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THE PULSATION METHOD FOR GENERATING CAVITATION DAMAGE

by
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Abstract

Results are presented for the cavitation damage of materials by a laboratory procedure in which the cavitation is applied in an intermittent, or pulsed, manner. It is found that the rate of damage in materials sensitive to corrosion is much greater for pulsed cavitation than for steady cavitation when the cavitating liquid is salt water. The damage rate is also increased by the pulsed cavitation for these materials when the cavitating liquid is distilled water but by a smaller amount than in the salt solution. For corrosion insensitive materials there is no significant difference between the cavitation damage rate when it is applied in a steady or in a pulsed manner.

1. Introduction

It is recognized that the accelerated nature of the damage produced by cavitation in laboratory experiments can affect the validity of predictions of the behavior of materials in applications in which the cavitation damage is extended over a long period of time. Experiments have shown[1] that large mechanical stresses of short duration are produced in a solid when cavitation bubbles collapse near its surface. The deformations in the solid structure produced by these stresses have also been observed[2]. These observations support the conclusion that fatigue is the physical phenomenon involved in cavitation damage. As a fatigue process, chemical or corrosive effects in the cavitation environment should be expected to play an important role in the cavitation damage, for it is known that fatigue failure occurs more rapidly when the cold working takes place in a chemically active environment. The greatly compressed scale of the exposure time in laboratory experiments on cavitation erosion may be expected to exaggerate the physical aspects of the process relative to the chemical aspects. This acceleration in the rate of the process is presumably the reason that the hardness of the material appears in laboratory experiments as a most important feature in determining its resistance to cavitation damage with its chemical properties appearing to be much less significant.

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[1] M.S. Plesset, "On Physical Effects in Cavitation," "Deformation and Flow of Solids," R. Grammel, editor, Springer, Berlin, Germany 1956, pp. 218-235.

[2] M. S. Plesset and A. T. Ellis, "On the Mechanism of Cavitation Damage," Trans. ASME, vol. 77, 1955, pp. 1055-1064.

2. Pulsing Technique for Studying Cavitation Erosion

A possible way to reduce the accelerated nature of the laboratory measurements would be to reduce the damage rate and extend the exposure time. This straightforward approach can present some practical problems which may be explained by considering the specific example of the magnetostrictive oscillator method for producing cavitation damage. This method is widely used, and the present experiments were performed with this type of cavitation generator. The magnetostrictive oscillator gives a periodic motion to the specimen which is immersed in the test liquid. At low oscillation amplitudes there is no cavitation, and in the apparatus used in the present experiments none appeared until the threshold amplitude of approximately 10^{-4} in. was attained. As the amplitude increases, the cavitation damage rate, as measured by specimen weight loss, is found to be a linear function as shown in Fig. 1. The threshold amplitude is independent of the specimen used; the slope of the weight loss line, however, depends on the specimen material. In our experiments it was convenient to operate at an oscillation amplitude of 0.0010 in. At this level the cavitation damage rates by the usual laboratory standards were moderate yet still accurately controlled and reproducible. It is evident that a reduction in damage rate by a factor of 10 is not possible, and any attempt to reduce the amplitude by a somewhat smaller factor would introduce difficulties for accurate measurement and reproducibility.

A technique has been developed[3,4] to avoid these difficulties

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[3] M.S. Plesset, "Pulsing Technique for Studying Cavitation Erosion of Metals," Corrosion, vol. 18, No. 5, pp. 181 - 188, May 1962.

[4] M.S. Plesset, "An Experimental Method for Evaluation of Resistance to Cavitation Erosion," Proc. Int'l. Assn. for Hydraulic Res., Inst. for High Speed Mechanics, Tohoku Univ., Sendai, Japan, Sept. 1962

which we term pulsed cavitation. In this procedure the specimen oscillation amplitude is raised to its full amplitude of say 0.0010 in. for the cavitating interval, the amplitude is then cut off to zero for the non-cavitating interval, and the pattern is repeated. A schematic representation of the pulsed amplitude pattern is given in Fig. 2. The inertia and damping of the system give a characteristic rise and decay time in the oscillation amplitude envelope. These characteristic times have been measured for our apparatus. If A is the steady oscillation amplitude, the amplitude rise can be represented by

$$A\,[\,1 - \exp(-t/\tau_r)\,]$$

with $\tau_r = 2.04 \times 10^{-3}$ sec., and the amplitude fall by

$$A \exp(-t/\tau_d)$$

with $\tau_d = 1.10 \times 10^{-3}$ sec. One can fix two features of the pulsed cavitation cycle independently. First, a choice may be made of the repetition period of the cycle as, for example, 13/60 sec. = 216.67 millisec.; and second, a choice may be made of the fraction of this total period during which cavitation damage occurs. If, for example, the effective interval during which cavitation damage occurs is to be 1/20 of the total period, then the corresponding duration of the pulse must be determined by integration of the oscillation amplitude envelope over the cavitation rate as a function of amplitude (cf. Fig. 1). For cavitation 1/20 of the exposure time with a period of 216.67 millisec., one finds that the required duration of the pulse is, as shown in Fig. 2, 12.30 millisec. The effective duration of the pulse pattern can be established independently of the specimen

material. This result is valid since the cavitation threshold amplitude is independent of specimen material and since the cavitation damage rate is a linear function of specimen amplitude. The effective cavitation pulse length depends only on the ratio of the operating amplitude A to the threshold amplitude, and does not depend on the slope of the cavitation damage rate as a function of amplitude. This behavior is most useful not only because the effective cavitation pulse length is then independent of the specimen material but also because relative amplitudes are more accurately known than absolute amplitudes.

The experimental procedure and the results shown in Fig. 3 - 8 have been described in Refs. 3 and 4. A brief recapitulation of some of the results given in these references will be presented in this section since thereby the pulsed cavitation procedure is more readily understood. In the next section new results will be described which give a more comprehensive view of the comparison between steady and pulsed cavitation. In the previous experiments two types of materials were investigated. The one type consisted of materials which are corrosion sensitive, such as mild steel and 4340 steel. The second type consisted of corrosion insensitive materials such as 17-7 PH stainless steel, Inconel X, and Inconel 718. A comparison of steady cavitation and pulsed cavitation weight losses is shown in Fig. 3 for mild steel. The steady cavitation results are shown by the solid lines and the pulsed cavitation by the dashed lines. The cavitation exposure in both situations is effectively the same except that for the pulsed application a cavitation damage time of 1 hour, for example, means an experimental exposure time of 20 hours. Similar results for soft 4340 steel are shown in Fig. 4. In both these materials

there is a large increase in the rate of weight loss in going from steady to pulsed cavitation in the salt solution, there is also a similar increase although of smaller magnitude in distilled water, and there is a decrease in the rate of cavitation weight loss in going from steady to pulsed cavitation in water buffered to pH8. Figure 5 shows the results with 17-7 PH stainless steel at a Brinell hardness number of 175. The rates of cavitation weight loss vary very little in going from steady to pulsed cavitation with this corrosion resistant material. The same sort of behavior is found with these materials in the hardened form as is clearly exhibited in Figs. 6 and 7 which compare 4340 steel directly with the corrosion resistant materials Inconel X and 17-7 PH stainless steel.

