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CAVITATION DAMAGE

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PREFACE

This report was written in 1959 as a chapter for a volume on the corrosion of stressed metals. Progress in the various topics scheduled for treatment in that volume rapidly outpaced the publication plans and they were cancelled in 1962. Interesting developments were also taking place in cavitation damage research during the period immediately following the completion of this monograph. In particular, the ideas of A. Thiruvengadam and N.S.G. Rao at the Indian Institute of Science on the use of strain energy concepts in achieving rational correlations first became known in the United States.

Many of the problem areas disclosed during the preparation of the present treatise, coupled with the promise of the importance of strain energy concepts, motivated in large part the research on cavitation damage being carried out at HYDRONAUTICS, Incorporated under Office of Naval Research sponsorship.

Since the present compilation provides a catalogue and convenient single source on what was known about cavitation damage through the year 1959, it is being issued in its present form as useful background to the research now in progress.

INTRODUCTION

There are few problems of stressed metals in corrosive media (or non-corrosive for that matter) that have been the subject of as much controversy as that of damage to materials under cavitation attack. In spite of an impressive accumulation of data and ideas on the mechanism of cavitation damage (mechanical, mechano-chemical, electrochemical, thermoelectric, etc.), the perennial controversies seem to continue with apparently undiminished vigor. In this treatise, we shall attempt to identify these various postulated mechanisms, examine the evidence for each, and then endeavor to place them in proper perspective with respect to the importance of the role that each may play in the initial and ultimate destruction of materials. Emphasis must of necessity be placed on the physical mechanisms involved, primarily because these have been shown to be the essential factors in cavitation damage, but also because very little systematic research has been done on the interaction of mechanical and chemical (or electrochemical) influences in corrosive media. As a matter of fact, only recently has the situation been clarified sufficiently to enable the design of significant experiments for studying these interactions in a rational and unobscured way.

The detrimental effects associated with cavitation have been recognized for many years, beginning particularly in the field of ship propulsion where cavitation damage to marine propellers, shaft struts, and rudders has plagued the designer of fast ships. Almost as soon as the problem was identified in the marine field, designers of hydraulic pumps, turbines and nozzles began to study the same problems of damage and loss of efficiency that result when cavitation occurs. In recent years, the increasing demands for operation of machines at ever higher speeds and lower pressures have served to focus further attention on these problems. In addition to the continuing requirements in these ("traditional") fields, new technologies have encountered cavitation, sometimes sought to be sure, and increased emphasis has been placed on problems of concern in this treatise. Problems of cavitation damage have been encountered in the high temperature pumping systems of nuclear reactors utilizing either pressurized water or liquid metals and in the pumping and handling systems for cryogenic liquids and liquid rocket fuels. Cavitation phenomena of interest in the damage problem (pressures, temperatures, etc.) are also increasingly the subject of study in the chemical industry where cavitation is being used more and more in various processes (cleaning, acceleration of reactions, etc.). Cavitation damage has also been found in diesel engine cylinder liners, and many more examples of interest might be cited; the list continues to grow every year.

To establish the background for the discussion of the damage mechanism, we shall first describe the processes occuring in cavitating flows, including the fluid mechanics necessary to such discussion, and the types of cavitation that are observed under various circumstances. We shall then describe what is known about the various physical and other factors (fluid dynamical and metallurgical) that play a role in the damage process. Methods of preventing cavitation and, in particular, cavitation damage will then be examined in the light of the foregoing material. Finally, some of the more important methods used in field installations and in the laboratory for studying cavitation damage under operating and accelerated conditions will be described.

