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Contract Nonr-220(28)

ON CATHODIC PROTECTION IN CAVITATION DAMAGE

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Summary

An experimental procedure has been developed which makes possible accurate and reproducible determinations of cavitation damage. This procedure has been applied to a study of the effect of cathodic currents on cavitation damage. A series of experiments in which the test liquid was a solution of salt in water showed a reduction in cavitation weight loss for all of the materials examined when the test specimen was made the cathode of an electrolytic cell and when the conditions were such that gas was evolved at the specimen surface. This protective effect against cavitation damage increased with increasing magnitude of the cathodic current. These observations support the view that the protective effect was due to the layer of hydrogen gas evolved on the surface of the specimen. A similar protective effect was observed when the specimen was made the anode in a test liquid which was buffered distilled water; in this situation the gas evolved at the specimen surface is oxygen. Additional evidence for this protective mechanism of a gas layer on the specimen surface was found in a series of experiments in which the voltage applied to the cell was reduced to a level at which no gas was evolved on the surface. There was then no protective effect with the specimen cathodic or anodic.

Introduction

Large mechanical stresses are known to be produced[1] in a solid when cavitation bubbles collapse near the surface and the importance of this physical effect has been emphasized in studies described elsewhere.[2] Some investigators[3,4], on the other hand, have emphasized the possibility of chemical effects in cavitation damage and have found a protective effect for a metal specimen when it is made the cathode of an electrolytic cell while it is being exposed to cavitation. The value of cathodic protection for a metal exposed to corrosion in an active liquid with no cavitation is well known. In such cathodic protection, the current flow in the cell reduces any galvanic action between possible anodic and cathodic areas on the surface of the metal. There is also the possibility of hydrogen liberation at the surface of the metal. The question which is to be considered here is whether making a metal the cathode of an electrolytic cell has any specific effect in protecting against cavitation damage. The series of experiments described below were designed to give some information on this question.

The Experimental Apparatus and Procedure

The apparatus used in the experiments is shown in Figs. 1-3 and a block diagram is given in Fig. 4. Alternating current is supplied at an adjustable frequency by an audio oscillator (see Fig. 4), and is amplified in a power amplifier so that a nickel transducer stack may be excited into mechanical oscillation. The amplitude of these mechanical oscillations of the transducer stack is increased by means of a solid steel exponential horn soldered to the end of the stack. This horn tapers to a cylindrical section in the end of which the specimen is screwed (Fig. 2). The specimens have a threaded portion and a cylindrical portion; the cylindrical section is 5/8 in.

in diameter and about 3/16 in. thick. The specimens were immersed to approximately half this cylindrical depth in the test liquid. The oscillations generated in the horn are such that the motion is almost totally confined to the axial direction; an account of this use of such a horn, together with the theory, may be found elsewhere.[5, 6] The vibration of the specimen was observed with a microscope and the amplitude was determined from a scale. A much more accurate way of following the relative amplitude of oscillation was furnished by the displacement pickup coil. This displacement detector consisted of a coil of wire wound on an annular magnet through which the horn passed. The oscillations of the horn generated an alternating current which was read on a vacuum tube voltmeter (see Fig. 4). The vacuum tube voltmeter reading made it very easy to hold the specimen oscillation amplitude constant during an experiment. The double amplitude of the oscillation was kept at 0.0020 in. for most of the test runs. The oscillation frequency was determined by the resonant frequency of the system which was approximately 14.2 kilocycles.

During a test run not only could the amplitude be held constant but the cooling requirement for holding the test liquid temperature constant was easily met. The specimens were accurately weighed before each run. After a run, the specimen was washed in distilled water, then in ethyl alcohol, and dried in a vacuum desiccator before being weighed.

When the specimen was made one electrode of an electrolytic cell, the second electrode was in every case a platinum wire insulated from the liquid except at its end (see Fig. 3) which was mounted in a plastic tripod. The exposed end was a disk, also of platinum. During these runs the current was held constant although the voltage was also measured. The current and voltage readings were relatively insensitive to the distance between the electrodes but this distance was kept at the constant value of 1.5 cm.

Modification in the Shape of the Specimens

The specimens which were used initially for the tests had flat surfaces exposed to cavitation. With specimens of this shape it was found that there was a serious lack of reproducibility in experimental results in spite of every effort to control the experimental conditions. This lack of reproducibility in the data was connected with the nonuniform nature of the cavitation damage on the specimen surfaces. This nonuniformity of the damage was evident in the formation of deep radial ruts, examples of which are shown in Fig. 5. The number and depth of these ruts varied from one specimen to another even when the test conditions were kept the same. There was some correlation of larger weight losses with a larger number of these radial ruts, and smaller weight losses with a smaller number. It may be remarked that the damage patterns found in the experiments described here are fairly uniform compared to other damage patterns observed with magnetostrictive devices.[7] These radial ruts or "stars" were investigated also for specimens of smaller diameter and it was found to occur in the same way as for specimens of larger diameter. The formation of the star pattern appeared to be unconnected with any vibration mode of the specimen surface, as is also indicated by the observations elsewhere[7] that these star patterns are independent of the specimen thickness.

The explanation of these star patterns in the cavitation damage with these flat specimens has hydrodynamic basis. As the specimen oscillates, the cavitation bubbles are formed in the half-cycle during which it moves away from the liquid. This motion of the specimen away from the liquid is accompanied by a flow which has a radially inward component over the specimen face. The cavitation bubble cloud is consequently somewhat concentrated toward the center of the face during this interval of growth of the bubbles. In the subsequent half-cycle during which the specimen moves into the liquid, the cavitation bubbles are collapsed. It is, of course, the bubble collapse that produces the cavitation damage. This motion, during this collapse portion of the cycle, must be accompanied by a liquid flow which has a component directed radially outward over the specimen surface. The bubble cloud consequently experiences some radial outward acceleration so that a flow region containing a mixture of bubbles and liquid is being accelerated into a flow region containing only liquid. In this collapse portion of the cycle, one has, therefore, a situation in which a lighter fluid medium is being accelerated into a heavier one. This situation produces a Taylor instability.[8] The cavitation cloud should therefore develop fingers, or rays, of bubbles. This type of behavior is observed and is shown in Fig. 6 which is a short exposure photograph of the face of a specimen while undergoing high-frequency vibrations in water. Once damage has been initiated in some radial directions, there would be a definite tendency for the instability to persist in these directions so that the more intense damage should appear in a star pattern. A mechanism of this kind with an element of randomness arising from an instability would clearly lead to difficulty in obtaining reproducibility of weight loss in damage tests.

This explanation of the lack of reproducibility in cavitation weight losses suggests a modification in the shape of the specimen, and the success of this modification, in turn, supports the explanation. On the basis of the mechanism just described, it follows that a reduction in the magnitude of the radial accelerations over the face of the specimen would make the damage patterns more uniform and would at the same time make the damage determinations more reproducible. Specimens were therefore tried which did not have completely flat surfaces but which, instead, were "dished" so that they consisted of a flat surface surrounded at the edge by a wall approximately 0.030 in. high and 0.010 in. thick (see Fig. 7). The damage pattern obtained with such a dished specimen face is shown in Fig. 8. It is extremely uniform, and it is clear that the reduction in the radial flow by providing a stagnation rim has eliminated any kind of preferential damage which took place previously. As might be expected, this type of specimen gave much more consistent results than the flat specimens, and it was adopted for all the experiments reported here. It is estimated that the error in cavitation weight loss determinations given below is within $\pm 2 \times 10^{-4}$ gms.

The Current Field in the Test Cell

Some studies were made of the electric current field between the platinum electrode and the test specimen which was of the dished-face type. The purpose of this investigation was to make certain that a significant fraction of the current flowed to the face of the specimen. The findings are illustrated for a specimen of mild steel (1018) made cathodic relative to the platinum electrode in a 3% solution of NaCl in distilled water. The circuit had an inherent back emf due to electrolytic action which always had to be subtracted from the external voltage readings. For a given current, the voltage between the electrodes was observed to decrease noticeably with the onset of cavitation vibrations. This observed reduction in the cell resistance is presumably due to the agitation and partial removal of poorly conducting layers of hydrogen gas at the cathode. The voltage as a function of cathodic current to the test specimen in the noncavitating (stationary) condition and in the cavitating condition is shown in Fig. 9.

In order to determine the proportion of the total current which passed through the cavitating part of the cathode surface, two dished specimens were prepared, one of which had the flat surface exposed to cavitation coated with insulating enamel and the other of which had its sides and the edge of the dish coated. The enamel used was FORMVAR, a material used by the General Electric Co. for wire insulation. The current readings for the salt solution are shown in Table 1 for a total impressed voltage of 3 volts. Since all the current measurements given in Table 1 were at the same voltage, they are inversely proportional to the cell resistance. As has been remarked, the cell resistance in all three configurations shows a marked decrease when cavitation is taking place. With no cavitation, there is only a small difference in the cell resistance between a specimen with its sides insulated and a specimen with its face insulated. In the cavitating condition, however, the cell resistance is found to be much lower for the specimen with insulated sides than for the face-insulated specimen. This "depolarizing" effect when cavitation is taking place over the specimen face indicates that some physical removal of hydrogen from the specimen surface is produced by the cavitation bubbles. These current measurements also indicate that a large fraction of the current flows to the face of the specimen while cavitation occurs.

Cavitation Damage Results in Salt Solution with Cathodic Currents

A series of experiments were carried out in a 3% solution of NaCl in distilled water with specimens made of several different materials.

The results with mild steel (1018) are summarized in Fig. 10. The composition of this material is as follows:

C	Mn	P	S
0.17%	0.73%	0.007%	0.024%

The Brinell hardness number (on the scale of a 10 mm ball with 500 kg load) averaged 160 and was found to vary only slightly with each specimen. Each curve shown in Fig. 10 is the average of the weight loss values which were measured with three different specimens. Examples of the data, and the average curve, are shown in Figs. 11 and 12.

The results with 4340 steel, of Brinell hardness number 210 (on the 3,000 kg scale), are summarized in Fig. 13. Each of these curves is the average of the data for three different specimens. Examples of the data, together with the average curve, for a few values of cathodic current are shown in Figs. 14, 15, and 16.

The results with 17-7 PH stainless steel, of Brinell hardness number 235 (on the 3,000 kg scale), are shown in Fig. 17. Examples of the data, together with the average curve, for a few values of cathodic current are shown in Figs. 18, 19, and 20.

The preceding series of experiments all showed very similar trends, but it seemed desirable to study a material of a quite different kind. It was thought of interest to examine a relatively inactive metal which could be easily obtained with high purity. Copper was therefore investigated with the results shown in Fig. 21. Figures 22, 23, and 24 show examples of the data obtained together with the averaged curves.

The trend found with specimens made of the various steels continued with the pure copper. It must be emphasized that in all of these experiments in the salt solution, the evolution of hydrogen was observed on the specimen surface even at the lowest cathodic current (1 milliamp). This finding of a protective effect against cavitation damage for such a range of materials suggests that the observed hydrogen evolution provided a cushioning effect. A further indication in this direction is the general result that the weight loss decreased monotonically with increasing rate of gas evolution, or with increasing cathodic current. This result is reasonable since the study of the current-voltage relation with and without cavitation indicated that some of the hydrogen layer was removed by the cavitation. Presumably, if the hydrogen gas layer was complete and undisturbed by the cavitation, the cavitation damage would disappear.

Cavitation Damage Results in Buffered Water with Cathodic and Anodic Currents

In order to give further indication that gas evolution is the significant effect in so-called cathodic protection, it would be most desirable to be able to perform cavitation tests while the specimen was the anode of a cell and at the same time had gas evolved at its surface. It was suggested to the writer by Mr. F. L. LaQue, of the International Nickel Co., that such experiments could be done quite readily in buffered distilled water with stainless steel specimens. Such a series of experiments was performed in distilled water buffered to pH 8. One electrode of the cell was platinum as before and the other was the specimen which was 17-7 PH stainless steel. In the first series of experiments, the specimen was the cathode of the cell, and cavitation damage was determined for cathodic currents of 20, 50, and 100 milliamperes. For all of these current values, hydrogen gas was visually observed to be evolved at the specimen. The results of the measurements of cavitation damage weight losses are summarized in Fig. 25. Examples of the data are shown in Figs. 26, 27, and 28. The reduction in cavitation weight loss which increases with the magnitude of the current is clearly demonstrated.

In a second series of experiments, the stainless steel specimen was made the anode of the cell and cavitation damage was measured for anodic currents of 40, 100, and 200 milliamperes. For all of these currents, gas could be visually observed to be evolved at the specimen. The gas evolved at the anode is oxygen and, in order to compare the anodic and cathodic values for the same volume rate of gas evolution, the anodic current must be double that of the cathodic current since the valence of oxygen is twice that of hydrogen. The summary of these cavitation weight losses with anodic currents is shown in Fig. 29, and examples of the data are shown in Figs. 30 and 31.

From the comparison of these cathodic and anodic experiments at corresponding currents, it is evident that there is a protective effect against cavitation damage in both cases which is roughly of the same magnitude. In making such a comparison it must be kept in mind that there is a weight loss in an anodic specimen entirely independent of cavitation damage which is produced by electrolytic solution of the anode material. The weight loss in a specimen exposed to cavitation damage should be corrected for this effect when the specimen is the anode of the electrolytic cell. After such a correction, a more precise comparison of the weight losses in the cathodic and anodic cases may be made. Figure 32 shows such a comparison. When the curves of this figure are compared with the open circuit weight losses, it is clear that there is a large protective effect which is very nearly the same in both cases. There is, however, an indication that the weight losses are slightly higher in the anodic case. This difference is so small that it might appear to be subject to question. In order to get additional information on this point, rather sensitive measurements are required. The following type of experiment was undertaken for this purpose. It may be noted in the experimental data that the initial values of the cavitation weight losses as a function of exposure time correspond to slower rates than the later values.

This initial behavior has been described as being due to an "incubation period". It is probably a result of incomplete roughening of the surface in the early stages of the cavitation damage. In the later stages of cavitation exposure, the weight losses become linear functions of exposure time, at least until the surface becomes severely damaged. This behavior of the weight loss has been used to get additional information on the relative effects in the cathodic and anodic cases. The results of these determinations of weight losses in the post-incubation, or linear, region are shown in Fig. 33. The anodic curve is shown after correction for weight loss due to electrolytic solution as a result of the current flow alone. Even after this correction is made, there is an indication that the rate of anodic cavitation weight loss is slightly greater than the corresponding cathodic weight loss.

It is clear that there is a protective effect both for the cathodic and anodic cases which is associated with gas evolution and which is to be ascribed to a cushioning effect of the gas being evolved. One may say, further, that the amount of the protective effect is roughly the same in the two cases. There is evidence, however, that the weight losses for corresponding values of the currents is somewhat greater in the anodic case than in the cathodic case. Such a result is not surprising since, in the anodic situation, anode material is going into solution by the electrolytic action of the current. That the weight loss under exposure to cavitation should be slightly enhanced under such conditions could very well be expected. This nonadditive, interaction, effect of the anodic current erosion and the cavitation erosion is under continued investigation.

A final type of experiment which is readily performed with a cathodic or anodic specimen in buffered distilled water is the reduction of the current level to so low a value that no visible gas evolution occurs. Such a reduction in current level for the cathodic experiments with the salt solution was not practicable since gas was observable at the cathode with currents as low as 1 milliamp. It was found that there was no observable gas evolution at a cathodic or at an anodic specimen in the buffered water at a current of 2 milliamps. Under such conditions, no protective effect in cavitation damage should be detected. In order to obtain high experimental sensitivity, the specimens used were in the post-incubation, or linear, stage of cavitation weight loss. Further, each specimen was run alternately as a cathode with 2 milliamp current and then at zero current. Similarly a specimen was run alternately as an anode at 2 milliamp current and then at zero current. The successive values of the cavitation weight losses were measured and they are shown in Fig. 34 for 4340 steel specimens and in Fig. 35 for 17-7 PH stainless steel specimens. The arrows in these figures show the direction of the successive cavitation experiments. It should be remarked that any anodic electrolytic weight losses at the current levels used would be extremely small. Within the limits of experimental accuracy there was no protective effect for these cathodic or anodic currents.

Conclusions

1. Experiments in a 3% solution of salt in water showed a protective effect in cavitation damage for a wide variety of materials when the test specimens were made the cathodes of an electrolytic cell. The reduction of the cavitation weight loss is associated with the evolution of gas (hydrogen) at the surface of the specimen.

2. Experiments in buffered distilled water showed a protective effect in cavitation damage both when the specimen was an anode and when it was the cathode of an electrolytic cell provided the voltage or current was high

enough so that gas would be liberated at the specimen surface.

3. Experiments in buffered distilled water at voltages or currents so low that no gas was evolved showed no protective effect either for cathodic or anodic specimens.

4. It is strongly indicated that a cathodic or anodic protective effect in cavitation damage is primarily due to a cushioning effect of the gas which is electrolytically liberated at the material surface.