The results just presented give comparisons of the effects of cavitation damage when the cavitation is applied in an intermittent, or pulsed manner and when it is applied in a steady manner. While the calculation of the effective duration of the cavitating interval is a straightforward matter, it might seem desirable to have an independent method of determining the accuracy of the ratio of the cavitating interval to the noncavitating interval. Since the difference between the damage in the pulsed cavitation and the damage in the steady cavitation is presumed to be related to the chemical activity of the environment, this difference should disappear when the cavitation takes place in an inert environment. Under this condition, only the physical effects of the cavitation can play a role and the results should be the same for steady and for pulsed cavitation. Such an experiment was performed by placing the cavitation system in a gas tight enclosure. The cavitating liquid was chosen to be toluene which is quite inert chemically. The air was removed from the system, the

toluene was deaerated and it was then saturated with helium. The system was then filled with helium to one atmosphere pressure. The specimen material used for the cavitation damage measurements was mild steel which shows a great difference between pulsed and steady cavitation (cf. Fig. 3). The results of the steady and pulsed cavitation in toluene with the helium atmosphere are shown in Fig. 8, and it is evident that the pulsed cavitation weight losses are essentially the same as the steady cavitation weight losses. The final weight loss in the pulsed experiment was about 4 percent less than the corresponding steady cavitation weight loss; this difference is within the error of the experimental procedure.

3. Effect of Variation of Pulse Parameters

The question may naturally be raised regarding the effect either of changing the repetition rate of the pulse pattern for a given pulse duration, or of changing the pulse duration for a given repetition rate.

A series of experiments were performed in which the pulse duration was kept constant at the value of 12.3 millisec, which corresponds to an effective pulse duration for cavitation damage of 10.83 millisec; the repetition rate was then varied from continuous cavitation to C 1/40. Cavitation damage data was obtained for 4340 steel and 17-7 PH stainless steel in distilled water over this range. As is evident from Figs. 3 - 8, the weight loss attains a linear variation with exposure time, and it is the rates of weight loss in this linear range which are shown in Fig. 9 for the various repetition periods. The weight loss per unit cavitating time shows almost no variation from continuous cavitation to C 1/40 for the stainless steel. The 4340 steel, on the other hand, shows a small rise in rate of

weight loss from continuous cavitation to C 1/10, and thereafter shows a more rapid rise. As is always the case, by the rate of weight loss is meant the weight loss per unit of exposure time to the cavitation. It follows that a cavitating interval of 1 hour for C 1/40 requires an experimental running time of 40 hours during most of which time the specimen is stationary. For these very long experimental times, it was considered desirable to correct the measured weight losses for the weight loss experienced by a specimen which is at rest in the liquid. The dashed curve in Fig. 9 shows the weight losses corrected in this way. This correction for the 4340 steel is relatively small, and is not observable for the stainless steel.

A similar series of experiments were performed in a 3 percent solution of salt in distilled water, and the results are shown in Fig. 10. The solid curves give the weight loss per unit cavitating time. The corrosion resistant materials, 17-7 PH stainless steel and Inconel 718, show essentially no effect of change in repetition rate. The corrosion sensitive material 4340 steel shows the effect of pulsing the cavitation which is quite marked even for the shorter repetition rates. The dashed curve gives the correction in the rate of weight loss for a static specimen in such a salt solution; there is no observable correction for the 17-7 PH stainless steel and the Inconel 718.

The duration of the cavitation pulse in all the experiments so far described was 12.3 millisec. with an effective cavitation damage duration of 10.83 millisec. Experiments were carried out for a pulse duration of one-half this value as well as for a pulse duration of double this value. The results are shown in Fig. 11 for a 3 percent salt solution in water.

Essentially no variations were observed with a corrosion resistant material like 17-7 PH stainless steel, and the results are presented only for 4340 steel. So far as these data are concerned, no systematic effects of change in pulse duration over the range thus far covered are apparent.

4. Discussion of the Results

The effect of a pulsed application of cavitation is quite clear. For a corrosion sensitive material such as mild steel or 4340 steel, the damage as determined by rate of weight loss is markedly increased while for a corrosion insensitive material such as 17-7 PH stainless steel there is very little change. The rise in damage for a corrosion sensitive material occurs even when the cavitating liquid is distilled water although the change is less than for salt solution. There is also some indication that the damage rate is decreased with pulsed cavitation applied in distilled water buffered to pH 8.

The rise in damage rate in pulsed cavitation with a material sensitive to a corrosive environment may be understood by supposing that a stationary specimen of such a material undergoes some chemical attack in the noncavitating interval. Even though the loss of material under such conditions is quite small, the rate of material loss can be increased during the initial portion of the cavitating interval. Under steady cavitation conditions the surface material is being removed so rapidly that there is not sufficient time for appreciable corrosive weakening of the surface.

Some measurements have been made to determine the magnitude of noncavitating erosion rates. The specimens used were made of 4340 steel and they were exposed to salt solution. The rate of weight loss was

measured by oscillating the specimens at a steady amplitude below the threshold amplitude for cavitation. The data are shown in Fig. 12. The point at zero amplitude gives the rate of material loss in a specimen at rest immersed in salt solution to the average depth used in all the oscillation experiments. It is of interest that the rate of weight loss is a linear function of amplitude. Since the oscillations are harmonic, this result means that the erosion rate is a linear function also of velocity or of acceleration. As is shown in the figure, the rate of weight loss changes to a much steeper linear function beyond the cavitation threshold. The voltage scale used in Fig. 12 is directly proportional to the oscillation amplitude (1 volt = 6.3×10^{-4} in.) and is used since the amplitude is conveniently measured by the alternating voltage generated in a pickup coil around the oscillating driver for the specimen. One might suppose that the noncavitating, low amplitude, rate of weight loss could be extrapolated to high amplitudes. If this linear extrapolation is made, one finds a noncavitating erosion correction which while still small is not negligible. One may roughly predict whether a material will show a large rise in cavitation weight loss with pulsed cavitation as compared with steady cavitation by examining its noncavitating erosion behavior. On this basis the pulsed effect with 4340 steel specimens should be very large in salt solution and much less in distilled water. Figure 13 does indeed show that the low amplitude noncavitating erosion of 4340 steel in distilled water is small.

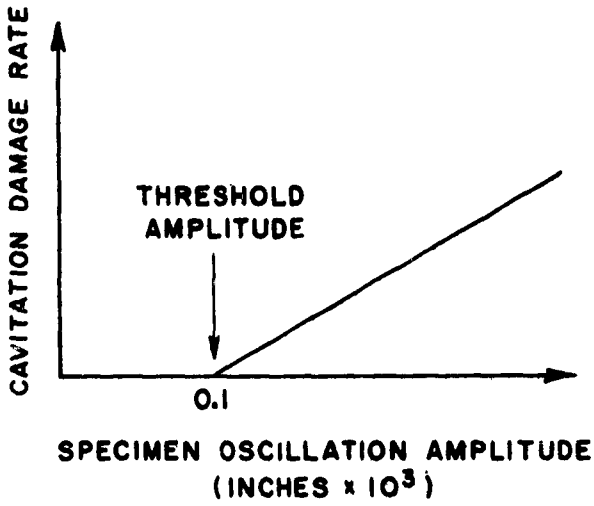

Figure 1. Cavitation Damage Rate as a Function of Specimen Oscillation Amplitude.