I. THE HYDRODYNAMICS OF CAVITATION

NATURE OF CAVITATION AND CAVITATION INCEPTION

Cavitation will occur in a liquid when the pressure is reduced to a certain critical value without change in the ambient temperature, or, conversely, when the temperature is raised above a critical value at constant pressure. Thus, from a purely physical-chemical point of view, there is no difference between boiling of a liquid and cavitation in a flowing liquid, at least insofar as the question of inception (onset) of cavitation is concerned. However, a certain distinction must be made depending upon whether the cavitation is a purely two-phase, one component, phenomenon with a vapor cavity or whether the cavity is initially formed by outgassing of dissolved or entrained gases at pressures well above the pressure of the vapor phase of the liquid. Although the thermodynamical conditions for the formation and maintenance of such types of cavities may differ considerably, from the hydrodynamical point of view no distinction need be made. Thus, for cavitation in a flowing liquid, it is of interest to examine some of the more common conditions under which low pressures may occur in engineering practice. Before proceeding with this description, however, it will be helpful to discuss briefly the physical nature and conditions surrounding the inception of individual cavities which eventually expand and retain their identity during a complex history of growth and collapse or coalesce and form a very large, more or less steady cavity. These will be described in greater detail in connection with the types of cavitation that are of interest here. The hydrodynamics of the small, transient cavities will be of primary interest in connection with the damage mechanism.

It is now generally agreed that cavitation in technically important liquids originate with the growth of undissolved vapor or gas nuclei existing in the liquid or trapped on microscopic foreign particles (see, e.g., Reference 1 and the references therein). On the basis of physical arguments, it is unlikely that completely dissolved gases can play an important role during the inception process except insofar as nuclei that would not grow under reduced pressure because they are of too small a size may reach critical growth size by prior diffusion of gas into the subcritical nucleus (2). Experimental evidence has also been obtained that water saturated with air, but denucleated by application of very high pressure, exhibits large tensile strength (of the order of several hundred atmospheres). Therefore, it is evidently necessary that nuclei be present for the inception of cavitation at pressures of the order of vapor pressure (3)(4). Environmental factors which must be considered in predicting the onset of cavitation include not only the average pressure and pressure-gradient conditions determined by the flow boundaries in the low pressure regions but also the magnitude and duration of pressure fluctuations in turbulent regions, and boundary layer effects including flow in zones of separation. Detailed discussion of these factors is outside the scope of this treatment, nor is it necessary in connection with the question of cavitation damage per se; further details will be found in References 1 and 5. The question of the formation of nuclei is somewhat more pertinent to the damage problem since, as we will point out in greater detail later, the presence of a significant amount of air or other gas in the bubble tends to alter the collapse pressures considerably.

TYPES OF CAVITATION

To illustrate the "types" of cavitation that may occur, it will be sufficient to consider the phenomena from an elementary point of view. In steady, irrotational flow of an incompressible fluid, the pressure equation may be written (neglecting effects of gravitational acceleration):

$$p = P + \tfrac{1}{2}\rho(U^2-u^2) \qquad [1]$$

where p is the local pressure,

P is a reference pressure, usually taken as the pressure in the undisturbed fluid,

u is the local velocity,

U is a reference velocity taken in the undisturbed fluid, and

ρ is the mass density of the fluid.

In dealing with cavitating flows, the pressures must, of course, be referred to the absolute scale. It is clear from Equation [1] that the pressure p may fall to very small values depending upon the velocity u. In general, cavitation will occur when p is of the order of vapor pressure.

Familiar examples of cavitation in flows which obey Equation [1] on individual streamlines are shown in Figures 1, 2, and 3. Figure 1 shows the cavitation developed in a venturi section; as the flow proceeds through the constricted section, the speed is increased and the pressure reduced, resulting finally in the cavitated regions near the boundaries with the liquid jet still intact in the center. Figures 2 and 3 illustrate two types of cavitation on the backs of marine propeller models. In Figure 2, a fully-developed, or "steady", cavity exists near the tip, while in Figure 3, cavitation has occurred in the form of discrete bubbles which grow in regions of low pressure and collapse as they proceed into high pressure regions where they eventually disappear; cavitation of this latter type may be termed "transient" and we shall be mainly concerned with such cavitation in connection with the mechanism of damage. The fluid dynamics of transient and steady cavities will be discussed in detail in a subsequent section.

Another type of flow in which low pressures occur is the vortex flow associated with lifting surfaces as in hydraulic machines. The equation of motion for a simple vortex approximating such real flows is

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{u^2}{r} \qquad [2]$$

which on integration and evaluation at the center of the vortex gives the pressure (see, e.g., Reference 7)

$$p_c = P - \frac{\rho\Gamma^2}{4\pi r_1^2} \qquad [3]$$

where p_c is the pressure at the center of the vortex,

Γ is the circulation (related to the lift of the blades on a propeller, for example),

r is the radial distance from the center of the vortex, and

r_1 is the radius of the vortex core.