5. An interesting, nonadditive or incremental, weight loss of small magnitude is indicated when a specimen is simultaneously losing mass by electrolytic current transfer and by cavitation damage. There is no indication as yet of any reverse effect due to any corrosion protection when a specimen is the cathode while being exposed to cavitation weight loss.

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Table 1

Test Specimen Cathode and Platinum Anode, Impressed Voltage 3 volts

Bare specimen	no cavitation	2.3 milliamperes
	with cavitation	6.2 "
Specimen with sides insulated	no cavitation	1.6 "
	with cavitation	4.4 "
Face-insulated specimen	no cavitation	1.5 "
	with cavitation	2.8 "

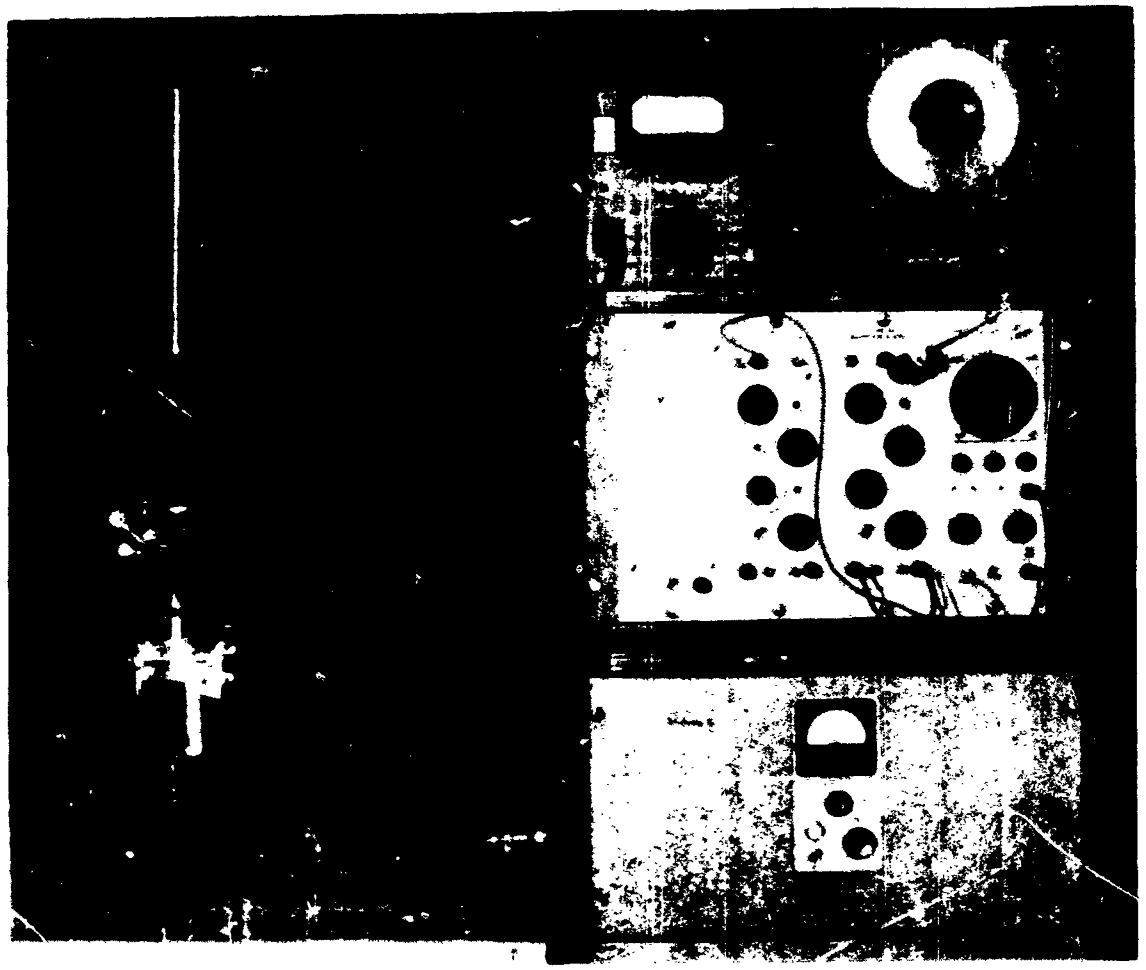


Fig. 1 - Apparatus used to generate cavitation including oscillator, amplifier, nickel stack, stainless steel horn and pick-up coil.

Fig. 2 - Specimen being attached to the end of the horn.

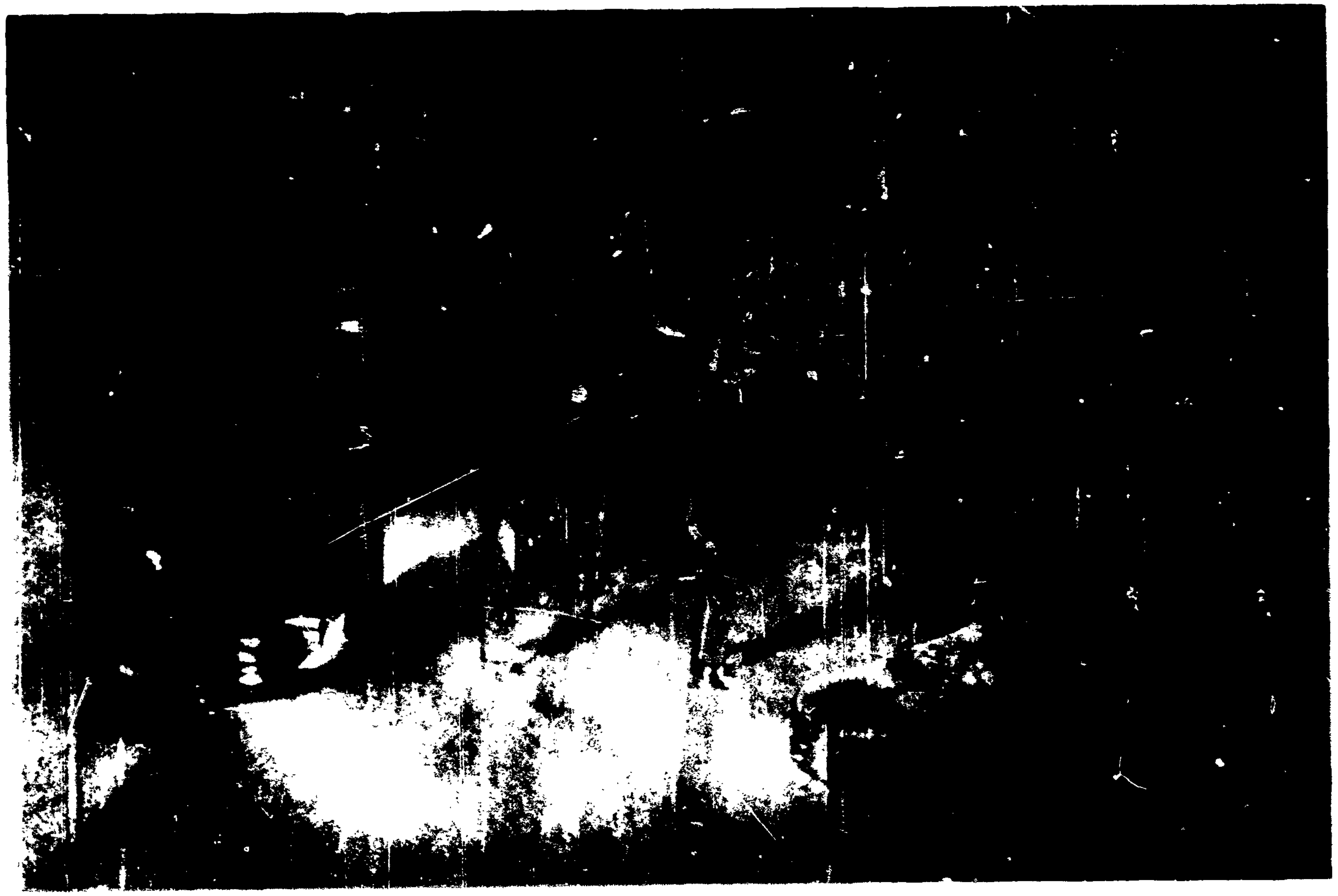


Fig. 3 - Platinum anodes used for cathodic protection tests.

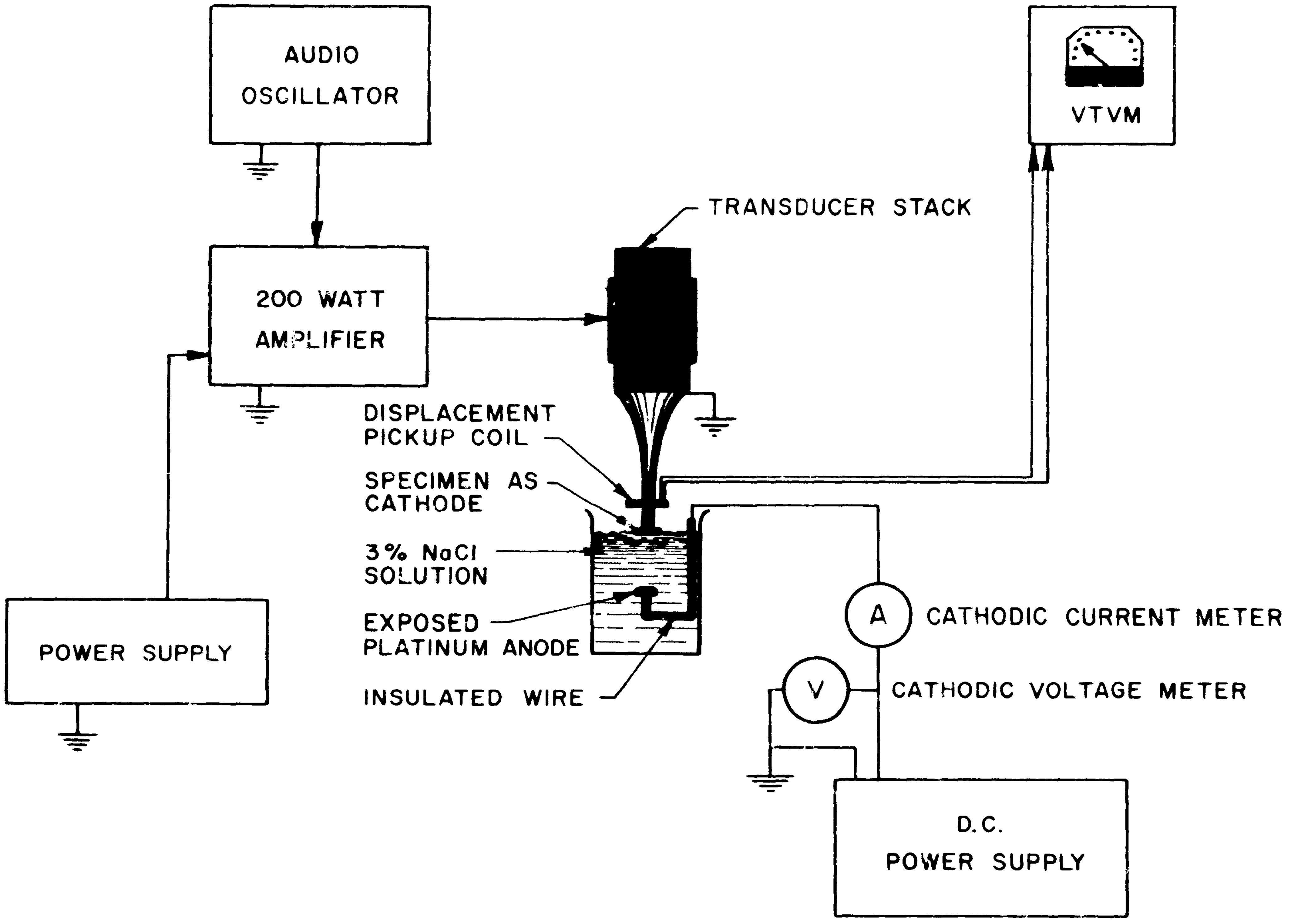


Fig. 4 - Block diagram showing the circuit used to generate cavitation on the specimen, and the circuit for cathodic protection.

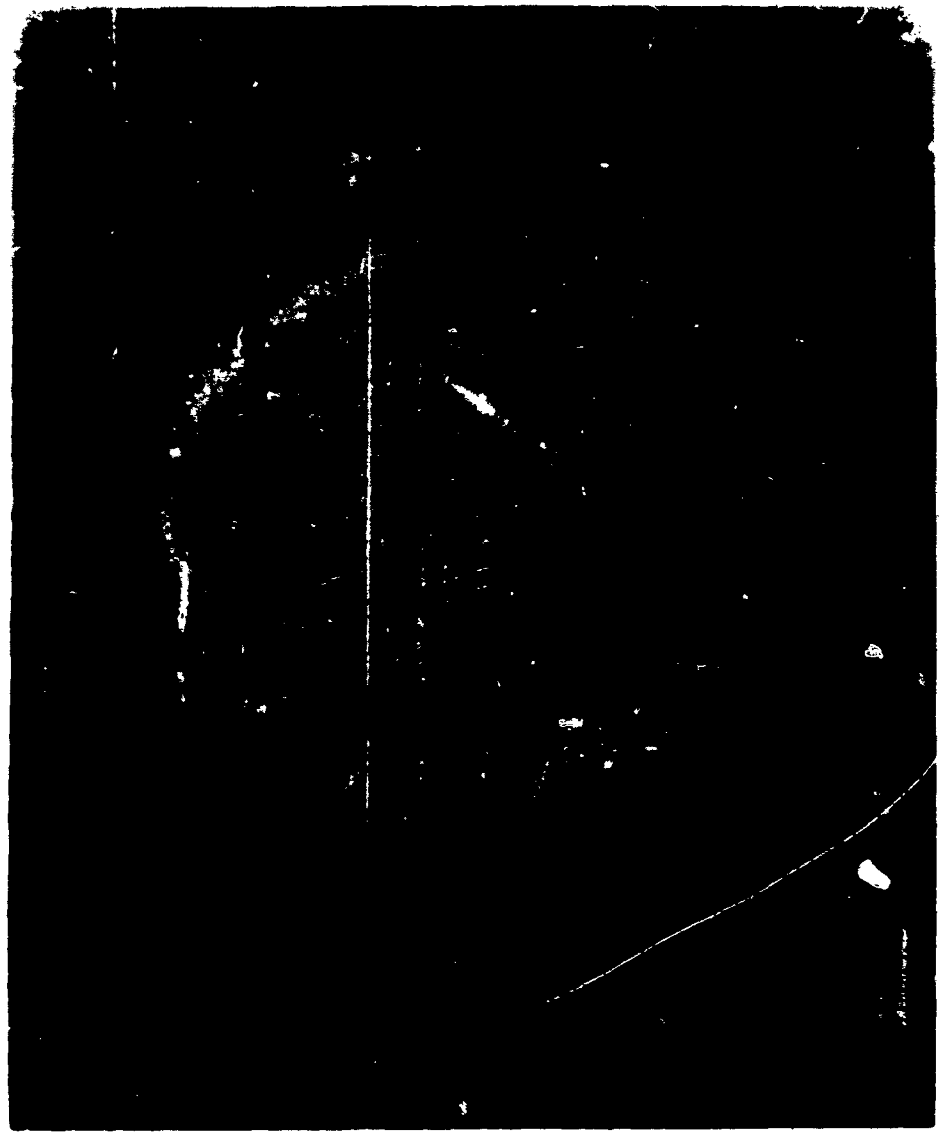


Fig. 5 - Cavitation damage on a flat specimen with no cathodic protection.

Fig. 6 - Cavitation cloud shown on the face of the oscillating specimen.

Fig. 7 - Photograph of a dished specimen.