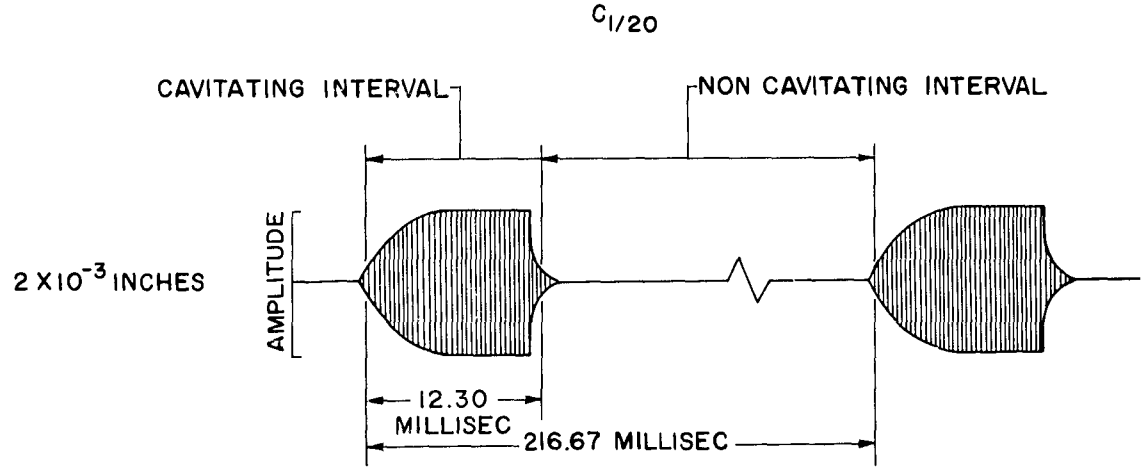

Figure 2. Schematic Representation of the Pulsed Cavitation Pattern for C 1/20 which corresponds to cavitation for 1/20 for the total exposure time.

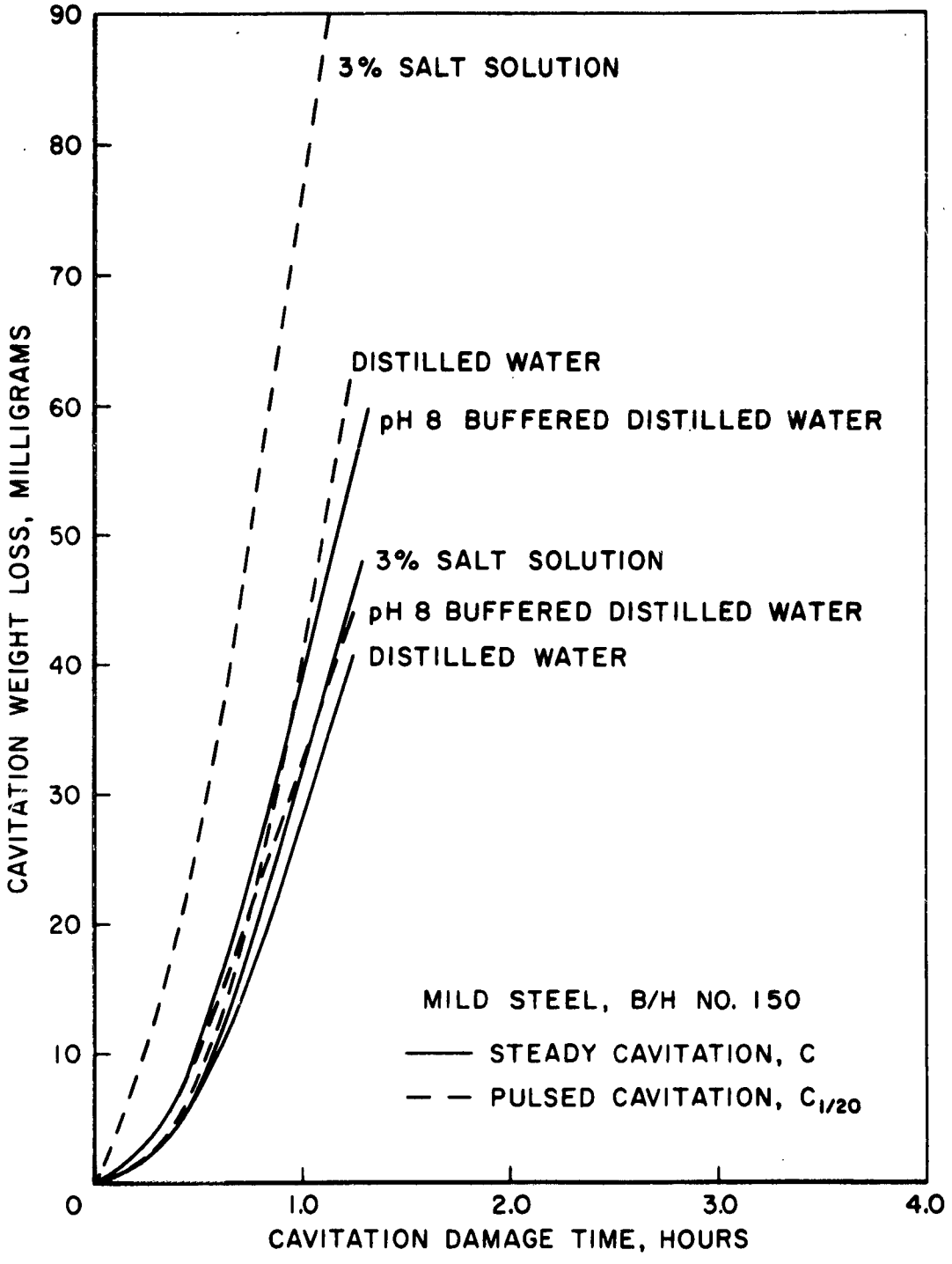

Figure 3. Cavitation weight losses for mild steel are shown under steady and pulsed cavitation conditions in distilled water, a 3 percent solution of salt in distilled water, and in distilled water buffered to pH 8.