Here, again, the pressure may fall to very low values depending upon the strength of the vortex. In the case of lifting surfaces, the conditions in the tip vortices, whose strengths are related to the lift distribution, may be described approximately by Equation [3]. An example of such a flow is shown in Figure 4 in which the tip vortices of a model propeller are clearly delineated.

Finally, in Figure 5 is shown the cavitation cloud produced in the acoustic field of a barium titanate transducer in a beaker of water at a frequency of about 20,000 cycles per second. These photographs have a magnification of 17 and are silhouettes taken with a xenon spark having a duration of about 1/2 microsecond. A description of the barium titanate apparatus, developed by A. T. Ellis (8) for producing accelerated cavitation damage, will be found toward the end of this discussion in the section on laboratory methods for accelerated damage experiments.

To complete the picture of the role of the hydrodynamics of such flows in the damage process, we will first examine some details of the dynamics of the "transient" cavitation bubbles and then discuss the so-called "steady" cavities in terms of the phenomena which may be associated with damage in the latter flows.

HYDRODYNAMICS OF "TRANSIENT" CAVITATION BUBBLES

To understand the origin of the theories and evidence that cavitation is associated with mechanical effects, it is necessary to examine the pressures that might be generated in a cavitating flow. As will be seen, it is theoretically possible to produce pressures many times that required for local failure of metals; however, a number of circumstances may arise in real fluids that tend to reduce these pressures by orders of magnitude -- thus accounting for an essential reason why the mechanical damage hypothesis has been questioned in the past. We will trace through the basic results first and then point out the various influences that tend to attenuate the maximum possible pressures.

The motions and pressures associated with the collapse of a spherical cavitation bubble have been treated in various detail by a number of writers. The classical solution for a perfectly empty cavity was first given by Rayleigh (9); for an incompressible fluid, the pressures at final collapse become infinite, and a number of modifications and refinements to the theory have been carried out to investigate the effect of the properties of real fluids. Surface tension tends to increase the rate of collapse; viscous effects, compressibility effects, and the effects of entrained air (or vapor which cannot dissolve rapidly enough to follow the collapsing bubble walls and acts as a permanent gas) all tend to slow down the motion and, hence, to reduce the maximum attainable pressures. Such studies have been made by Flynn (10), Trilling (11), Gilmore (12), and Poritsky (13), to cite only a few who have considered some of these questions. (A more exhaustive bibliography will be found in Reference 1.)

Because of the extreme complexity of the behavior of cavitation bubbles and particularly because of the impossibility of describing in detail the properties of the liquid-bubble system (size of initial bubble, air content of the bubble, vapor behavior, deformations due to instabilities of the bubble walls -- to mention only a few of the important factors), it is not possible to state unequivocally the pressures developed or the pressure history during the motion and collapse of such bubbles. Many estimates have been made - with as many answers as estimates depending upon the initial assumptions concerning the influence of the properties of the liquid and the contents of the bubbles. Such estimates range from pressures that are too low for damage because a high air content was assumed to be present in the bubbles (but with the accompanying high temperatures associated with the compression of the gas) to values that are clearly more than sufficient for stressing materials beyond their yield points. Such computations will be found in papers starting with Rayleigh (9) and Cook (14) and proceeding through many variations by Ackeret (15)(16), Silver (17), and Beeching (18), among others, to the more modern refinements of the authors cited above (10)(11)(12)(13). For spherical bubbles, results based on the Rayleigh model but including surface tension effects (as worked out by Beeching, for example) give pressures of the order of hundreds of tons per square inch as compared with Silver's results which give an order of tens of tons per square inch when the velocity of bubble collapse is assumed to be limited by the rate at which vapor phase can be condensed. These pressures are, of course, sufficient to account for fatigue failure of most metals. On the other hand, Ackeret assuming that the vapor of air in a bubble obeys a polytropic equation of state found maximum pressures of the order of only tens of atmospheres but with accompanying temperature rise in the gas of the order of thousands of degrees Centigrade. That very high temperatures might indeed occur in the gas contained in collapsing cavities has been suggested as a cause of luminescence (19) in cavitated regions, the mechanism being dissociation of the gas when heated during compression. We will refer again to the possible temperature increases associated with collapsing cavities in connection with damage mechanisms which depend on heating effects.