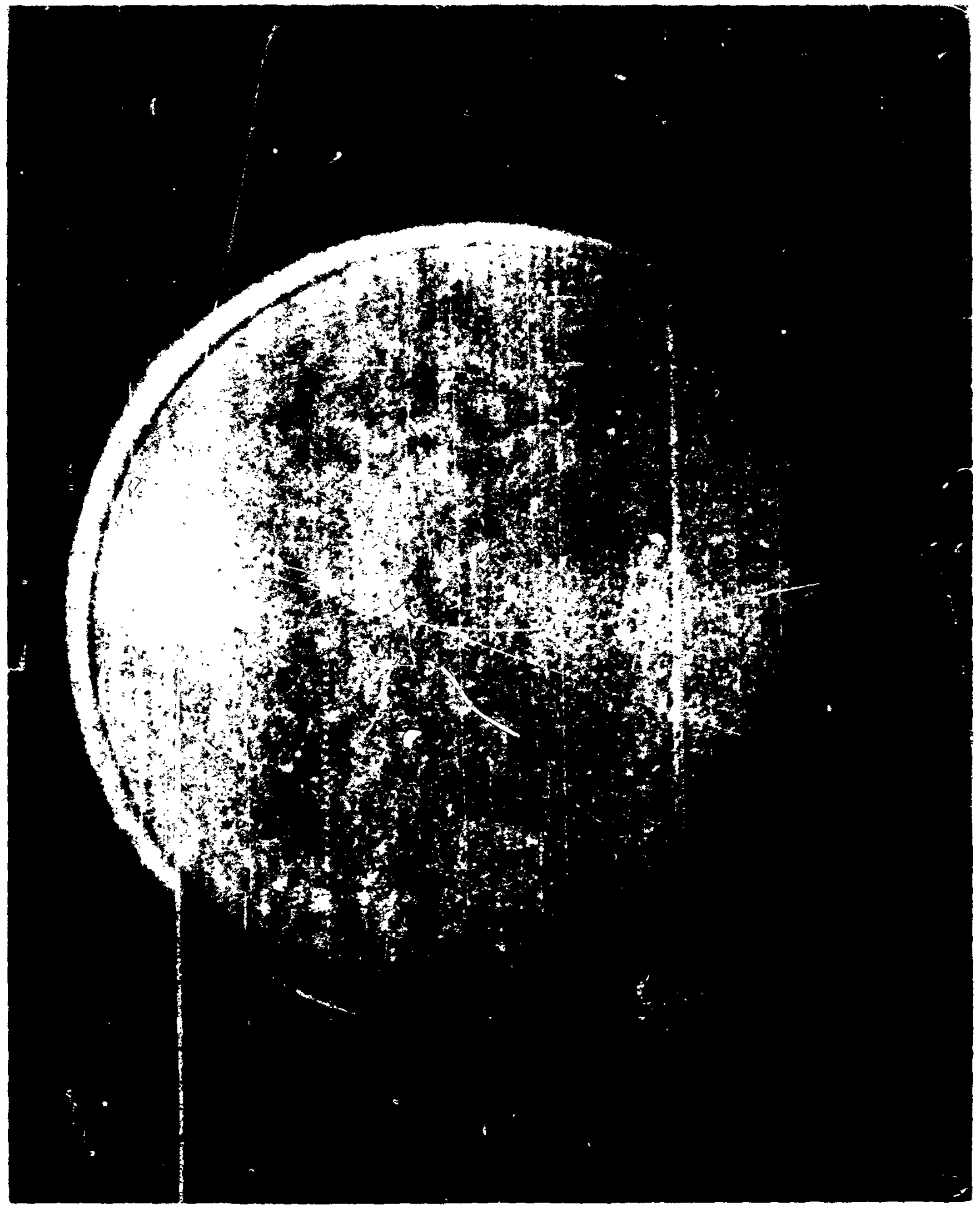


Fig. 8 - The damage pattern obtained with a dished specimen. The damage pattern has this uniform appearance with or without cathodic current.

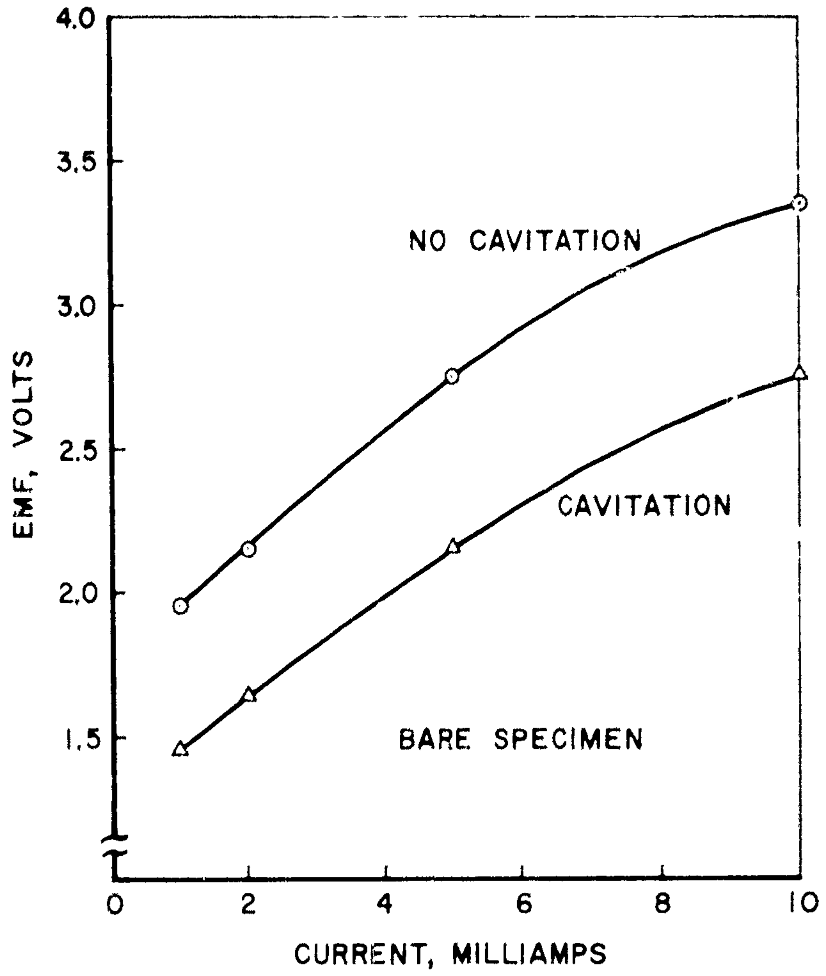


Fig. 9 - Emf as a function of cathodic current with and without cavitation on the cathode.

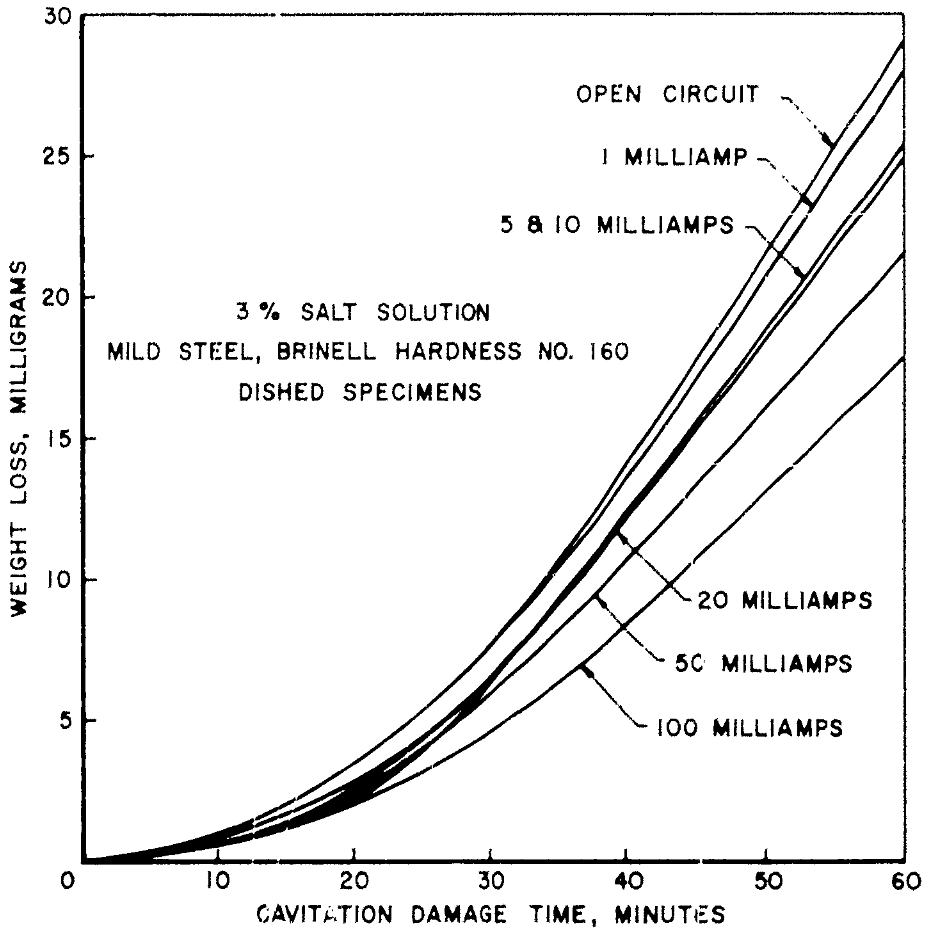


Fig. 10 - Weight loss for dished specimens as a function of damage time - different levels of cathodic current.

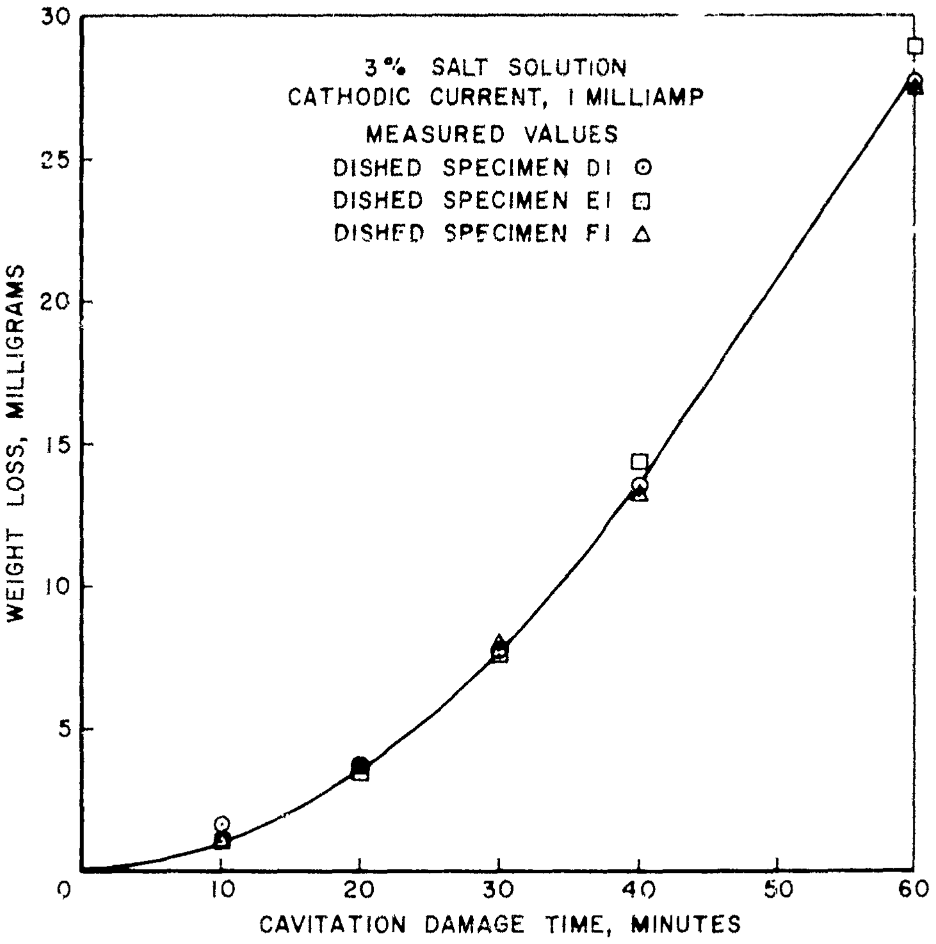


Fig. 11 - Weight loss for dished specimens of mild steel as a function of damage time - 1 milliampere of cathodic current. Test liquid was 3% solution of NaCl in distilled water.

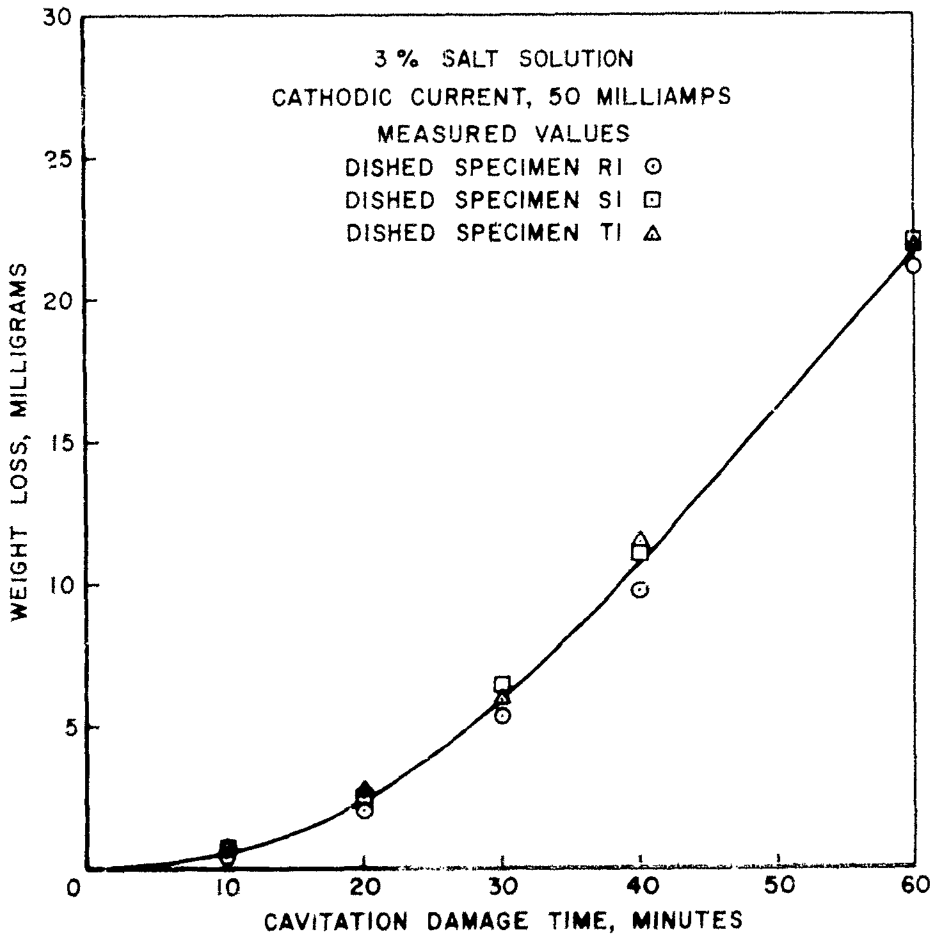


Fig. 12 - Weight loss for dished specimens of mild steel as a function of damage time - 50 milliamperes of cathodic current. Test liquid was 3% solution of NaCl in distilled water.

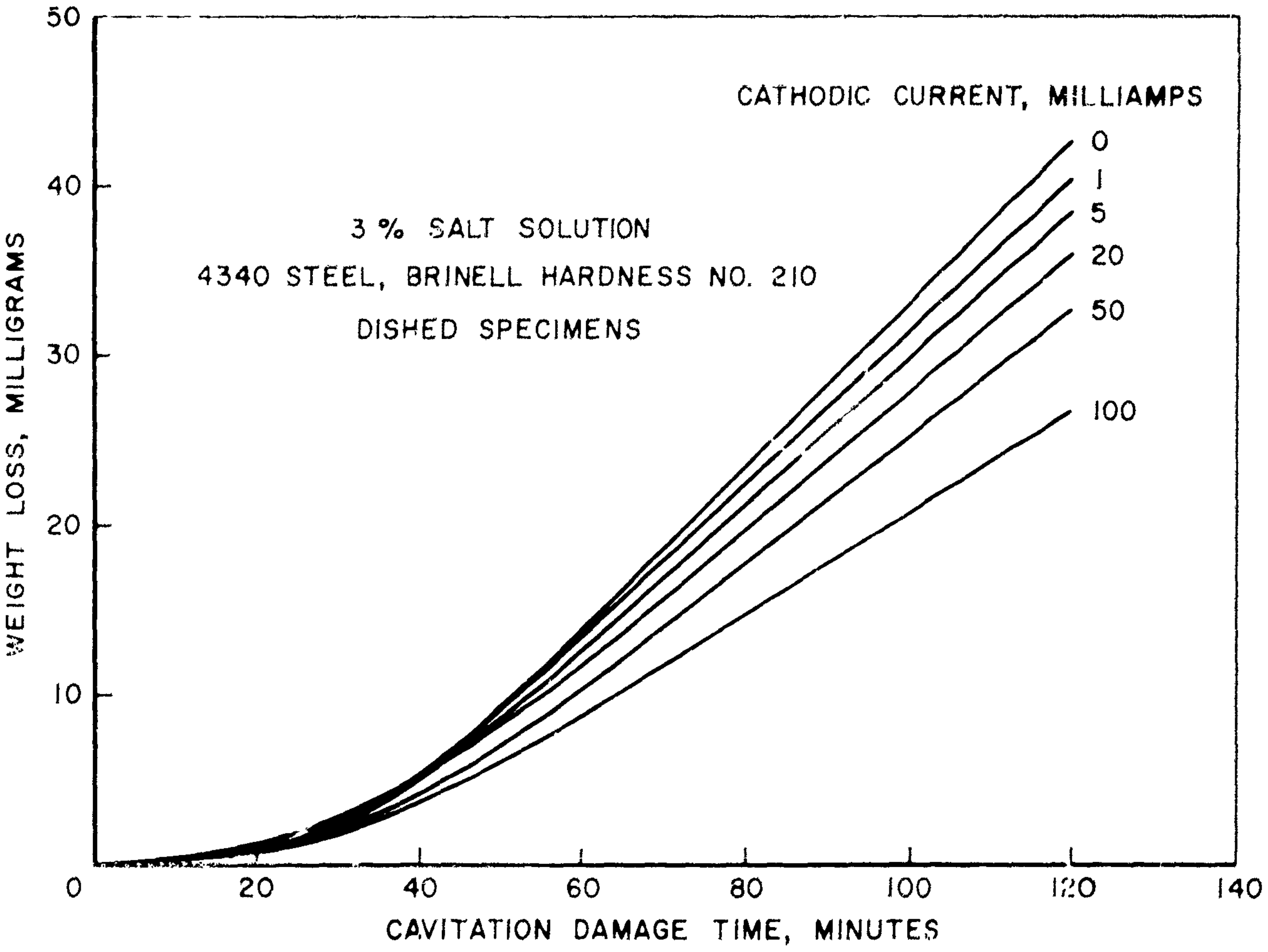


Fig. 13 - Summary curves of cavitation weight losses in 4340 steel for several values of cathodic current. Each of these curves is the average of the data for 3 different specimens.