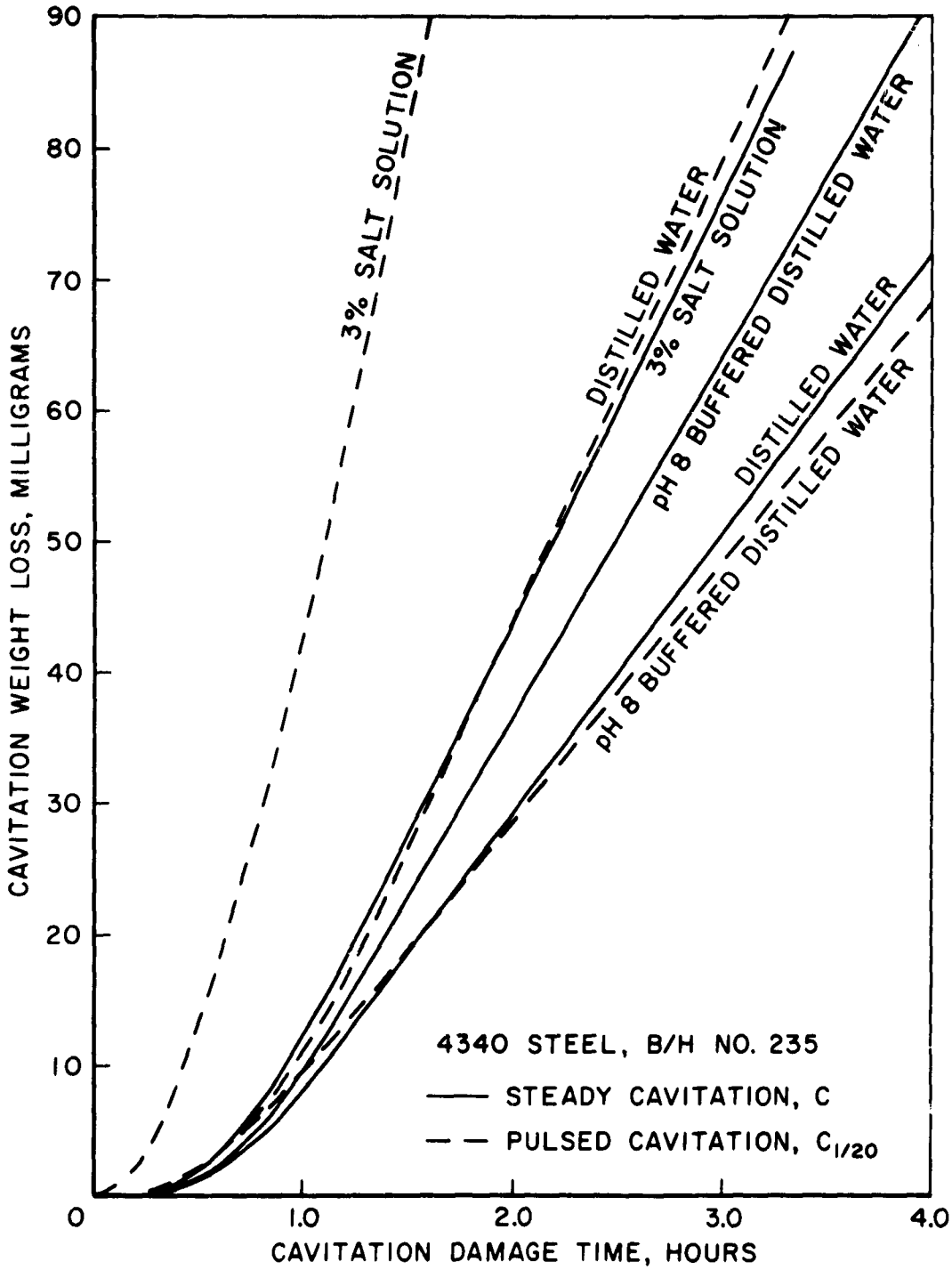

Figure 4. Cavitation weight losses for 4340 steel in the soft condition (Brinell hardness number 235) are shown under the different experimental conditions.

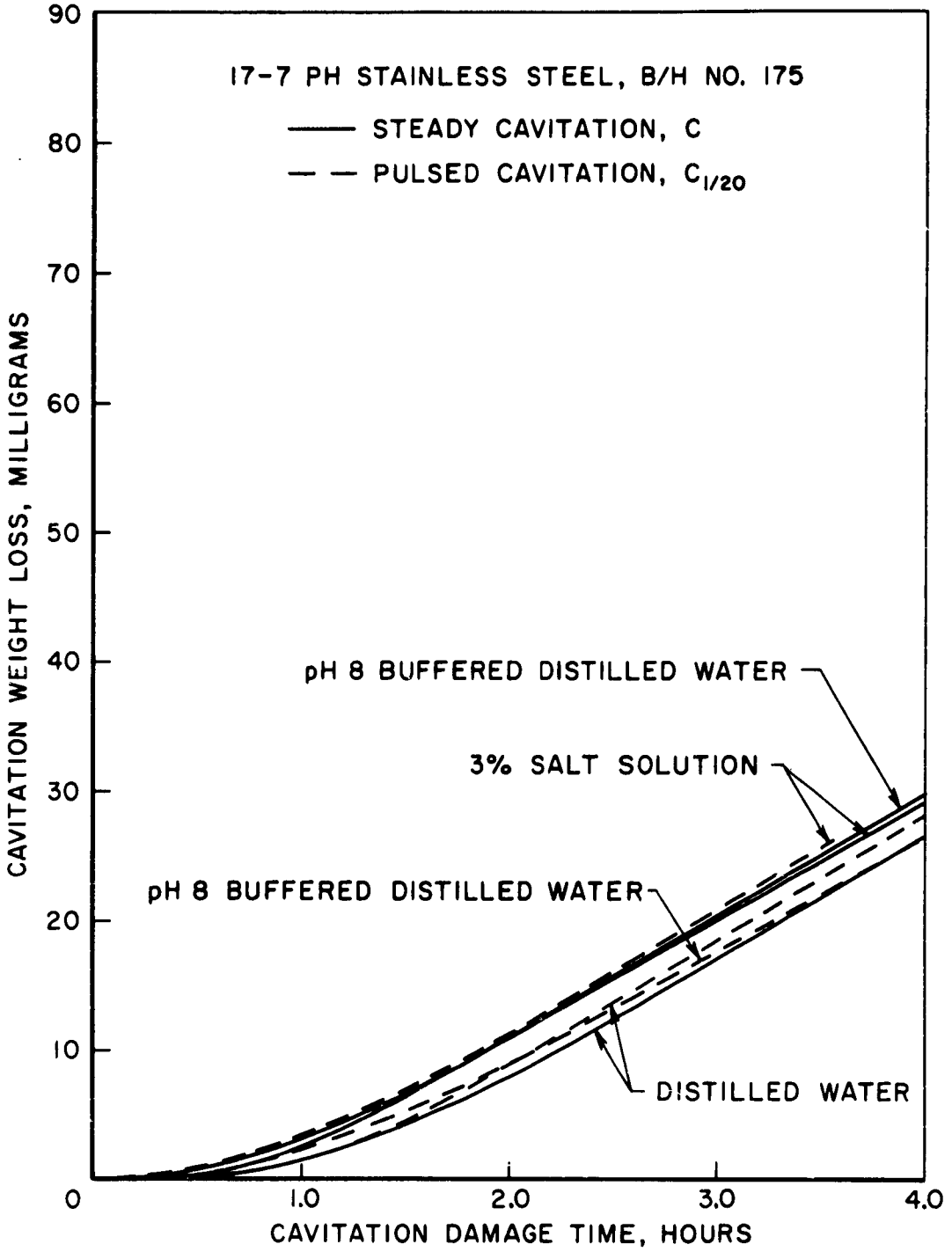

Figure 5. Cavitation weight losses for 17-7 PH stainless steel in the soft condition.