Where all of the results cited above refer to spherical bubbles, it is known that most bubbles will not collapse spherically because of impressed pressure gradients and instabilities that arise for a number of reasons which need not be detailed here. The important point is that the pressures developed under nonspherical collapse may be orders of magnitude less than those mentioned above. Attempts to measure directly the actual pressures in cavitated regions have been frought with difficulty since the rise of pressure to its maximum value occurs in a time of the order of a microsecond and over a very small area. Instrumentation in early experiments lacked sufficient resolution to obtain results consistent with the theoretical computations and usually give pressures that were only of the order of a few tons per square inch (20)(21)(22)(23). Consequently, adherents of the mechanical damage hypothesis inferred from experiments on actual damage of materials that the pressures must indeed be high enough for failure to occur either by direct stressing or fatigue. More recently, experiments have been made with equipment capable of response sufficiently rapid to enable the measurement of pressures during single bubble collapse with some degree of confidence that the above difficulties could be avoided or at least accounted for. Measurements by Vennard and Lomax (24) showed maximum pressures as high as 30,000 atmospheres but the methods used in data reduction have been subject to criticism. Sutton (25) using a photoelastic technique, reported stresses as high as 200,000 pounds per square inch in CR-39, a thermosetting polymer of allyldiglycol carbonate, which was used as the photoelastic specimen. Careful measurements under controlled conditions by Jones (26) (subsequently confirmed in an independent set of experiments (27)) resulted in peak pressures of at least 12,000 atmospheres. All of these experiments were carried out in deaerated water (although the actual entrained air in the collapsing cavity is not known, of course). In general, the pressures in both aerated and deaerated water are so high that shock waves should be formed, and Mundry and Güith (28) had successfully taken Schlieren photographs of the radiated shock waves associated with collapsing cavities. The obvious conclusion from these results is that there can be no doubt that collapsing cavities of the type discussed here can certainly develop pressures sufficiently high for mechanically produced damage to materials. In fact, the question that should be at the forefront of investigations concerning cavitation damage is that of the importance of non-mechanical mechanisms and of the interaction of mechanical with other mechanisms, and this view is ginning to permeate much of the research now in progress.

HYDRODYNAMICS OF "STEADY" CAVITIES

It is characteristic of some cavitating flows that the cavity appears as a large, smooth, stationary surface. Such cavities often appear to be filled only with vapor or air (or both). On the other hand, a cavitating region made up entirely of small, transient cavities may exhibit the properties of a "steady" cavity in that the average envelope of such a region does not vary with time. In large cavities of this type, the liquid flows along the boundary of the cavity and re-enters at the downstream end. Depending on a number of factors not yet completely understood, the reentering fluid may fill the cavity completely and cause it to collapse, whereupon the cycle of growth, filling, and collapse reoccurs. When the velocities are high enough, and presumably when the rate of entrainment of the reentering liquid becomes great enough, the entrained liquid is swept out of the "cavity" region, the reentrant jet has insufficient momentum to refill the cavity, and the cavity then remains essentially filled only with vapor phase and air diffused from the proximate liquid. The reentrant jet still appears but is dissicated before it can fill the cavity again. Under these conditions, the trailing end of the cavity exhibits quite an unstable motion leading to oscillating forces that are of rather low frequency and certainly not of sufficient magnitude to cause damage in the sense considered here. (Such oscillations may, however, induce rather severe vibrations in adjacent structures). An illustration of such cavities is shown in Figure 6; here a cavity is formed behind a disk supported from the downstream side. In the photograph taken at the high frame rate, the very rough appearance of the cavity wall is seen clearly. A number of small, "transient" cavities may be seen travelling along the boundary of the cavity wall. The appearance is characteristic of cavities in which the reentrant liquid still can fill the cavitating region and cause oscillations of the type described above. Such cavities have been studied by Eisenberg and Pond (29), Shal'nev (30), and Knapp (31), and details of their behavior will be found in the papers of these authors.