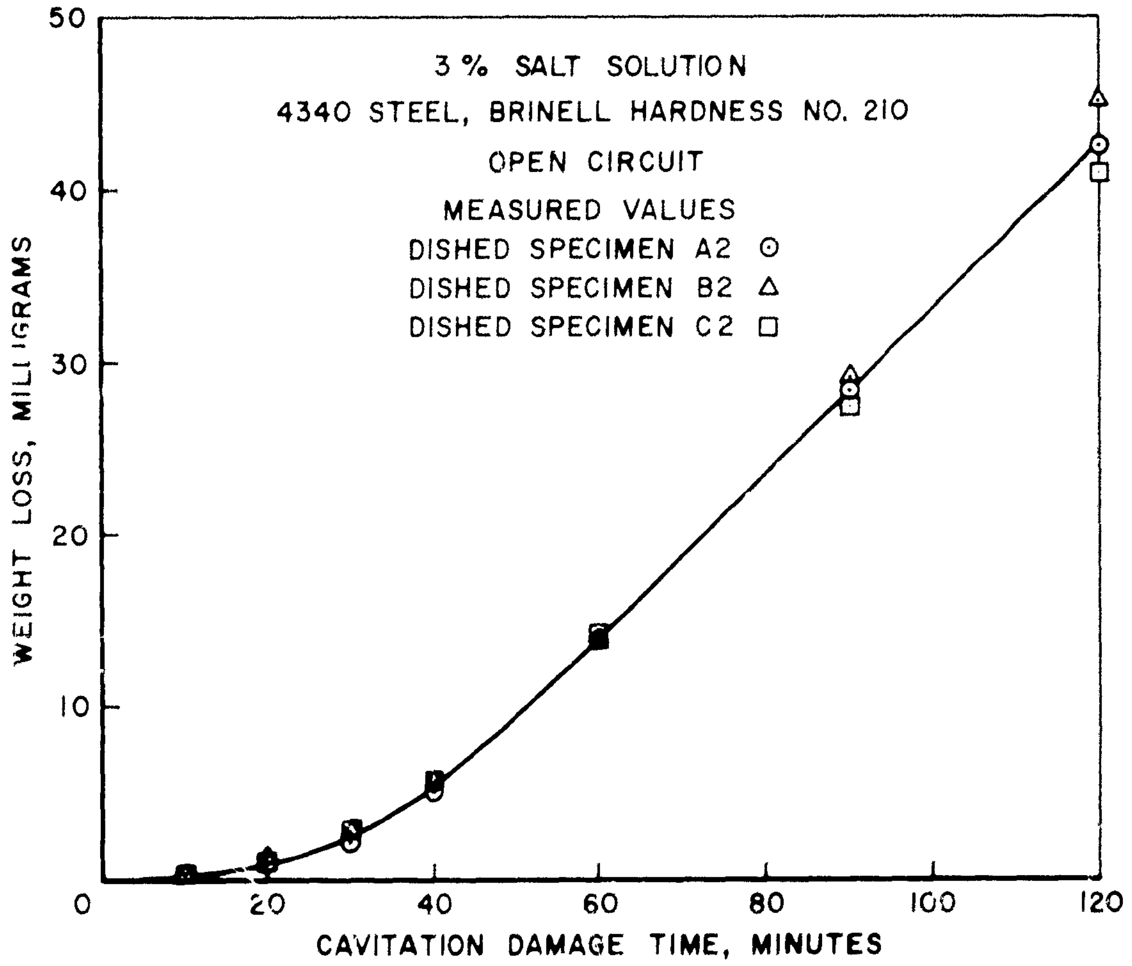


Fig. 14 - Cavitation weight loss determinations for 4340 steel specimens in 3% solution of NaCl in distilled water with no cathodic current.

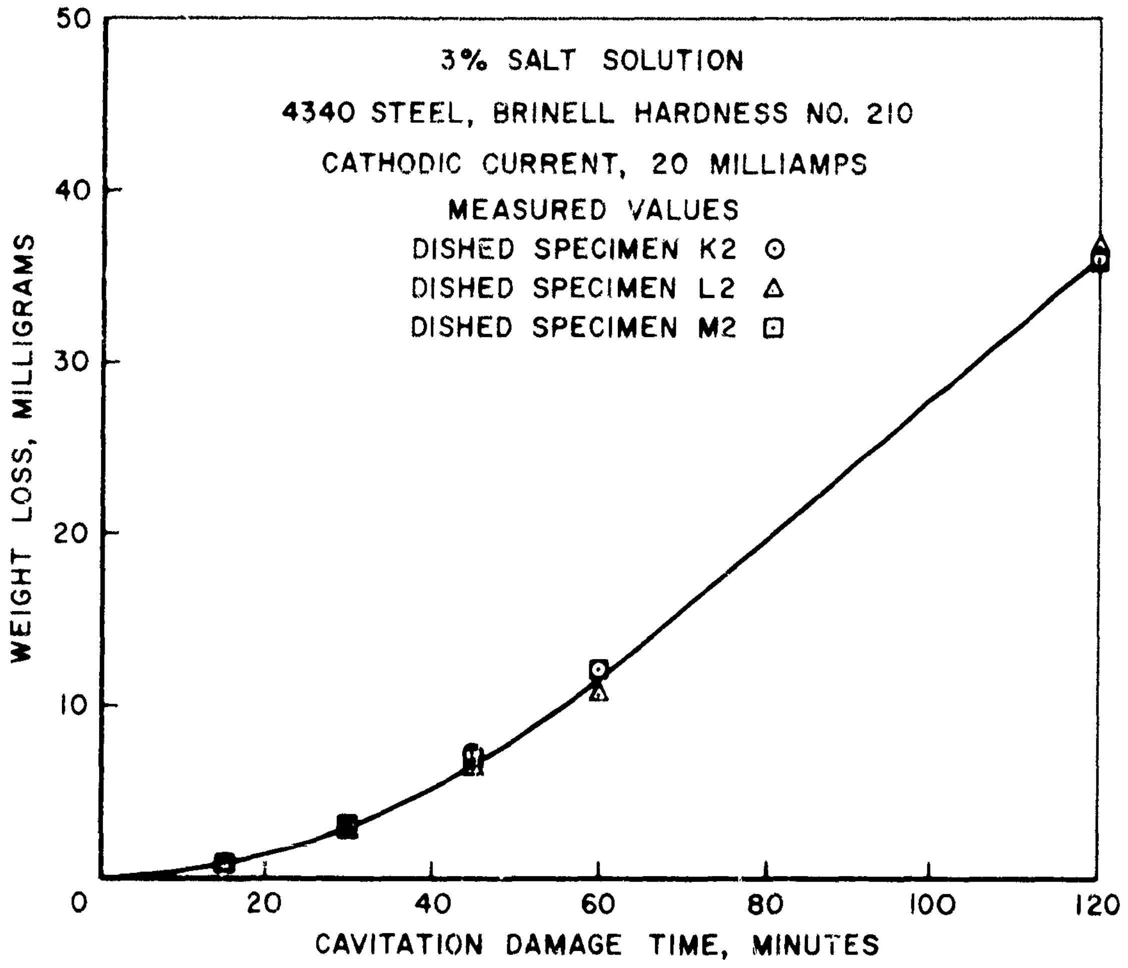


Fig. 15 - Cavitation weight loss for 4340 steel specimens in 3% salt solution with cathodic current of 20 milliamperes.

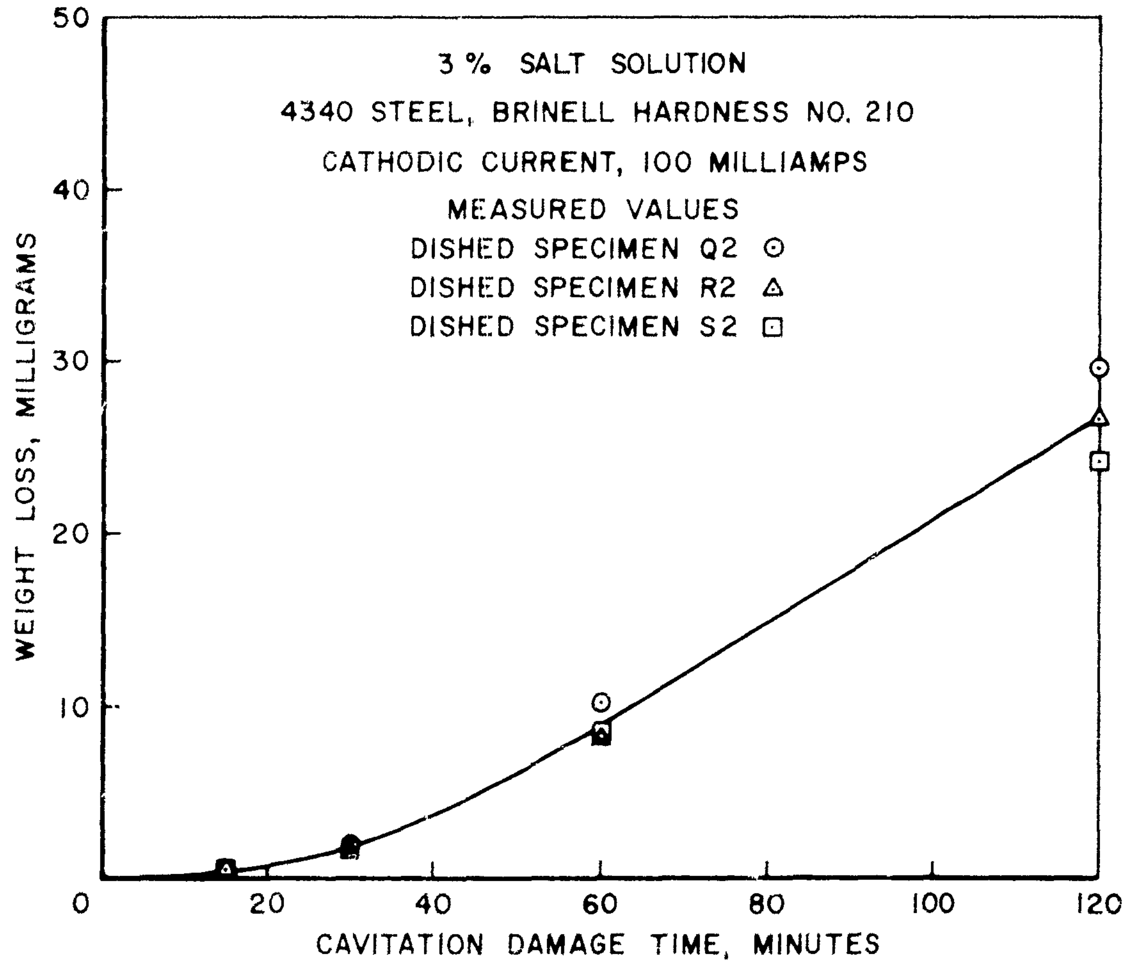


Fig. 16 - Cavitation weight loss for 4340 steel specimens in 3% salt solution with cathodic current of 100 milliamperes.

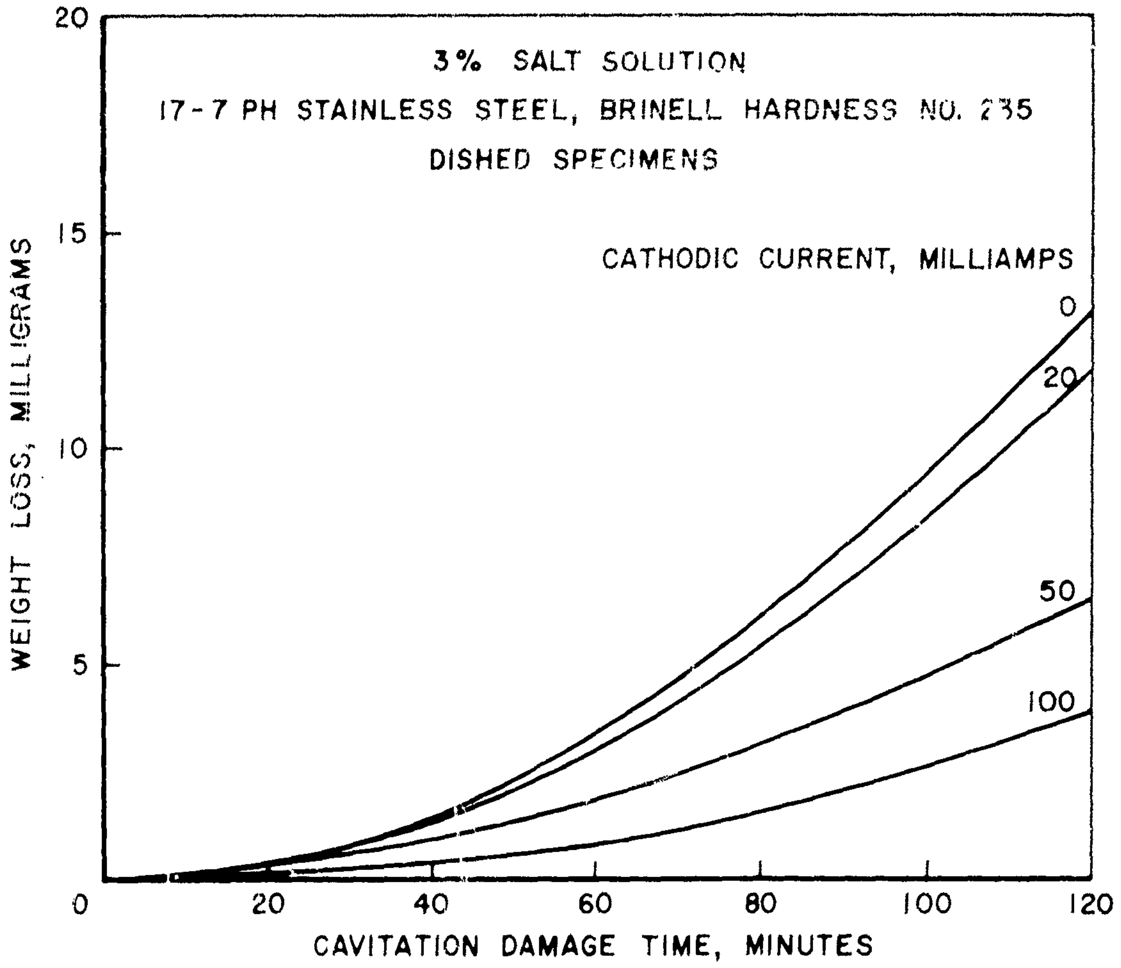


Fig. 17 - Summary curves of cavitation weight losses in 17-7 PH stainless steel for several values of cathodic currents. Each curve is the average of the data for 3 different specimens.