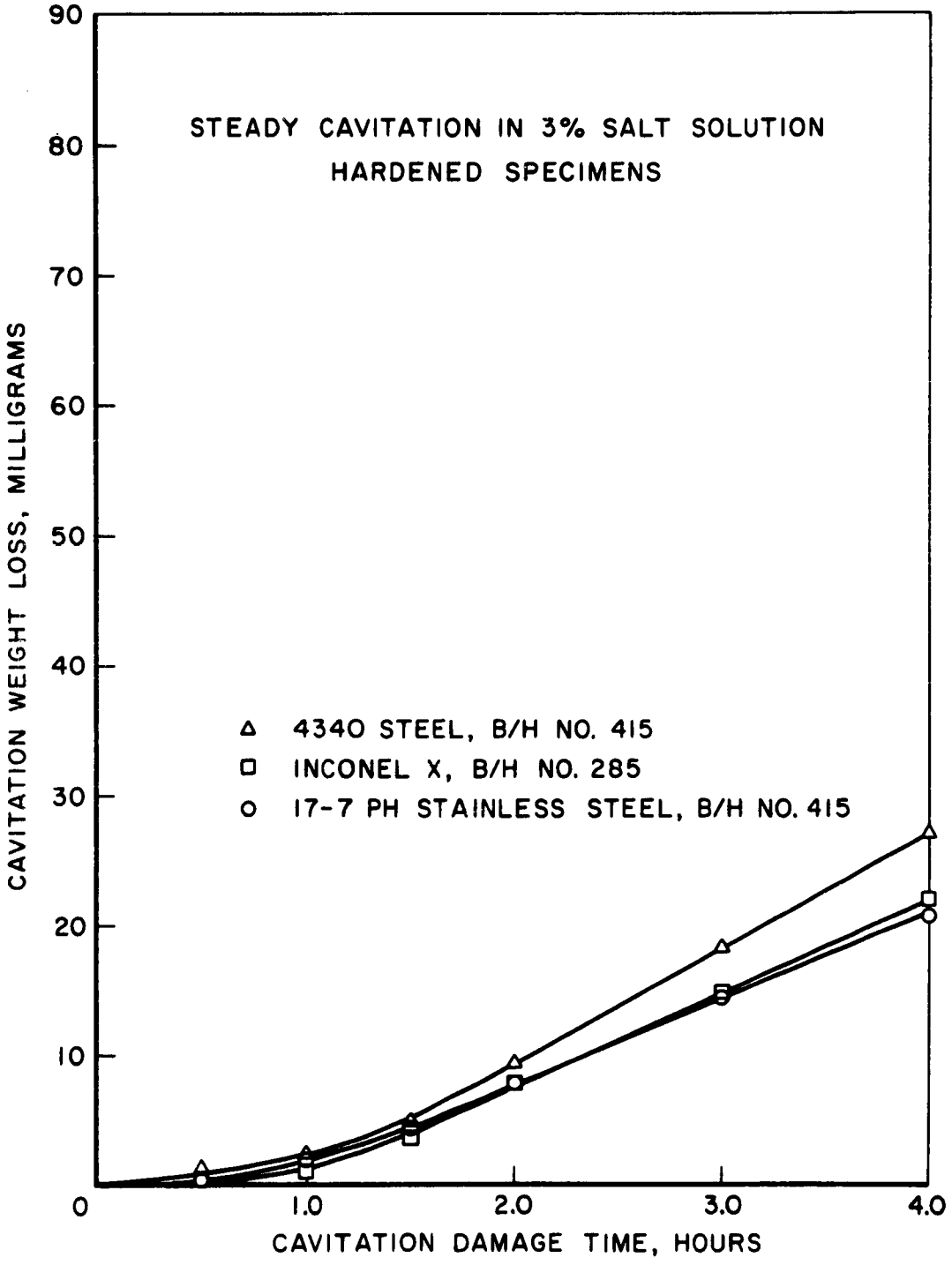

Figure 6. Cavitation weight losses with steady cavitation for hardened specimens in salt solution.

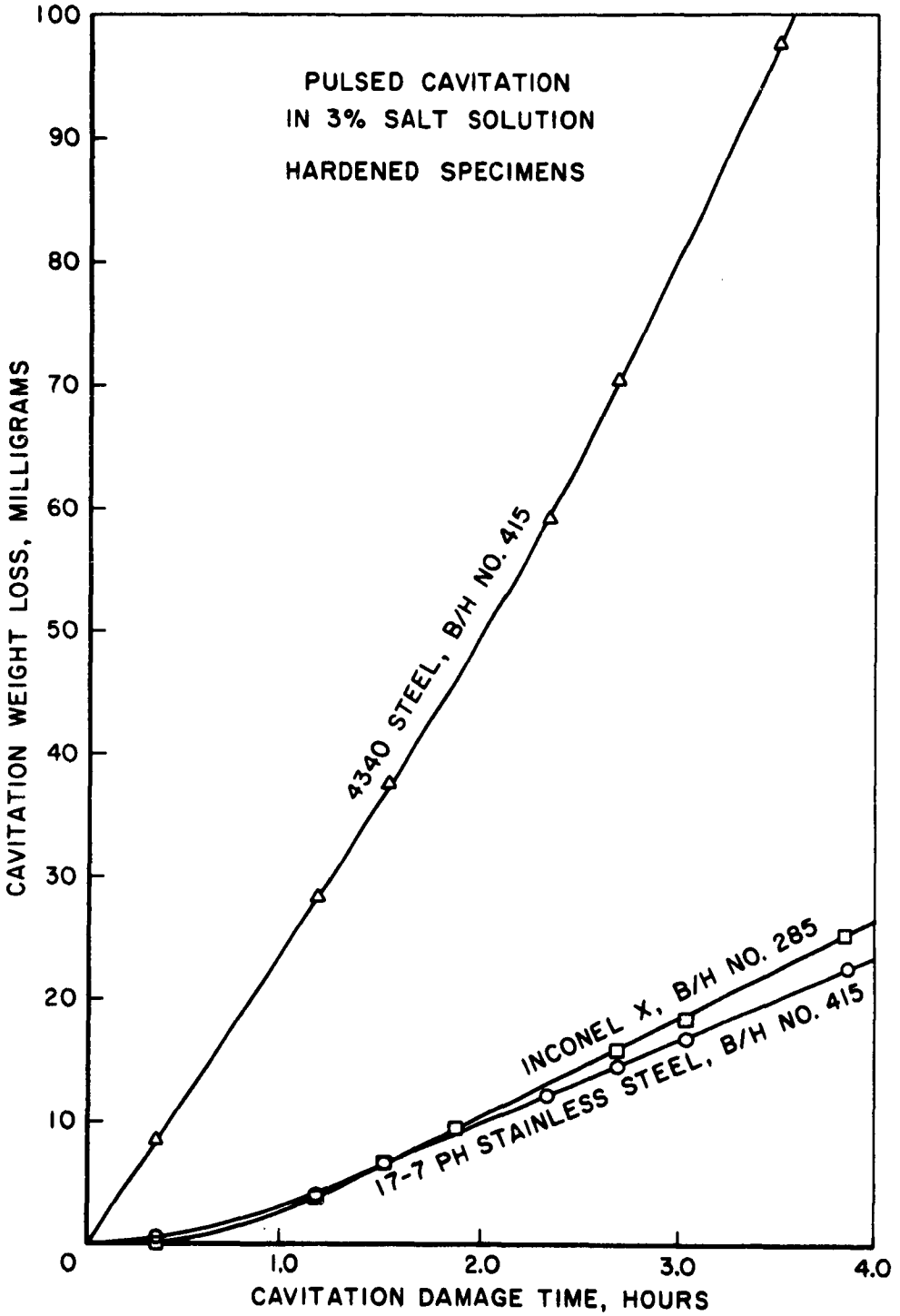

Figure 7. Cavitation weight losses with pulsed cavitation for hardened specimens in salt solution.