Just how damage is caused in such flows is not known for all cases. Under conditions where the cavity is completely filled with vapor or air, no oscillations occur, and there are no transient cavities evident in the flow, the only possible source of impact forces is that of droplets detached from the reentrant jet during its passage through the highly turbulent region at the downstream end. Whether such droplets can possess sufficient momentum to cause damage is not known; however, the damage caused by water droplets impinging on a metal specimen does cause damage of the same nature as that associated with cavitation bubble collapse. The evidence will be discussed subsequently. A known cause of cavitation damage in so-called steady cavity flows is associated with conditions under which transient cavities are observed to exist along the cavity boundary and are convected with the reentrant fluid toward the body about which the cavity has formed. This phenomenon has been described by Knapp (31), for example, and will be discussed further in connection with methods for laboratory experiments on cavitation damage. It is just in this downstream region that the pressure in the liquid is rising and will cause these bubbles to collapse, so that, if they are brought close enough to the material, the high pressures associated with collapse of these transient cavities will act directly to cause damage. While this is, of course, consistent with the observation that damage almost always occurs at the downstream end of a cavitated region of this type, there has also been mention of damage at the leading edge of large cavities. Rasmussen (32), among others, has shown unmistakable evidence of damage at this position. He postulates that this is due to the high tension that must be produced at the liquid-solid interface when there is great affinity between liquid and solid and, on the basis of the theoretical tensile strength of water, concludes that the rupture force to separate liquid from solid is more than sufficient to cause a tensile rupture of the solid material. This conclusion is untenable for the following reasons. Except under the most extreme conditions of water treatment is it possible to obtain tensions in water of more than a few atmospheres (4). For cavitation to occur at all in an experiment of the type conducted by Rasmussen, the conditions for inception must be those described in the foregoing. A more likely explanation of such results is associated with the instability of the separation point for large cavities on blunt bodies such as those used by Rasmussen. Since the separation point (leading edge) moves upstream and downstream considerably and with fairly high frequency, small bubbles close to the body will tend to grow and collapse in that region without being convected along the cavity boundary. Consequently, it is not surprising that damage occurs at this position for such unstable conditions. It is also possible, in principle, that local "microscopic" cavitation might occur as a result of the pressure fluctuations in a turbulent boundary layer (4). Thus, in the low pressure region near the leading edge of the large cavity, small bubbles might grow and collapse in a very small area, and with rather high frequency, and cause damage in the manner mentioned by Rasmussen. However, this suggestion has not been investigated and there is little evidence on which to settle the question. Finally, mention should be made of the suggestion of possible electrochemical effects associated with fluctuations of a liquid-vapor-solid interface, and this will be discussed in a later part of this chapter.

Another observation made by Rasmussen (32) deserves mention at this point. He points out that in his experiments on blunt bodies, cavitation damage occurred over the entire length of the cavitating region although he offers no explanation for this occurrence. On the basis of the description of the behavior of such cavities as given above, such a result could be expected. As the cavity grows and collapses, it sweeps the entire length of the region over which it can exist; thus, it would be expected that transient cavities would be brought into contact with the surface of the body sufficiently often during the cycling process to cause rather uniformly distributed damage. Rasmussen's observations clearly confirm this prediction.

Except to indicate the very high temperatures that might be associated with the collapse of transient cavities and the resulting possibility of sonoluminescence, no mention has been made of the chemical processes that are possible in such cavities. We will consider the latter questions when discussing corrosion theories of cavitation damage.

II. MECHANISMS OF CAVITATION DAMAGE

INTRODUCTORY REMARKS ON THE SEQUENCE AND NATURE OF CAVITATION DAMAGE

Perhaps the most important reason for the great confusion and variety of postulates concerning cavitation damage has been the fact that most of the early observations of such damage were made on machines, such as ships' propellers and hydraulic turbines, which operate in essentially corrosive media. Only in recent years has any real attempt been made by investigators to design experiments that truly control the corrosive influences as well as the mechanically important properties of the liquid medium. Consequently, there has yet to be published a clear description of the process that takes place during cavitation damage so that one may obtain a rational picture of the sequence of events. Aside from the still confused state of our understanding of this process, the phenomenon is such a complex one, involving as it does so many variables, that a coherent account is still not possible without assuming a priori that the mechanisms of importance are known. Not only must account be taken of the fluid dynamical aspects, but also of the electrochemical and metallurgical as well, since the processes may indeed vary depending upon the importance of each of these factors in any particular situation. We will attempt to give such a picture of the sequence of events only by way of orientation for what follows. Some points are sufficiently universal to allow a fairly unified recital while others will be considered as modifications of the more general observations. The detailed consideration of each of the factors involved will be discussed subsequently and related where possible to the following elementary description of events.