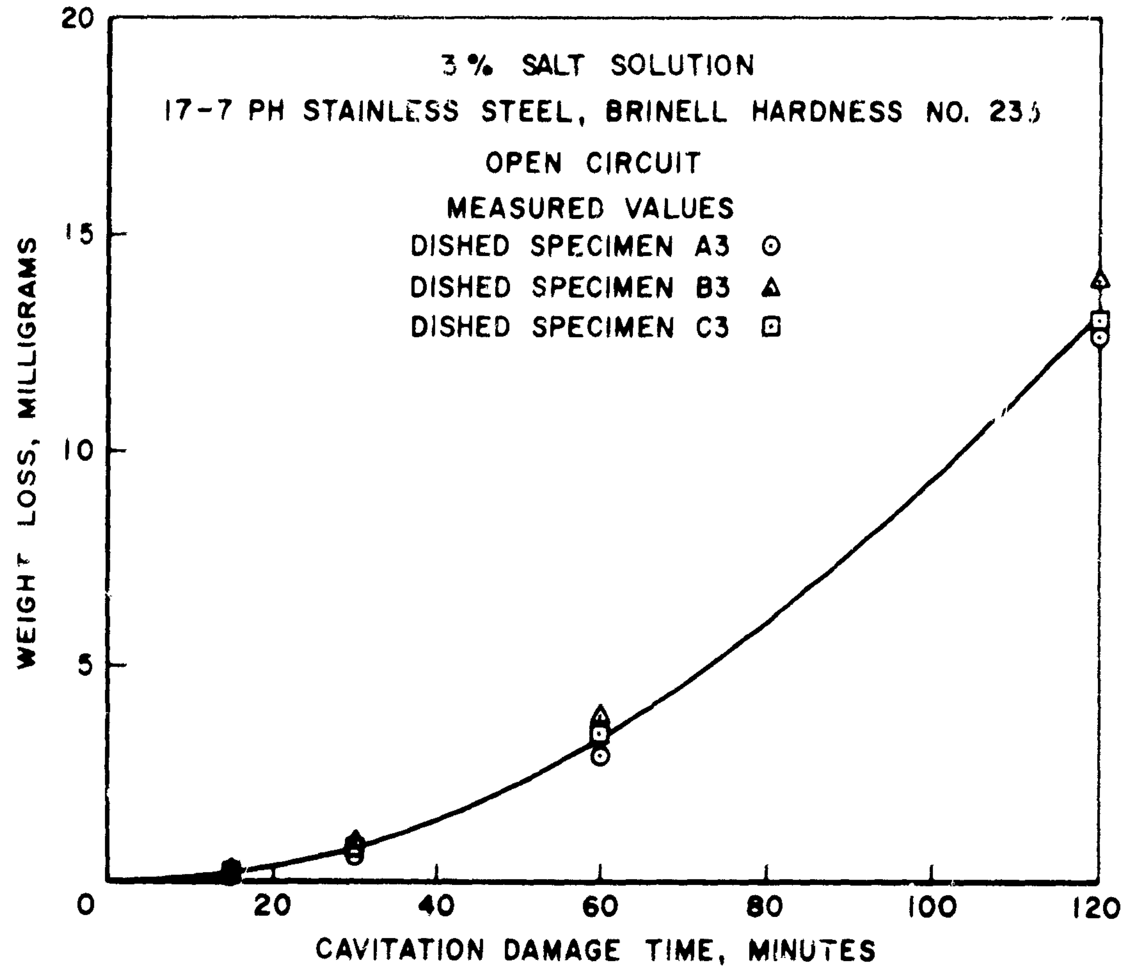


Fig. 18 - Cavitation weight loss for 17-7 PH stainless steel in 3% salt solution with no cathodic current.

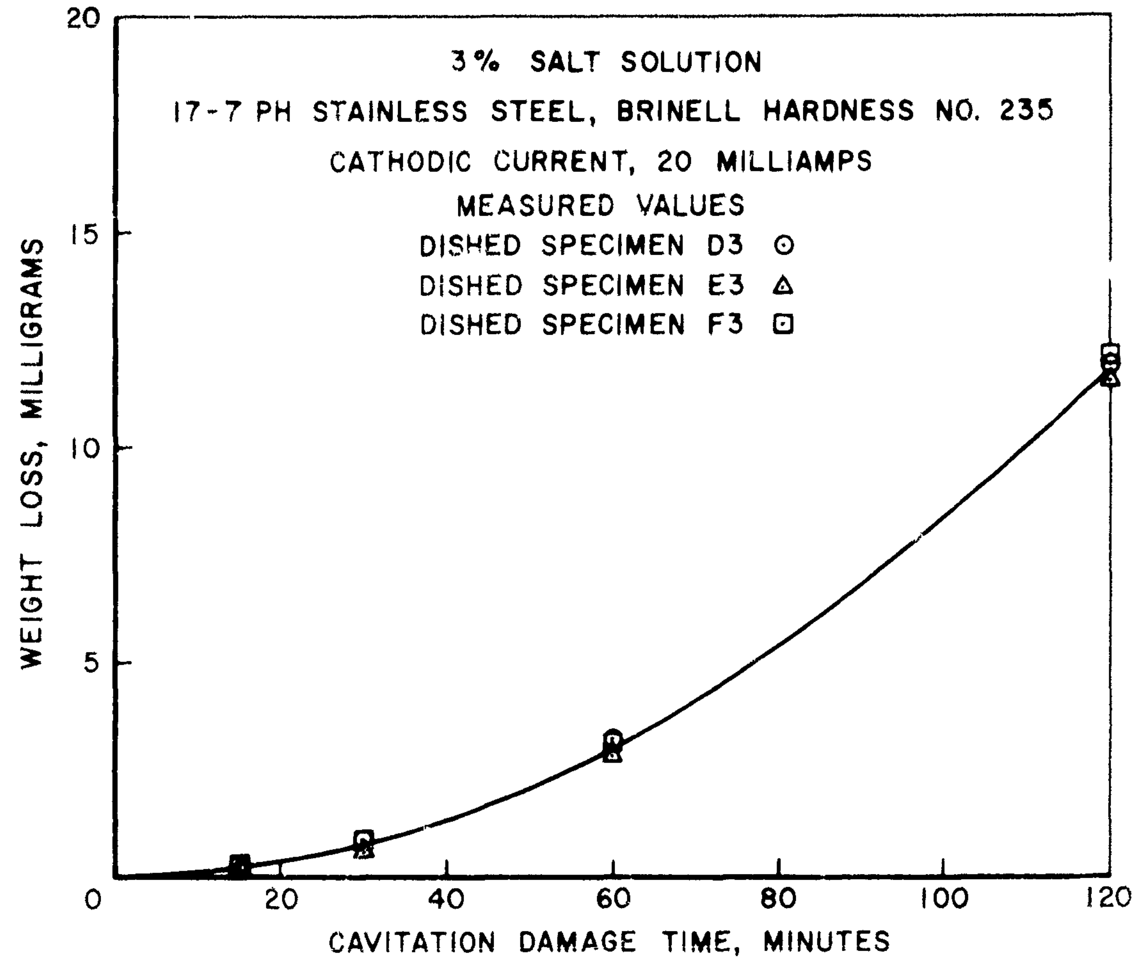


Fig. 19 - Cavitation weight loss for 17-7 PH stainless steel in 3% salt solution with cathodic current of 20 milliamperes.

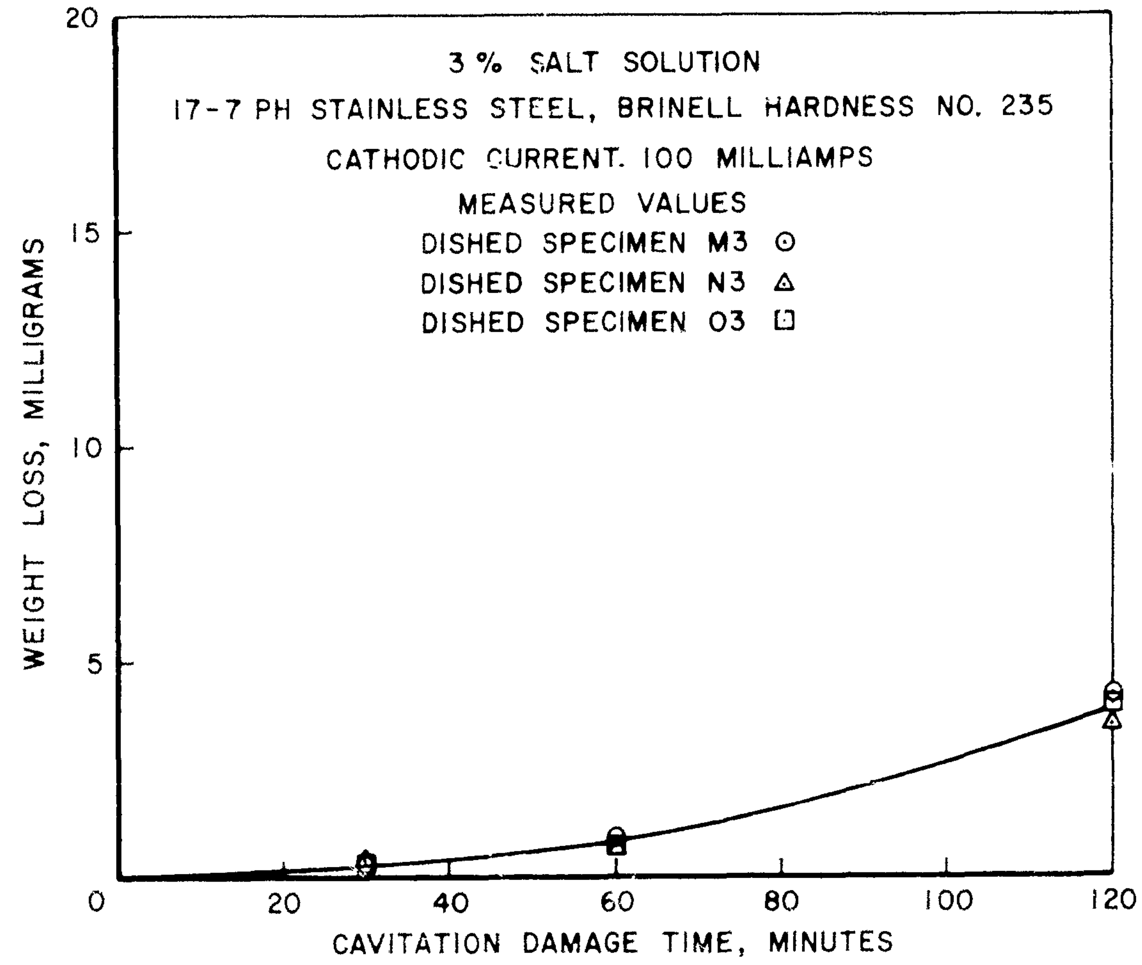


Fig. 20 - Cavitation weight loss for 17-7 PH stainless steel in 3% salt solution with cathodic current of 100 milliamperes.

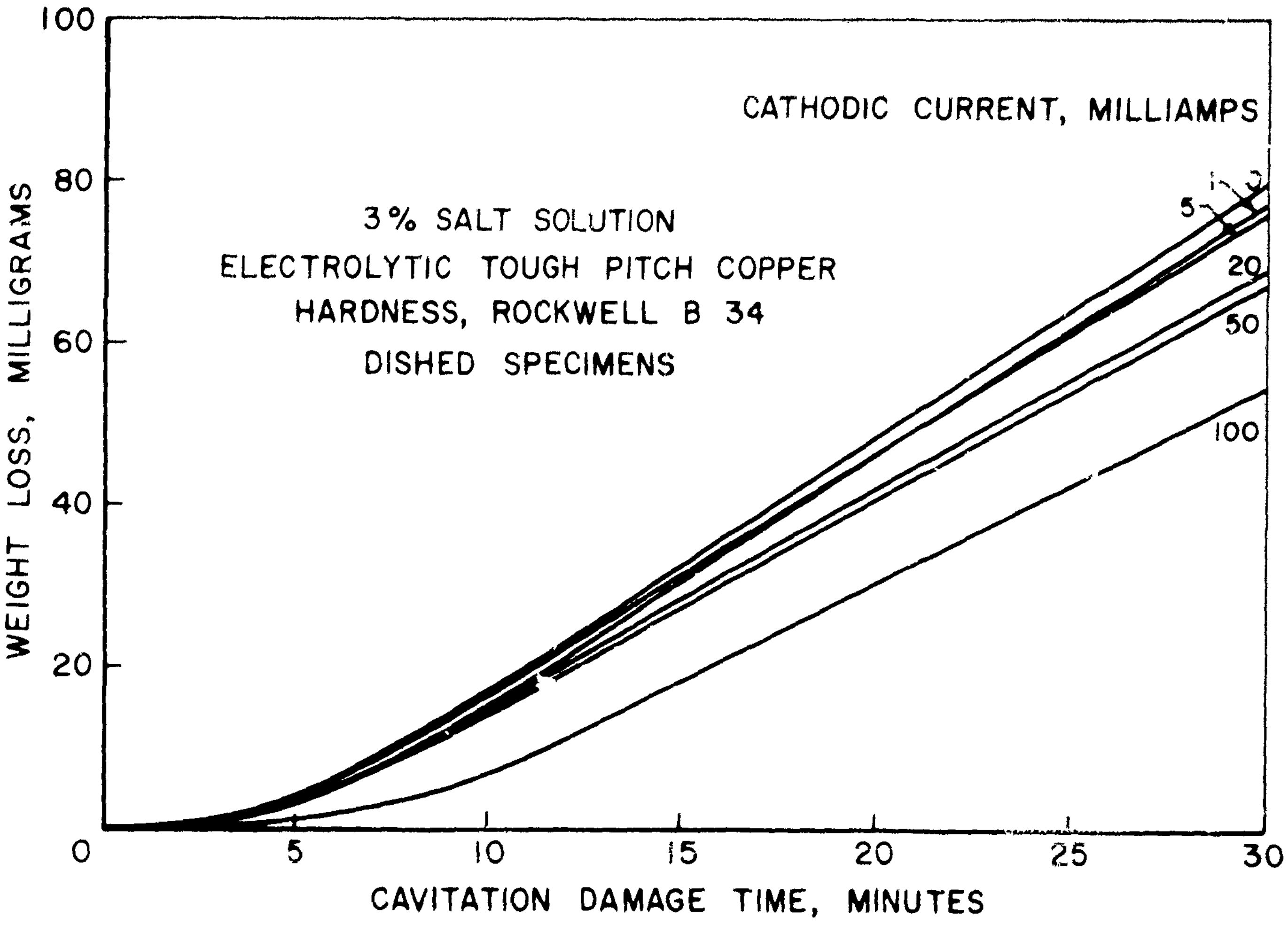


Fig. 21 - Summary curves of cavitation weight losses in pure copper for several values of cathodic current. The test liquid was a 3% solution of NaCl in distilled water.

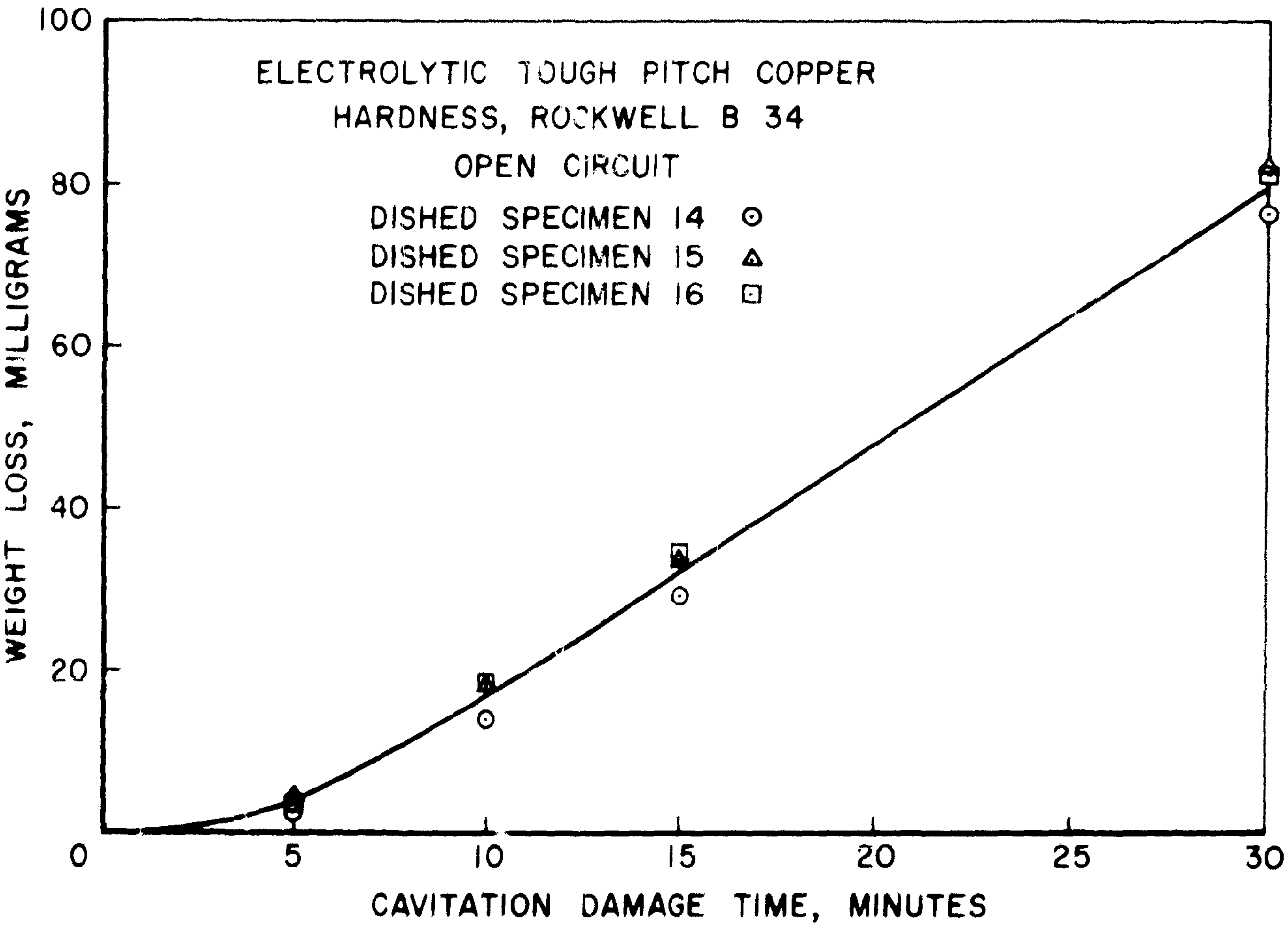


Fig. 22 - Cavitation weight loss determinations for pure copper specimens in 3% solution of NaCl in distilled water with no cathodic current.