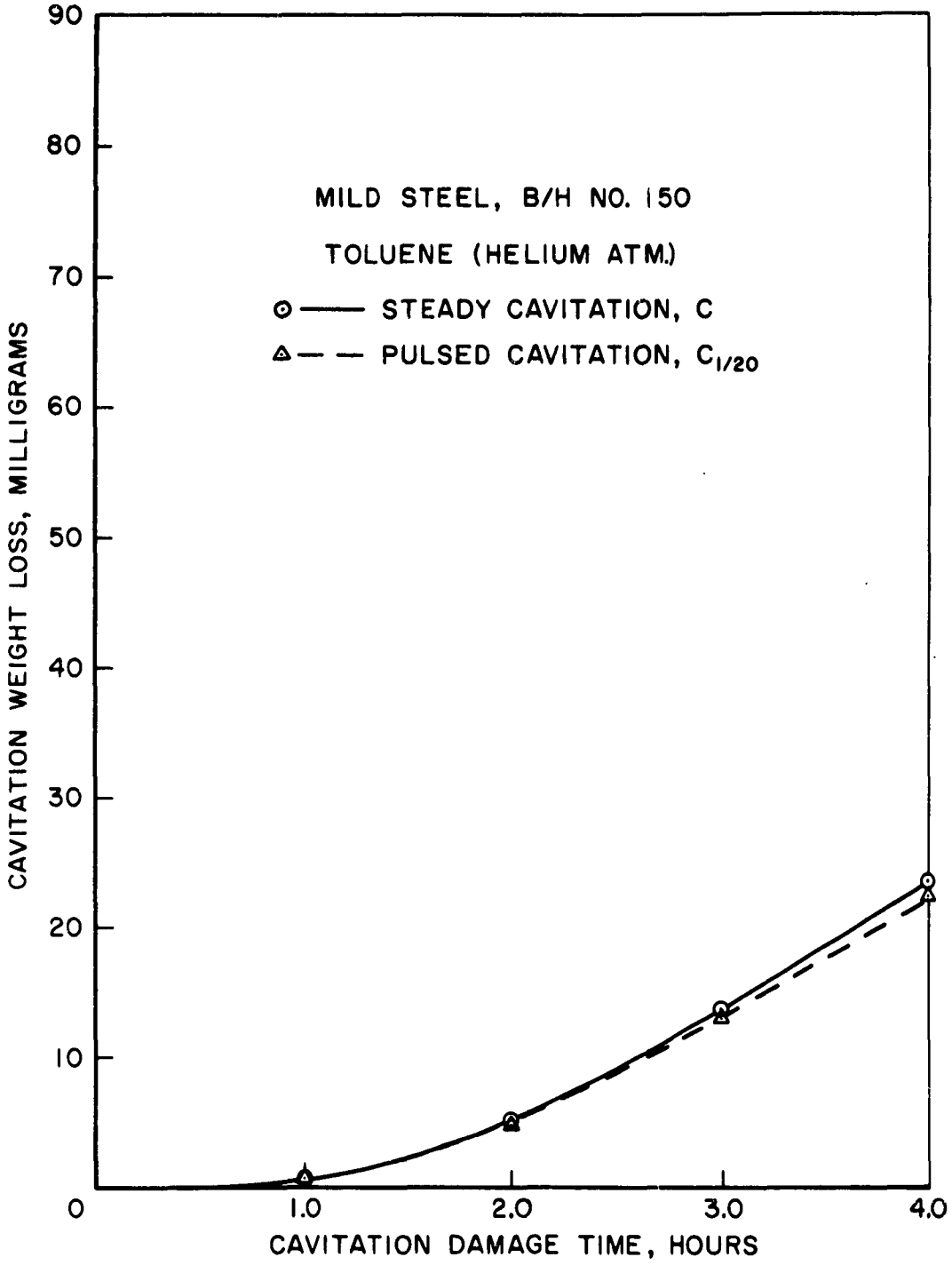

Figure 8. Cavitation weight loss in a chemically inert environment. The specimen material was mild steel; the cavitating liquid was toluene which was deaerated and saturated with dissolved helium; the atmosphere above the liquid was also helium at 1 atmosphere pressure. The pulsed cavitation weight losses are very nearly the same as the steady cavitation weight losses.

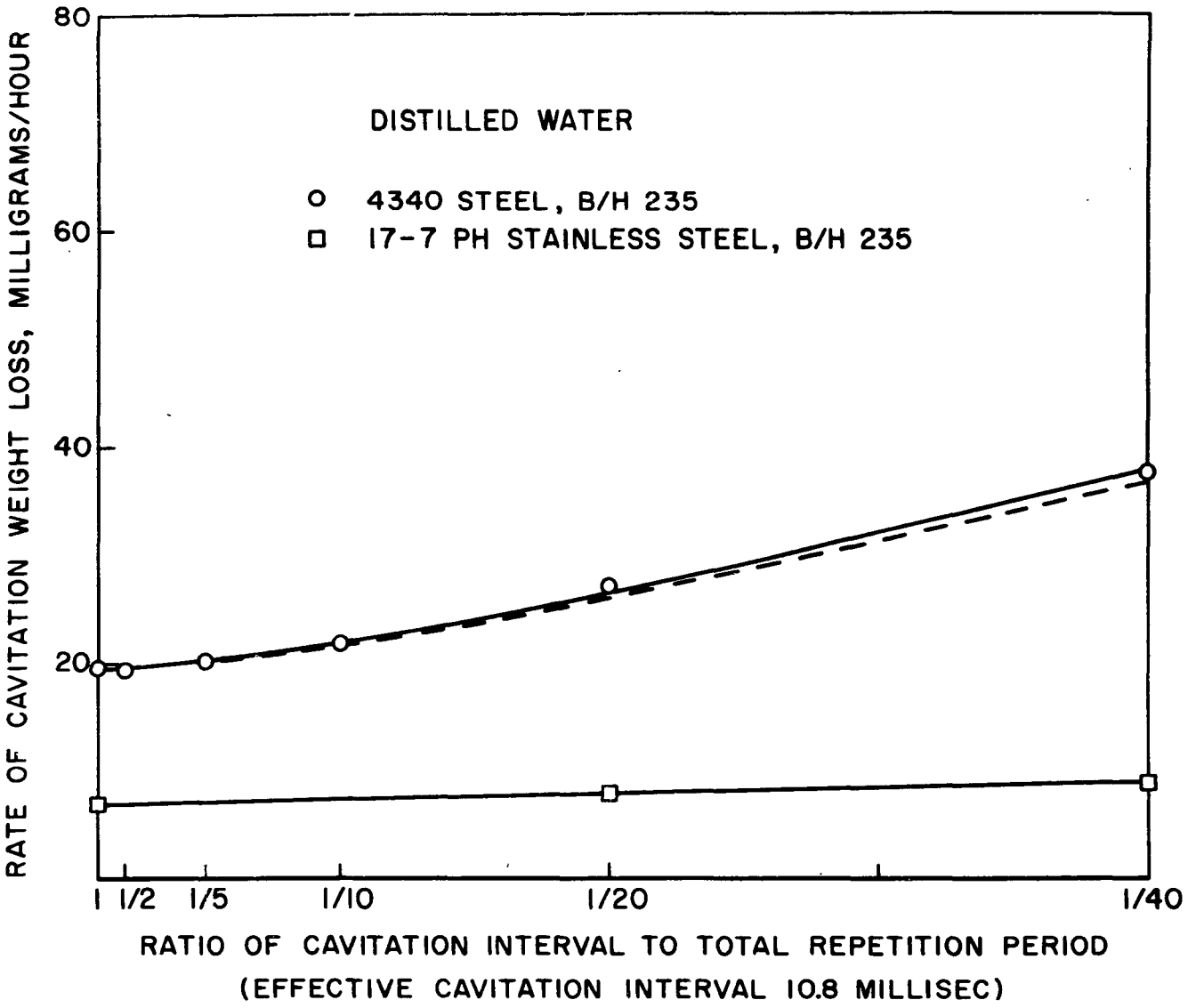

Figure 9. The solid curves show the effect in distilled water of variation of the repetition rate for a fixed pulse period of 12.3 millisec duration which is equivalent to a cavitation interval of 10.83 millisec. The repetition rates include steady cavitation (C 1), the repetition rate of 21.66 millisec (C 1/2), 54.14 millisec (C 1/5), 108.3 millisec (C 1/10), 216.67 millisec (C 1/20), and 433.34 millisec (C 1/40). The dashed curve contains the correction for the rate of static, noncavitating, corrosion.

