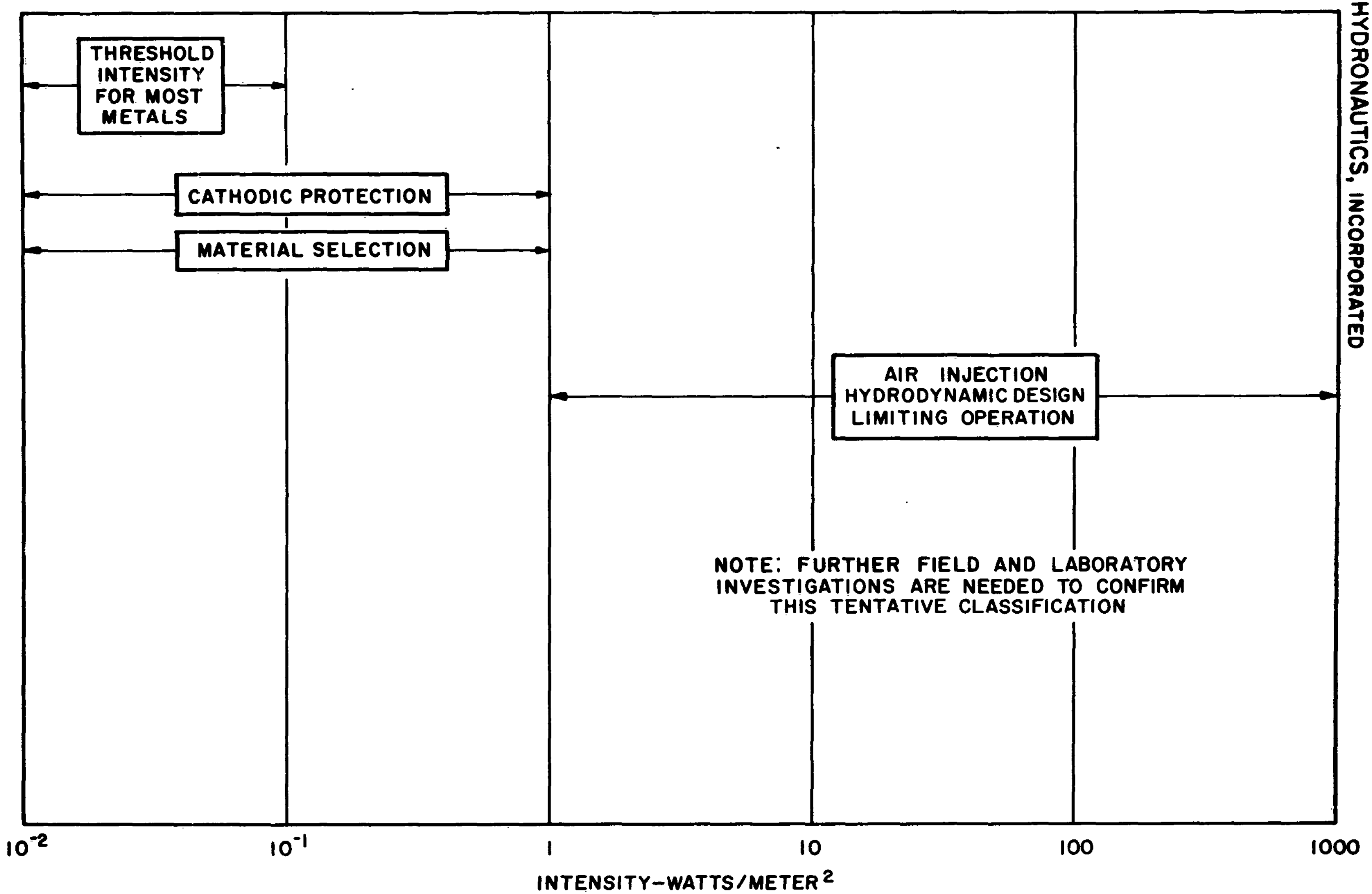


FIGURE 4—RANGE OF INTENSITIES FOR THE POSSIBLE APPLICATION OF KNOWN PROTECTION METHODS

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13. ABSTRACT A nomogram called "Cavitation Damage Intensity Estimator" is presented for estimating cavitation damage intensities of field installations. This simple approach is based on an earlier definition of cavitation damage intensity as the power absorbed per unit area of the eroded material. Using this estimator and the data published for field installations, the damage intensity is estimated for ships' appendages, ships' propellers, valves, Diesel engine cylinder liners, hydraulic turbine runners and pumps. These estimates show that the intensities for propellers and valves can be several orders of magnitude higher than that for laboratory test devices. A summarized analysis shows the field experience and laboratory experience in the proper perspective in terms of their intensities. The possible usefulness of various protection methods are projected for various intensity levels. The threshold intensity of cavitation damage is found to be proportional to the endurance limit of metals. These ideas are only preliminary in nature and further coordinated field and laboratory efforts are suggested in this direction.

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