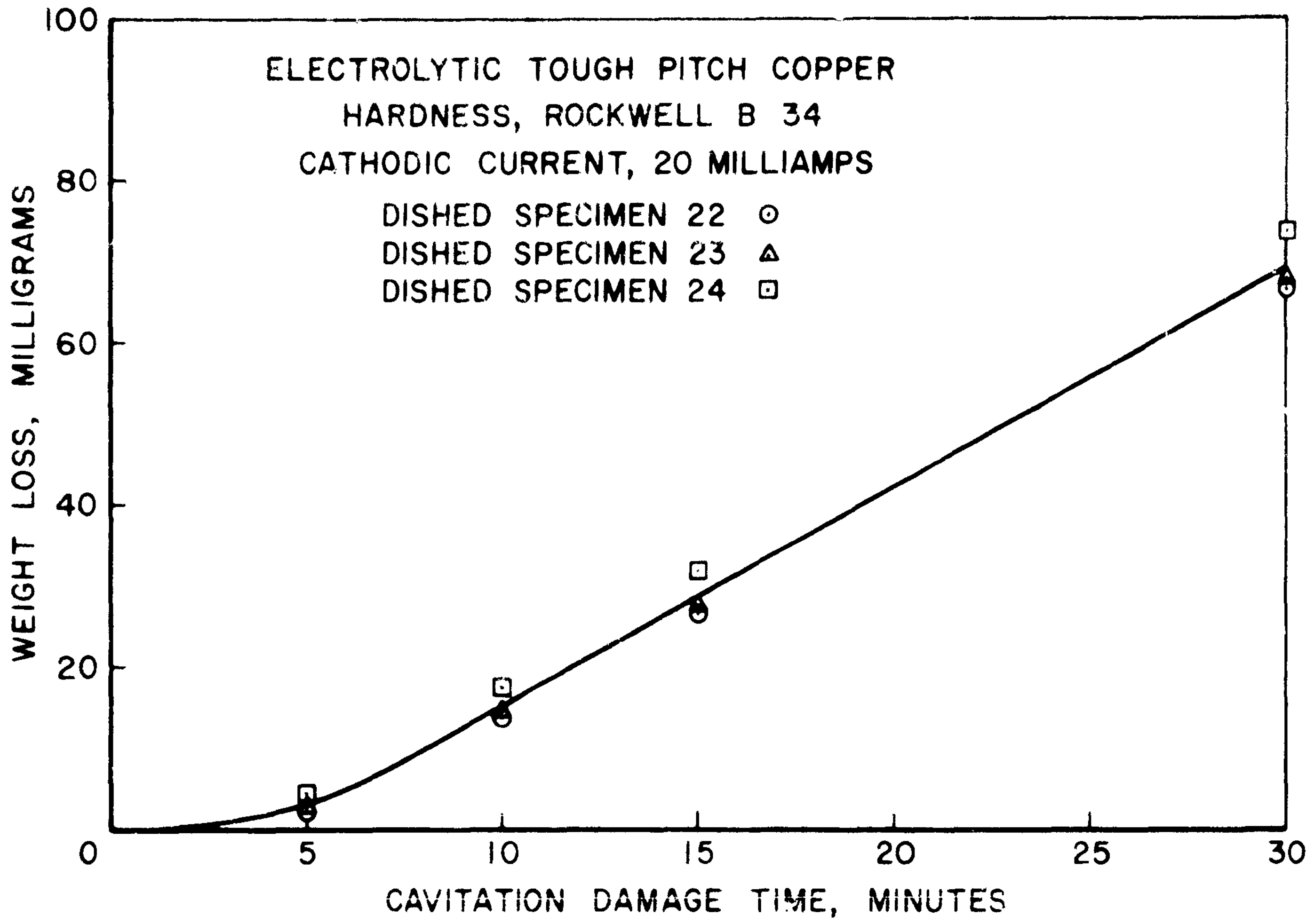


Fig. 23 - Cavitation weight loss determinations for pure copper specimens in 3% salt solution with cathodic current of 20 milliamperes.

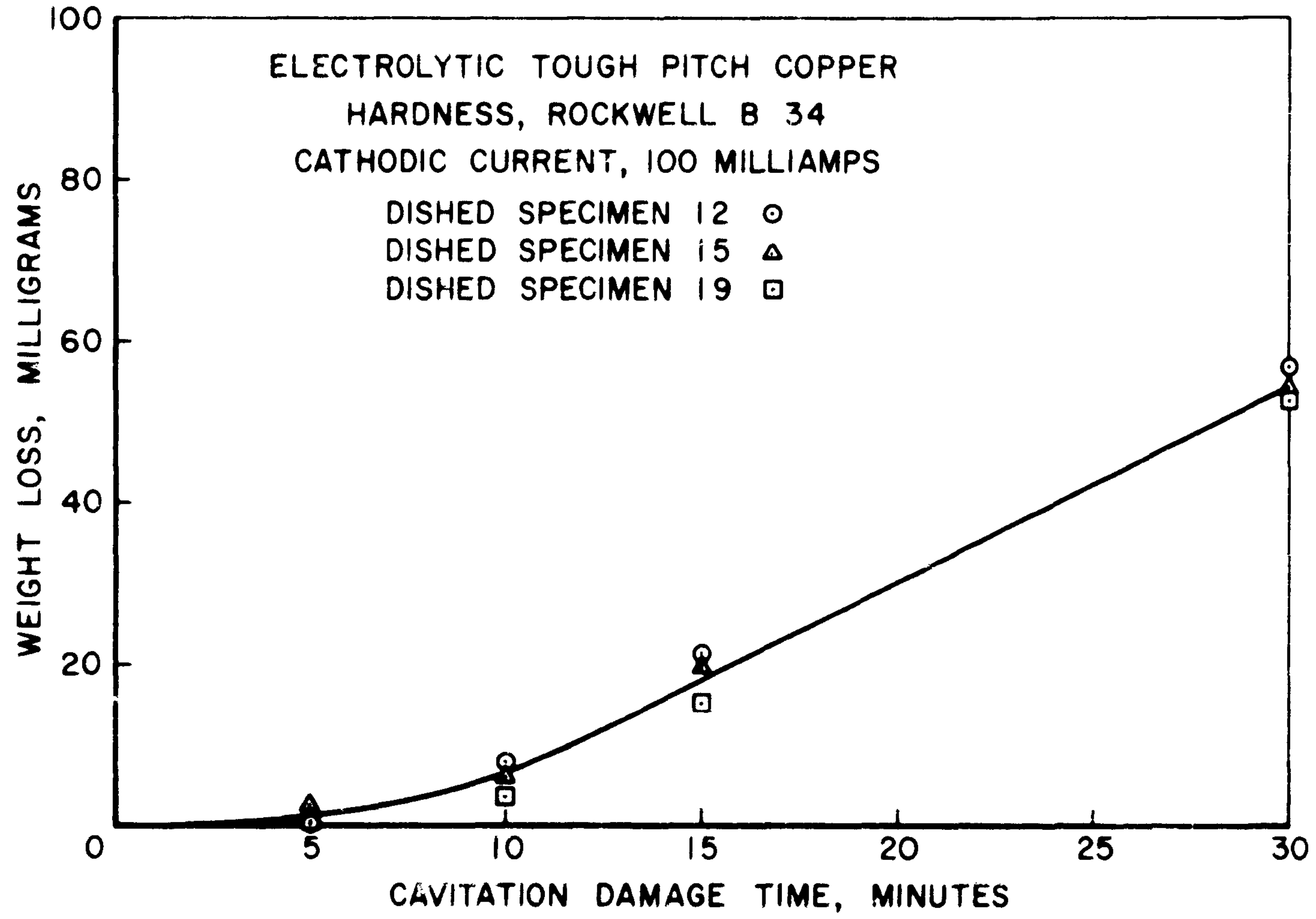


Fig. 24 - Cavitation weight loss determinations for pure copper specimens in 3% salt solution with cathodic current of 100 milliamperes.

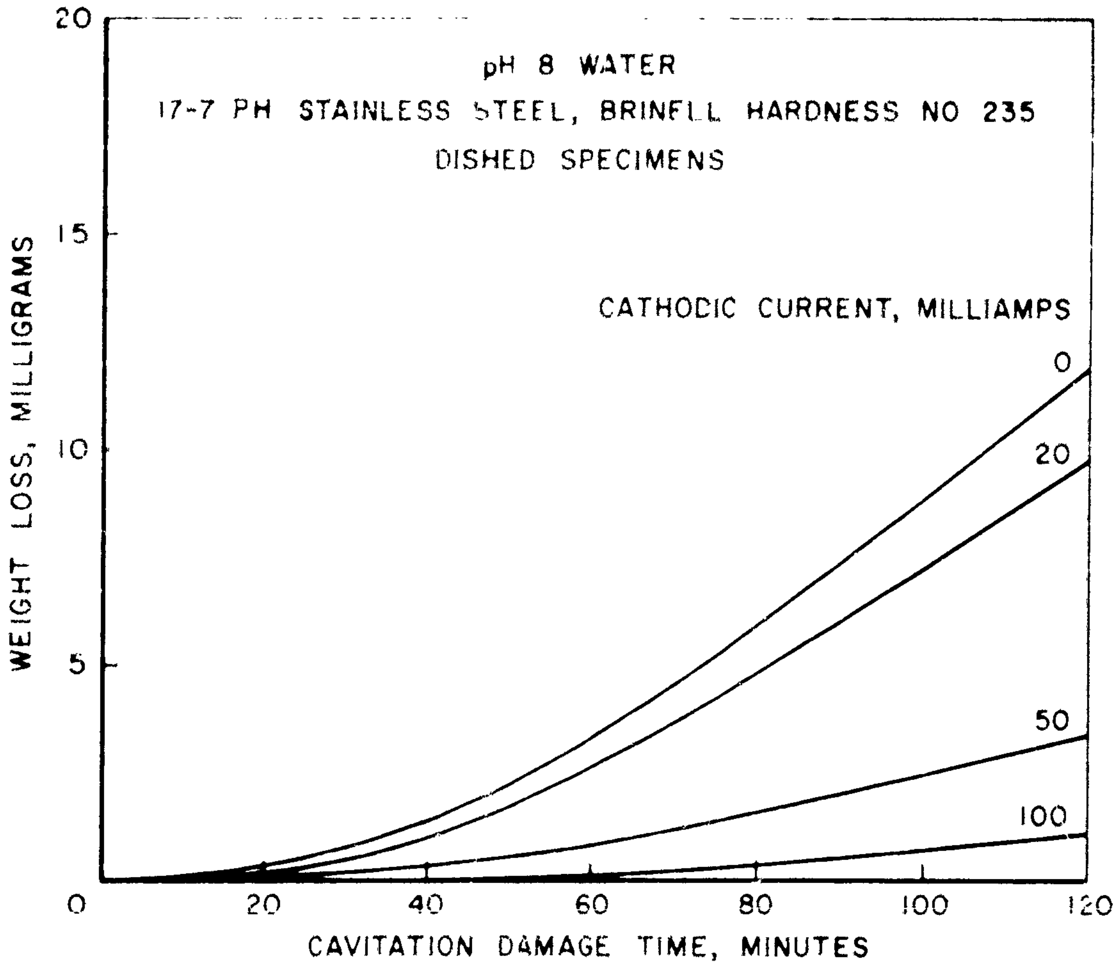


Fig. 25 - Summary of cavitation weight loss observations with 17-7 PH stainless steel specimens as cathodes in buffered distilled water.

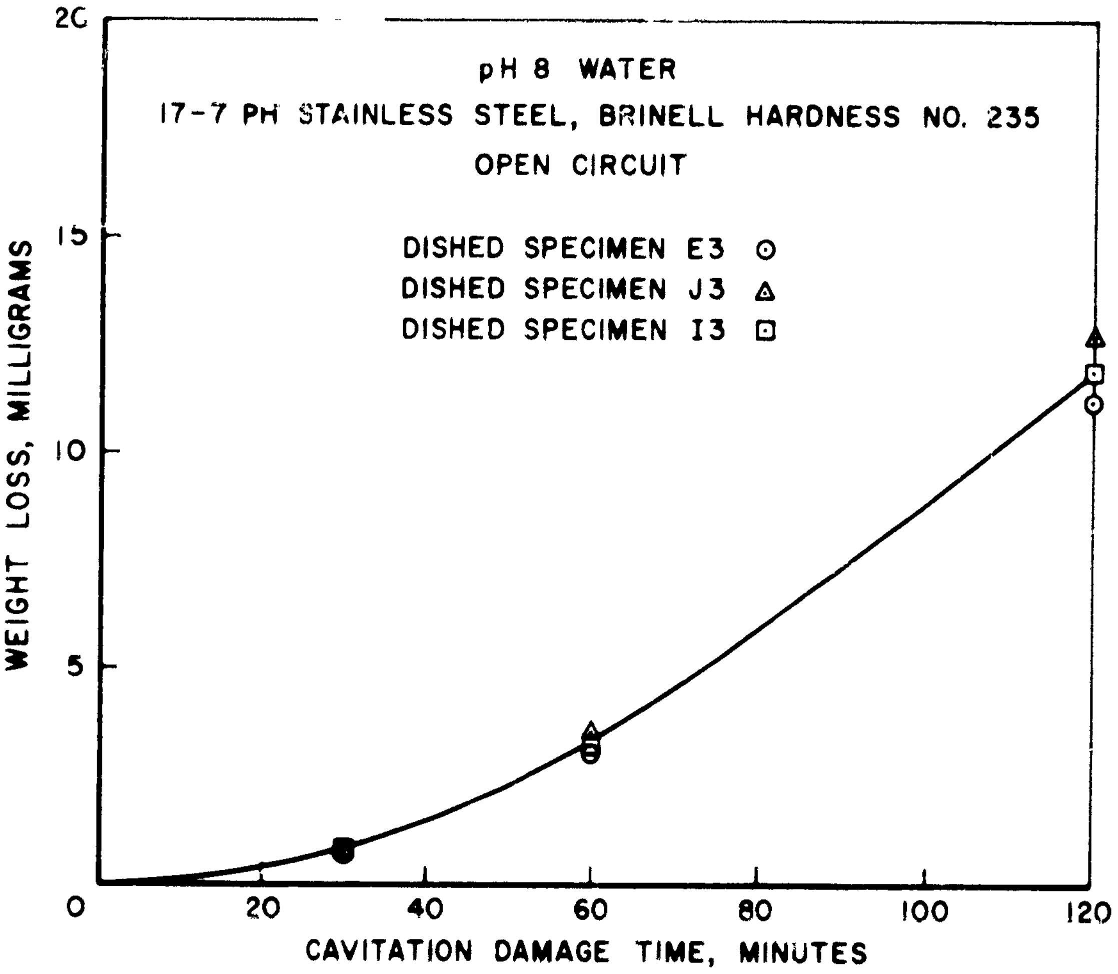


Fig. 26 - Cavitation weight loss determinations for 17-7 PH stainless steel in buffered distilled water with no current.