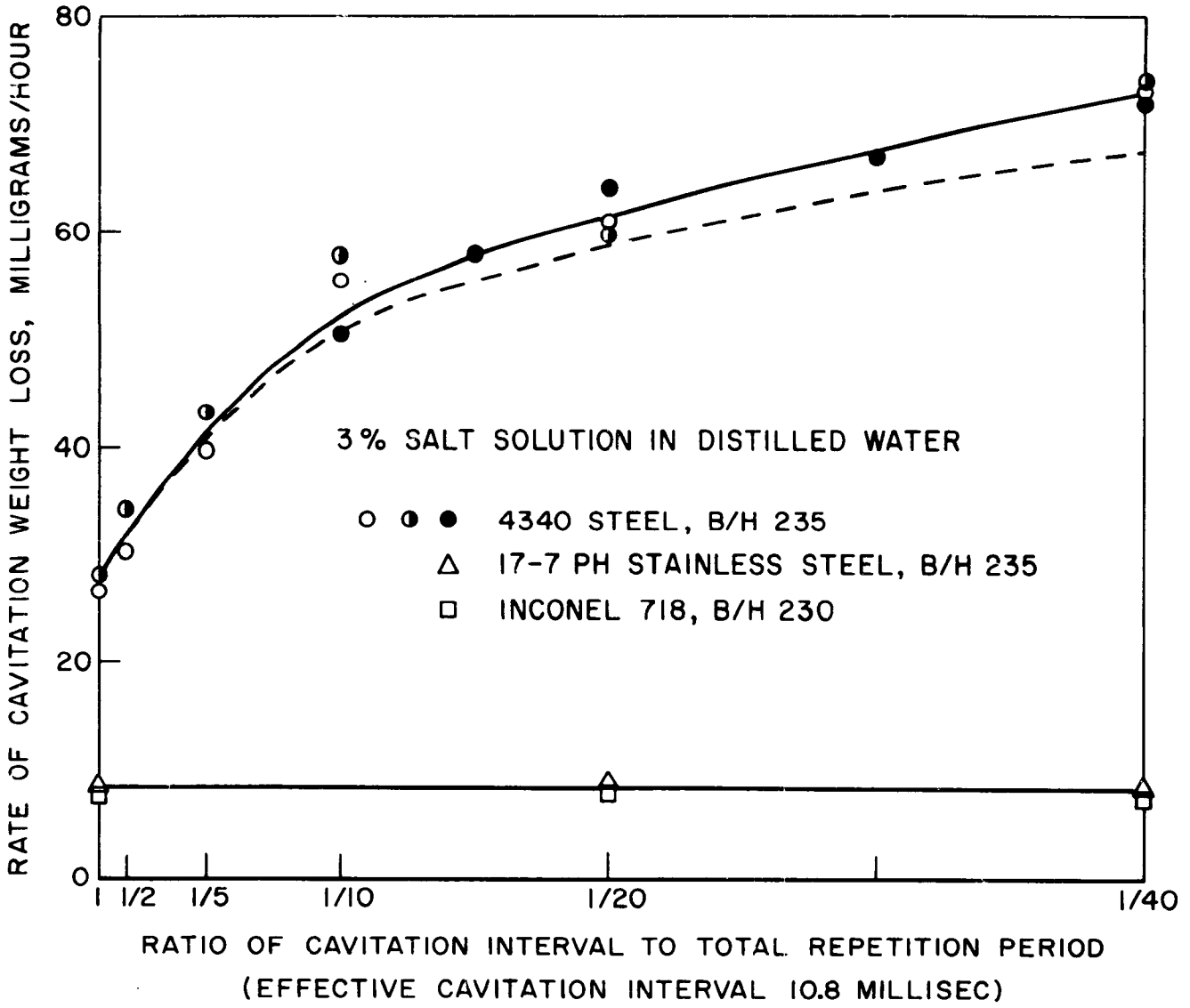

Figure 10. The effect of variation of repetition rate for the fixed pulse duration of 12.3 millisec is shown in the solid curves for salt solution. The dashed curves contain the correction for static, noncavitating, corrosion.

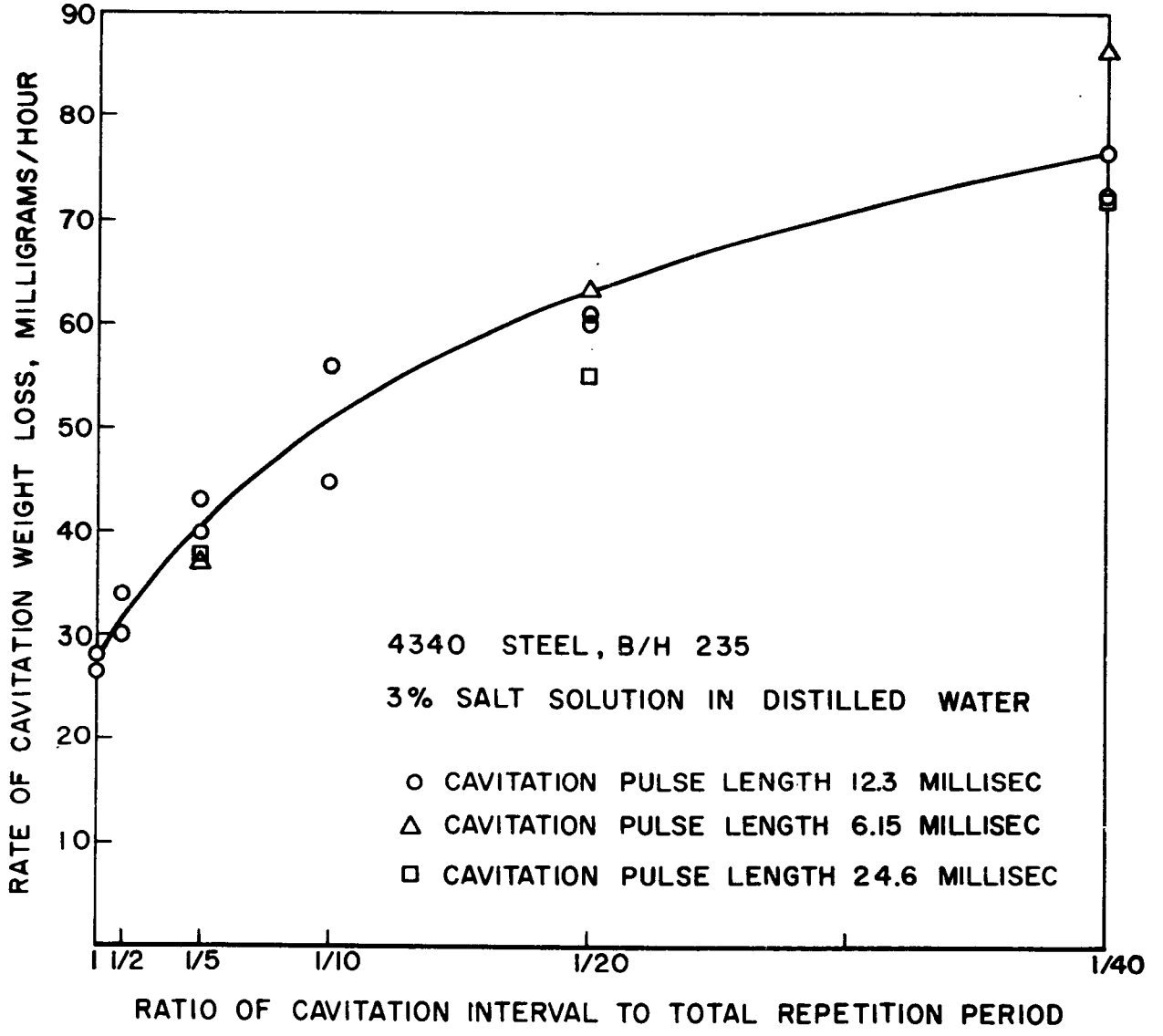

Figure 11. The effect of variation of the pulse duration on rate of weight loss is shown for a range of repetition periods. The liquid was a 3 percent solution of salt in water.