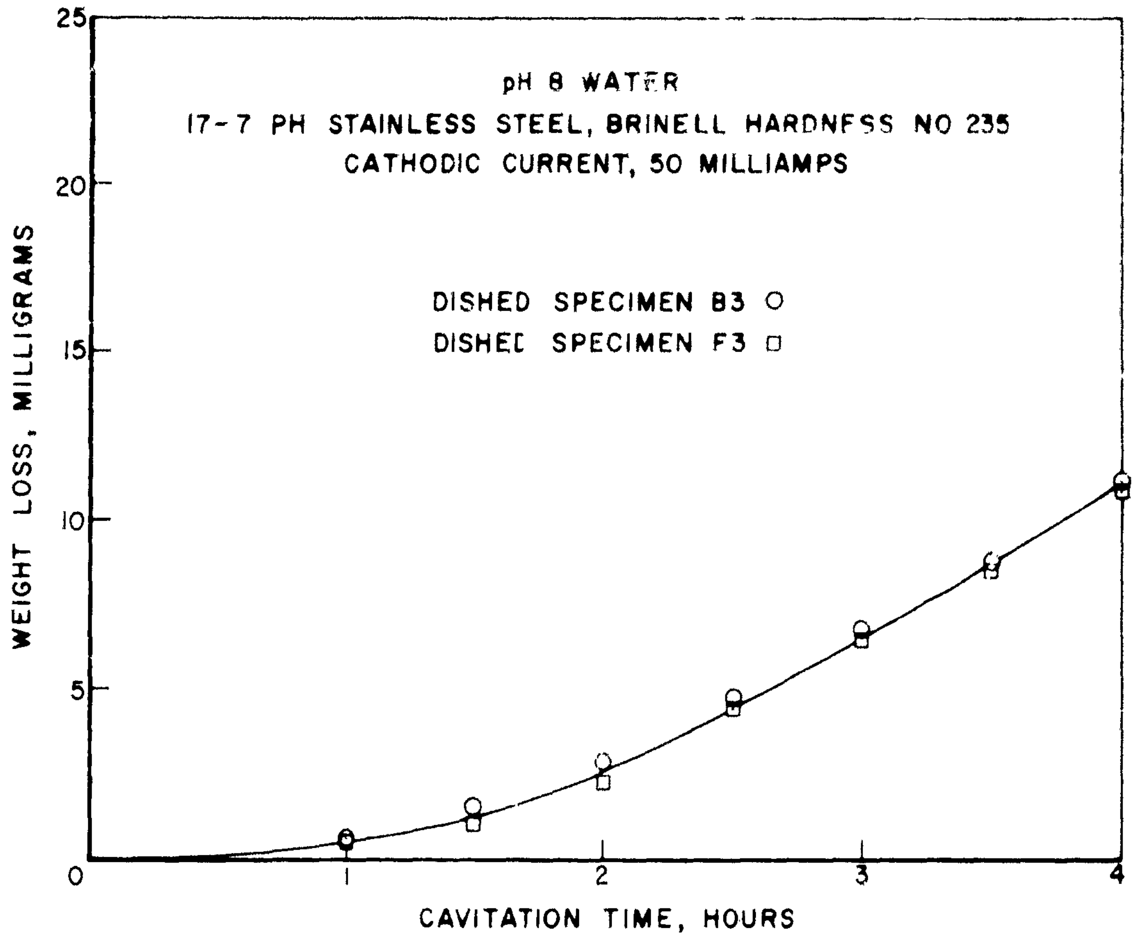


Fig. 27 - Cavitation weight loss determinations for 17-7 PH stainless steel in buffered distilled water with cathodic current of 50 milliamperes.

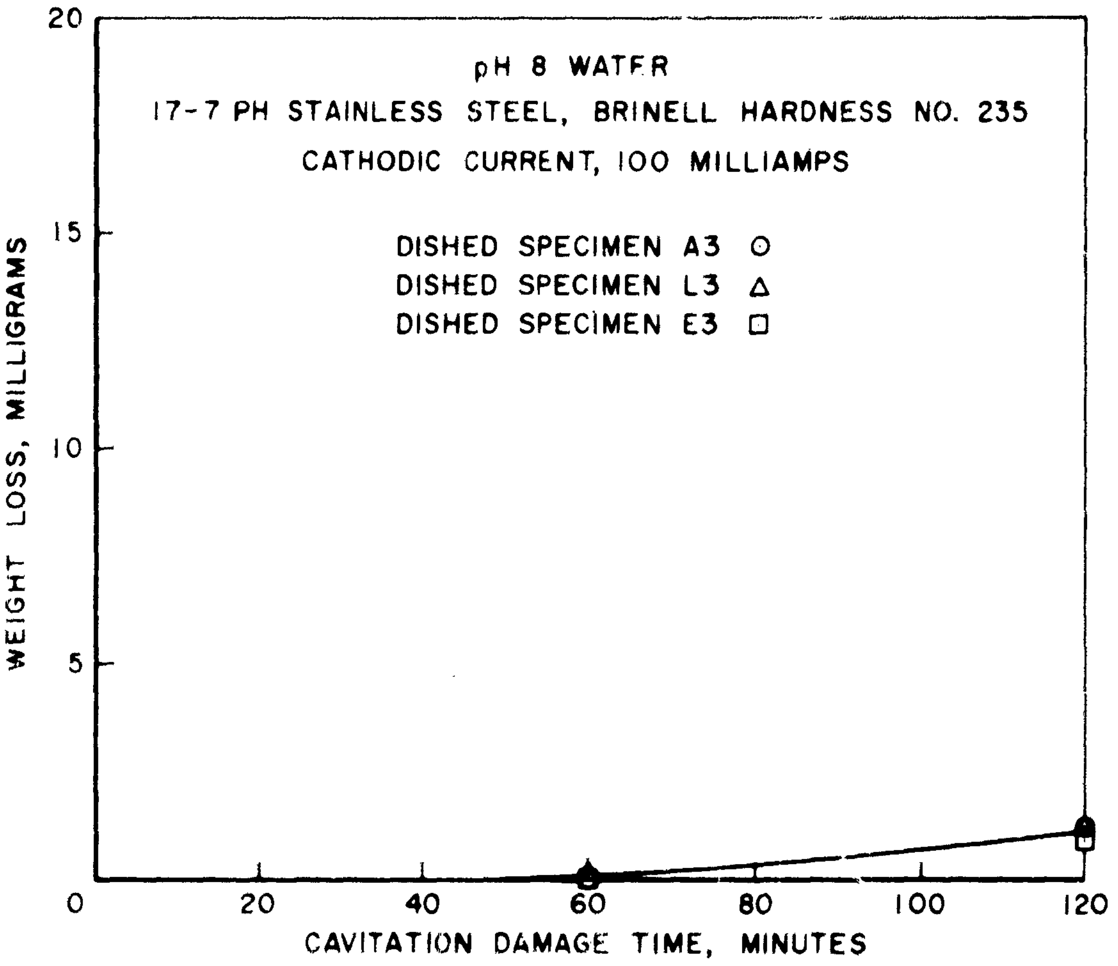


Fig. 28 - Cavitation weight loss determinations for 17-7 PH stainless steel in buffered distilled water with cathodic current of 100 milliamperes.

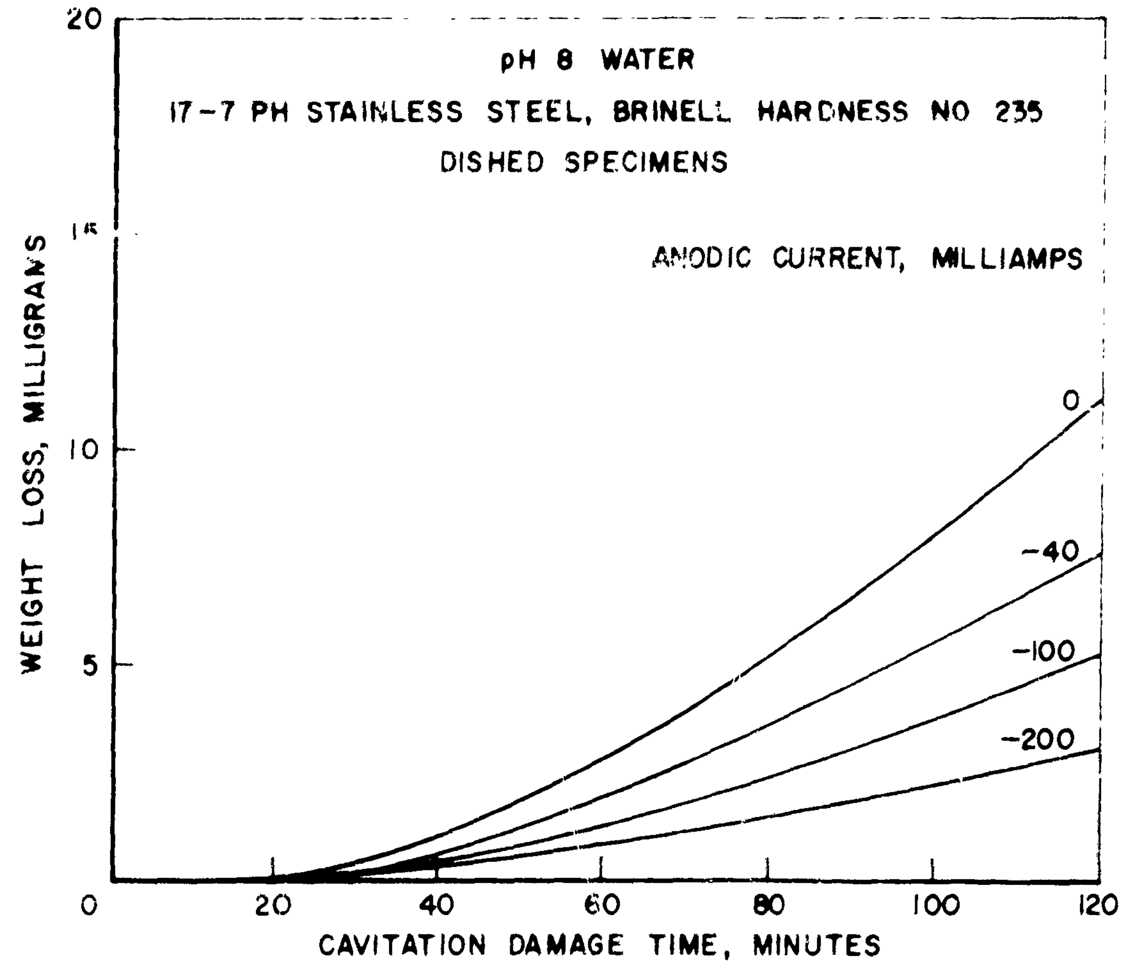


Fig. 29 - Summary of cavitation weight loss observations with 17-7 PH stainless steel specimens as anodes in buffered distilled water. The anodic current values are double the cathodic current values so as to give corresponding rates of gas evolution in the two cases: oxygen with valence 2 for the anodic case, hydrogen with valence 1 for the cathodic case.

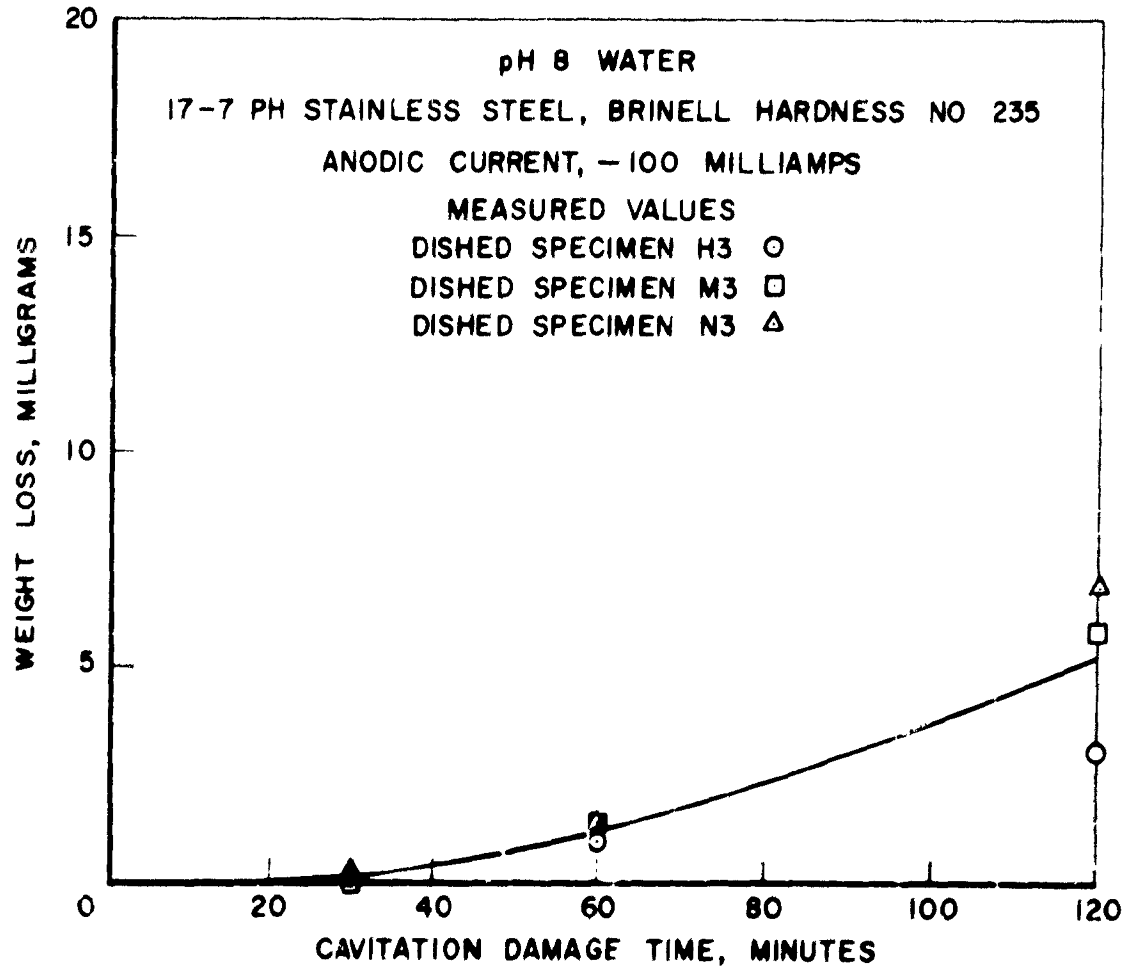


Fig. 30 - Cavitation weight loss determinations for 17-7 PH stainless steel in buffered distilled water with anodic current of 100 milliamperes.

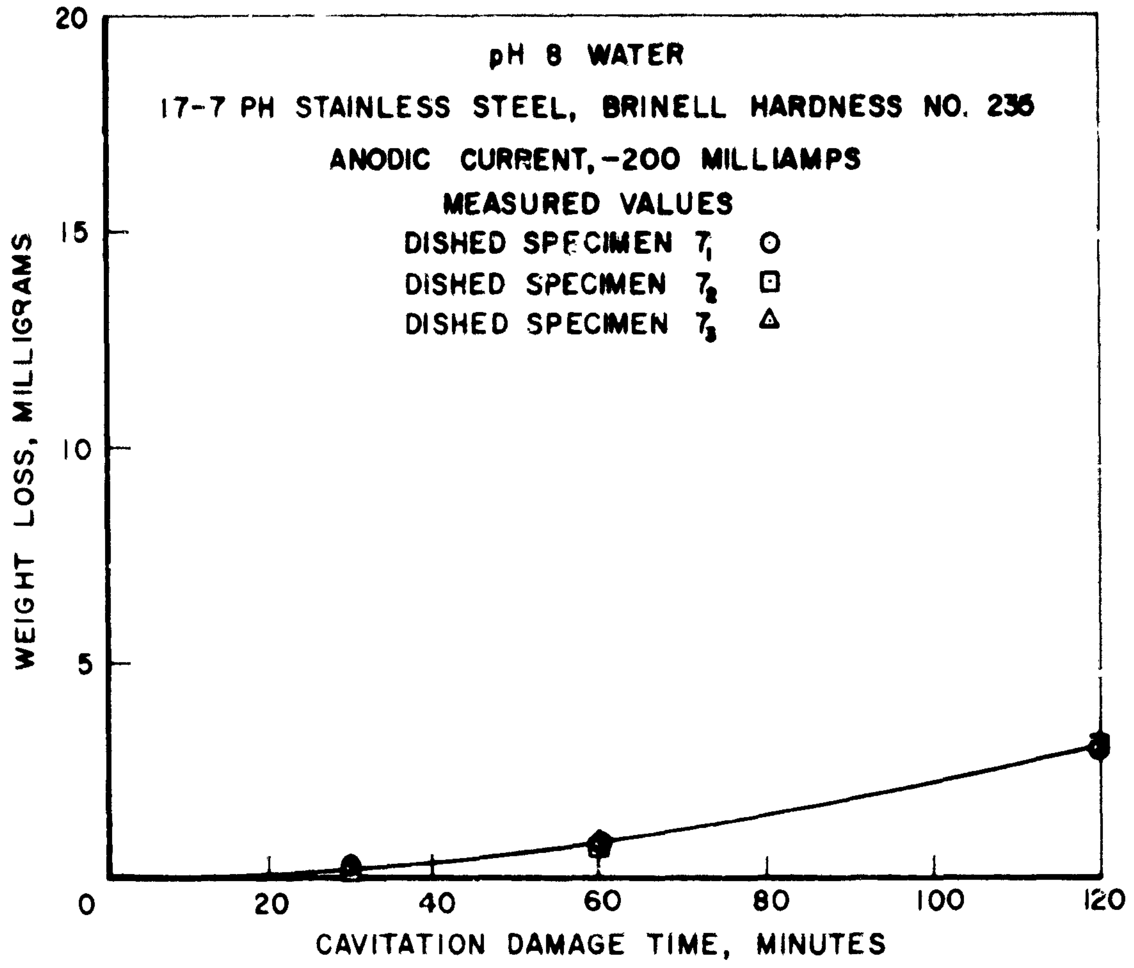


Fig. 31 - Cavitation weight loss determinations for 17-7 PH stainless steel in buffered distilled water with anodic current of 200 milliamperes.

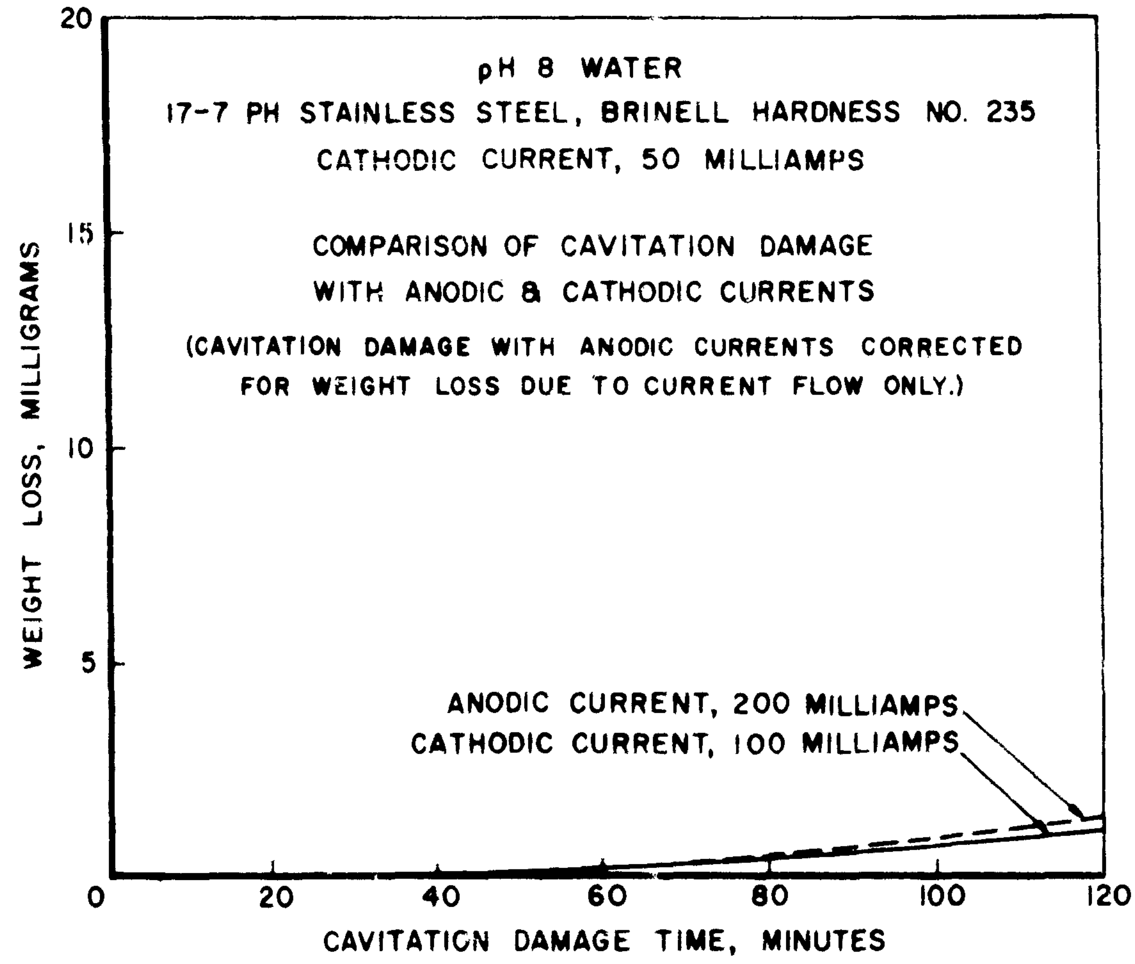


Fig. 32 - Comparison of cavitation weight loss for stainless steel specimens with anodic and cathodic currents. The observed weight loss for the case in which the specimen is the anode of the cell is corrected for the weight loss due to current flow only.

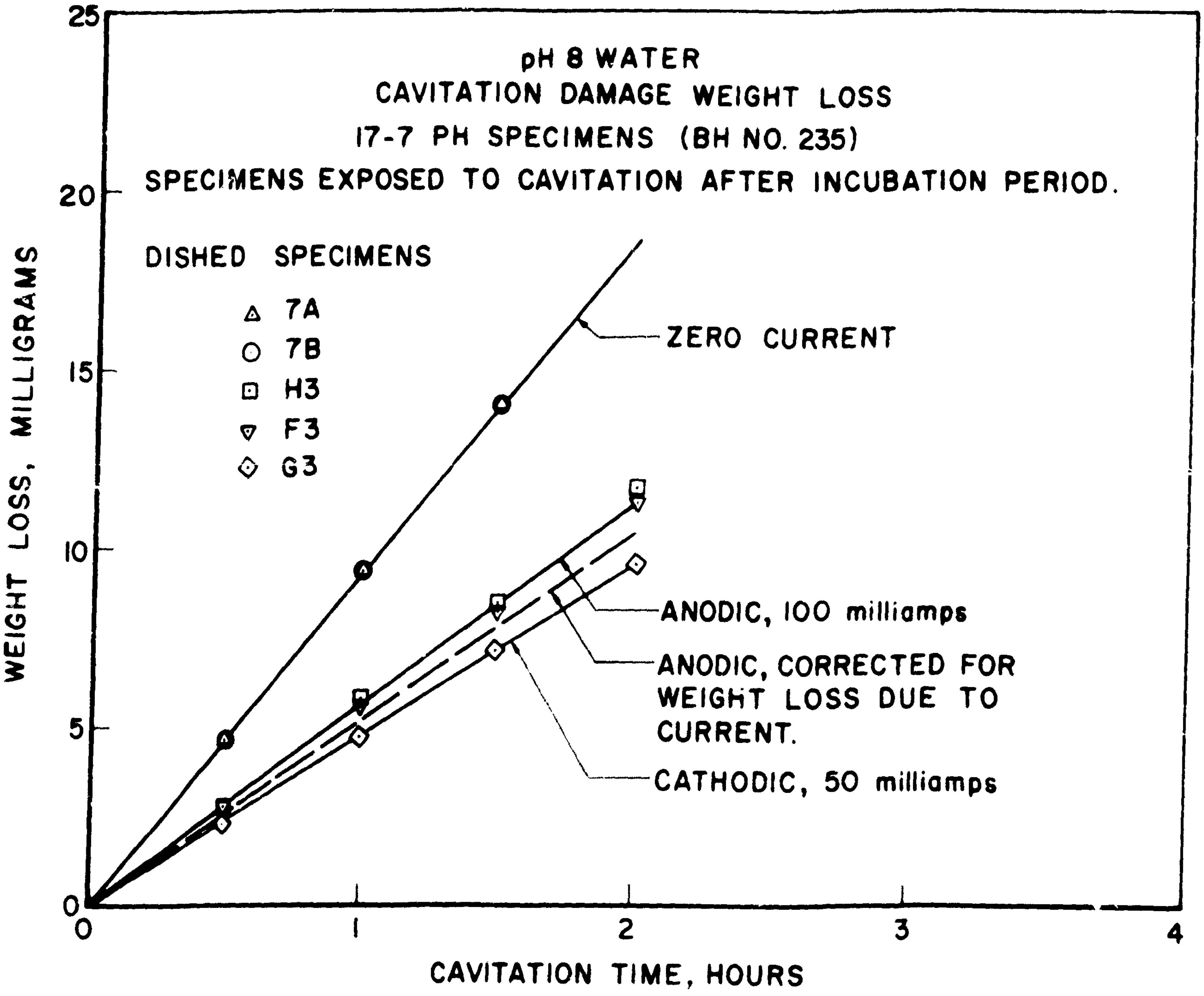


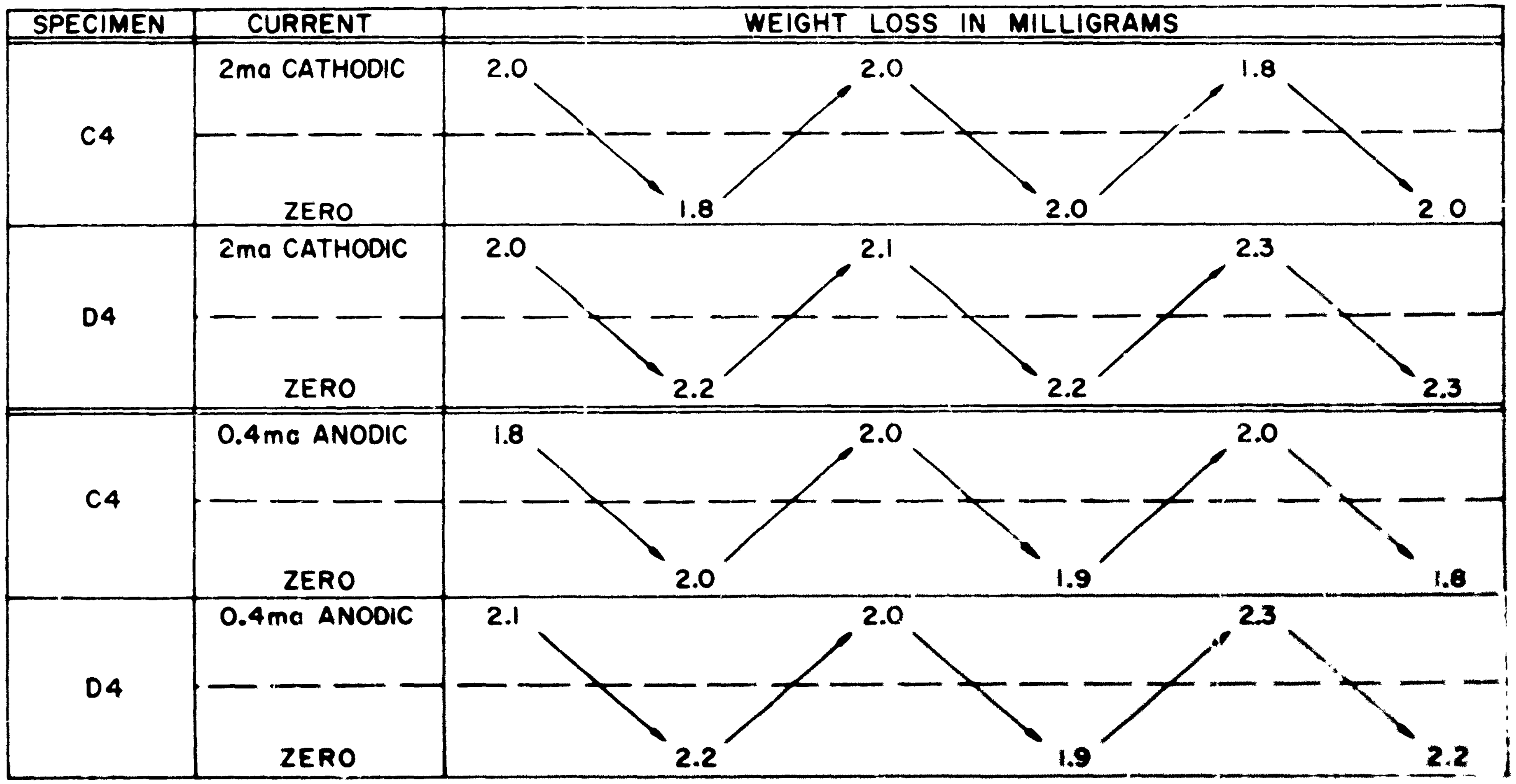
Fig. 33 - Comparison of anodic (100 milliamperes) cavitation weight losses with cathodic (50 milliamperes) cavitation weight losses. The dashed anodic curve shows the correction due to electrolytic solution by the current only and is to be compared with the cathodic curve.

4340 STEEL, BH NO. 210

CAVITATION WEIGHT LOSS FOR SUCCESSIVE 5 MINUTE EXPOSURES

DISTILLED WATER, BUFFERED pH 8

NO VISIBLE GAS EVOLUTION AT THE SPECIMEN FOR THESE CURRENTS



SPECIMEN	CURRENT	WEIGHT LOSS IN MILLIGRAMS					
C4	2ma CATHODIC	2.0		2.0		1.8	
	ZERO		1.8		2.0		2.0
D4	2ma CATHODIC	2.0		2.1		2.3	
	ZERO		2.2		2.2		2.3
C4	0.4ma ANODIC	1.8		2.0		2.0	
	ZERO		2.0		1.9		1.8
D4	0.4ma ANODIC	2.1		2.0		2.3	
	ZERO		2.2		1.9		2.2

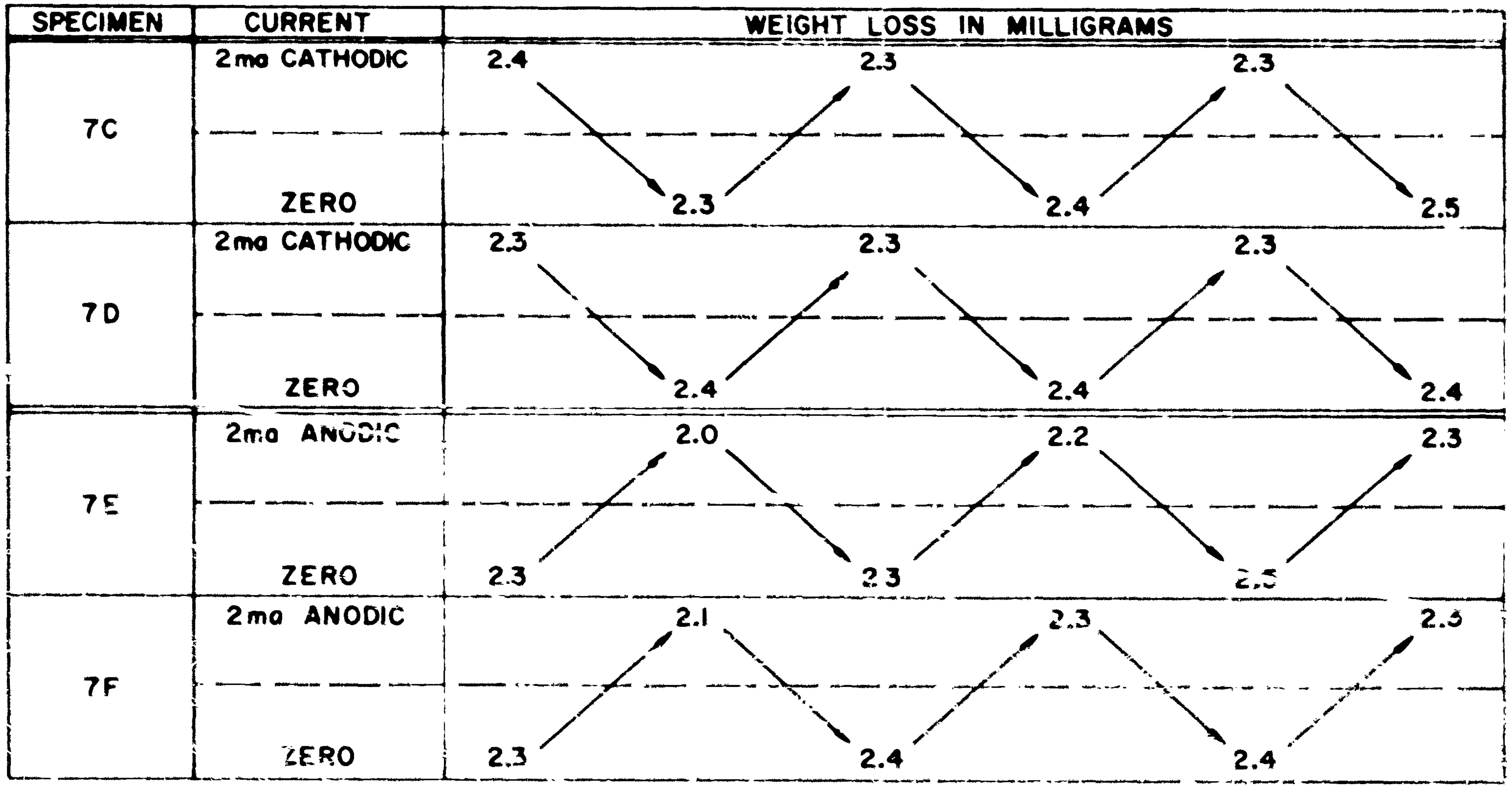
Fig. 34 - Cavitation weight losses for 4340 steel in buffered water. The arrows show the sequence of successive runs with the same specimen.

17-7 PH STAINLESS, BH NO 235

CAVITATION WEIGHT LOSS FOR SUCCESSIVE 15 MINUTE EXPOSURES

DISTILLED WATER, BUFFERED pH 8

NO VISIBLE GAS EVOLUTION AT THE SPECIMEN FOR THESE CURRENTS



SPECIMEN	CURRENT	WEIGHT LOSS IN MILLIGRAMS					
7C	2ma CATHODIC	2.4		2.3		2.3	
	ZERO		2.3		2.4		2.5
7D	2ma CATHODIC	2.3		2.3		2.3	
	ZERO		2.4		2.4		2.4
7E	2ma ANODIC		2.0		2.2		2.3
	ZERO	2.3		2.3		2.5	
7F	2ma ANODIC		2.1		2.3		2.3
	ZERO	2.3		2.4		2.4	

Fig. 35 - Cavitation weight losses for 17-7 PH stainless steel in buffered water. The arrows show the sequence of successive runs with the same specimen.