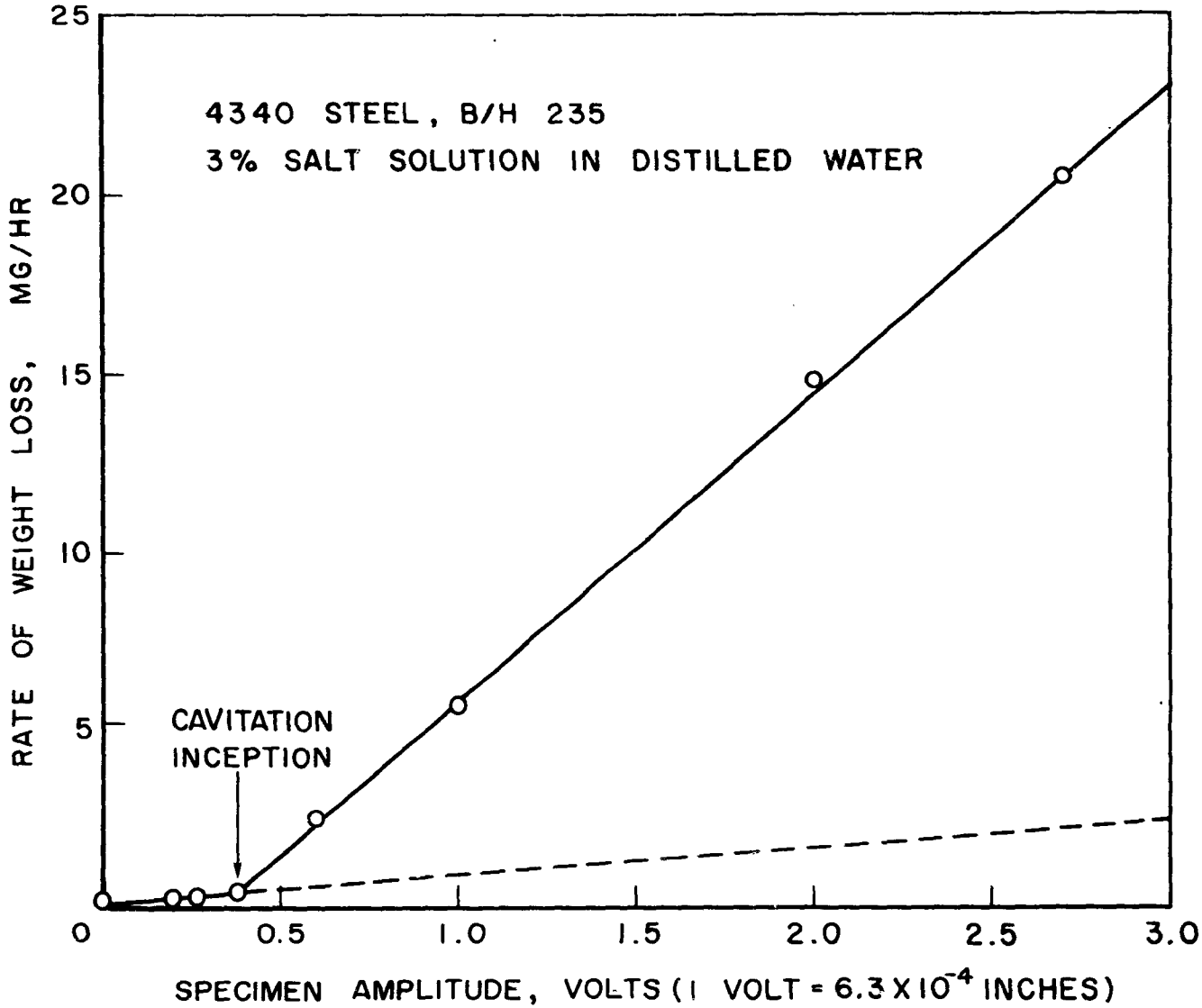

Figure 12. Rate of weight loss in the noncavitating and cavitating region is shown as a function of specimen amplitude for 4340 steel in salt solution. The voltage scale used for the abscissa is directly proportional to specimen amplitude, 1 volt = 6.3 x 10-4.

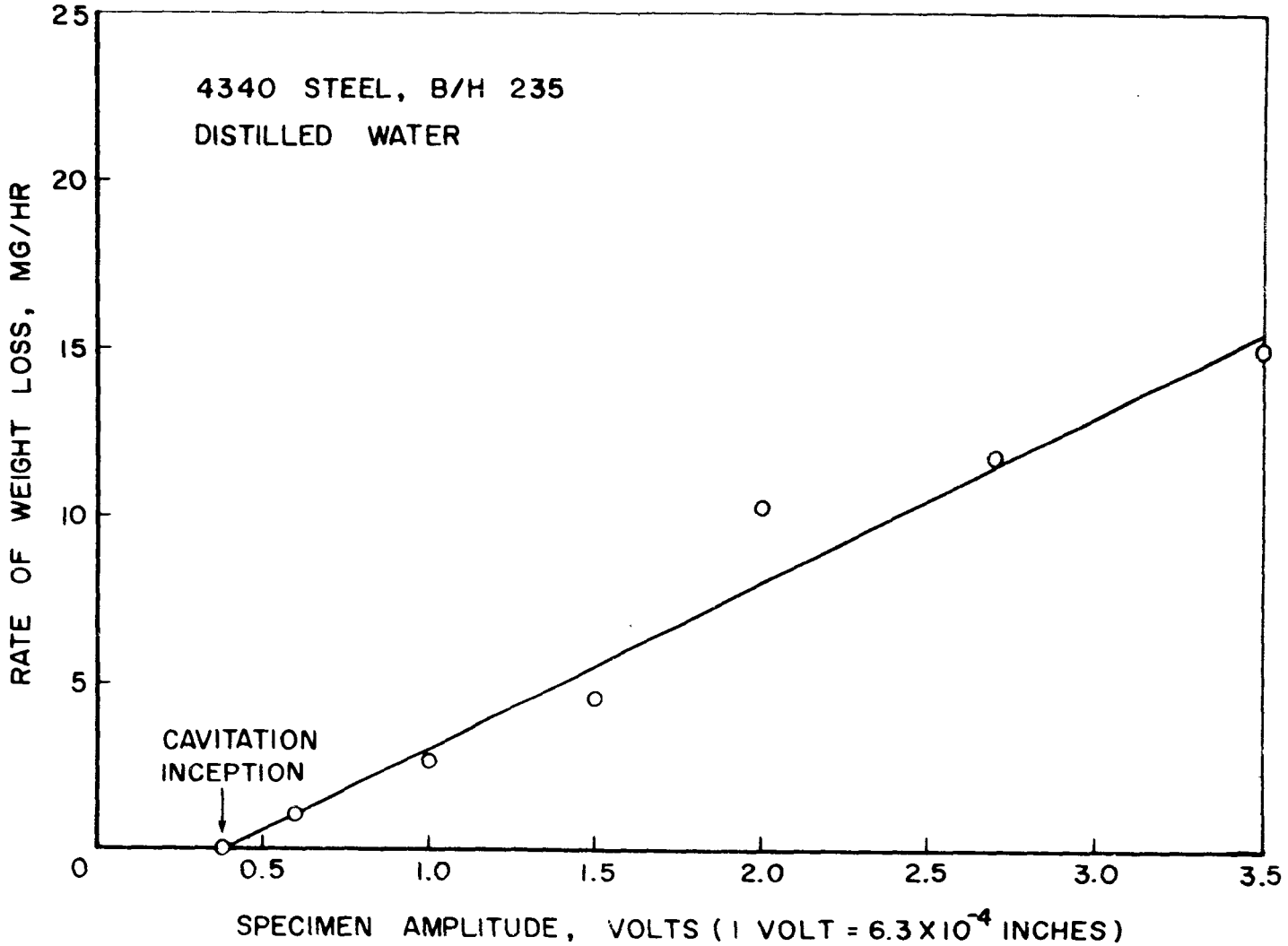

Figure 13. Rate of weight loss in the noncavitating and cavitating region is shown as a function of specimen amplitude for 4340 steel in distilled water. The noncavitating erosion rate is extremely small.

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