There is ample evidence and apparently little remaining controversy that the initial damage associated with cavitation attack is mechanical in nature. It is only in consideration of the intensity and rate of subsequent damage that the role of non-mechanical influences is subject to conjecture and disagreement. Furthermore, the nature of the damage is so intimately related to the response of materials to impingement attack versus chemical reactivity that it is often difficult to separate the effects in an unambiguous manner. Thus, inert materials will show only plastic deformation for relatively long periods of exposure to cavitation pressures while materials that react rapidly in corrosive media will yield corrosion products almost immediately upon exposure. Materials tested in non-corrosive liquids and atmospheres show plastic deformation immediately upon exposure to cavitation pressures. In general, ductile materials show no weight loss for long periods; brittle materials exhibit weight loss early in the process. A polycrystalline or monocrystalline specimen exhibits plastic deformation at varying rates depending upon its hardness and yield properties, with associated cold-work and eventual fatigue and failure. An example of extreme damage under cavitation attack is shown in Figure 7. Such damage is typical of the extent to which material will fail and actually be lost when exposed to cavitation for long periods of time.

For relatively ductile materials, there appears to be a well defined "incubation" period during which no material is lost from the specimen. This is illustrated in Figure 8 for a variety of materials. The term <u>incubation period</u> was applied to this behavior early in the history of studies of cavitation damage which were based solely on measurements of weight loss. It is a somewhat unfortunate choice of description since it implies that a certain time of exposure is required before damage can occur. Actually, it is now known that plastic deformation occurs during this period with little or no loss of material until actual rupture of portions of the specimen and loss of particles. In brittle materials such as cast irons, for example, material is lost almost immediately and no "incubation" period is observed. For certain materials, there is evidence that the incubation time is proportional to the corrosion fatigue limit.

Concurrently with the mechanical attack that occurs as described in the foregoing, a number of electrochemical and thermal effects may occur. Observations have been made which indicate rather clearly that cavitation erosion may be accelerated by the concurrent action of corrosive effects. In such situations, the resultant damage may be described as the net result of the mutually assisting effects of impingement attack in removing the products of chemical reactions, while the corrosive effects tend to produce material that is more susceptible to mechanical failure and removal than the virgin material. There has also been some speculation, based on observations of discoloration of test speciments, that high temperatures -- produced either in the field or as a result of mechanical stressing -- may play a role in the cavitation damage process.

Several other speculations have been advanced to account for damage in cavitating liquids. These indicate that the corrosive effects not entirely accounted for by fatigue mechanisms are associated with the generation of electric currents in adjacent crystals of the material as a result of alternating mechanical or thermal stresses and deformations produced by the forces or temperatures associated with the collapse of cavities. Clearly, such a mechanism, if valid, is restricted to a certain class of materials.

It is clear from even the rather superficial description given above that the evidence for the various postulates must be discussed in terms of the fluid dynamical, metallurgical, and electrochemical factors involved and of the possible interactions and relations between them.

DETAILED DESCRIPTION AND EVIDENCE FOR THE KNOWN AND POSTULATED MECHANISMS OF CAVITATION DAMAGE

The evidence for the various postulates of cavitation damage will be examined in terms of both the environmental factors and the metallurgical observations that tend to support the conclusions drawn from the numerous investigations that have been made. Detailed correlation of the properties of materials with their behavior and ability to resist cavitation damage will be the subject of a later discussion.

1. Mechanical Effects

The fluid dynamical aspects of cavitation damage that account for the existence of very high pressures as a source of damage have already been discussed in some detail. We will now examine the metallurgical observations that support the view that mechanical effects are the primary cause of damage in a cavitating flow. Subsequently, we shall go into detail on the properties of the liquid environment that correlate with and also tend to support this view.

Physical and Metallurgical Aspects

By far the most important source of information on the metallurgical changes that take place during cavitation attack has been laboratory experiments in which accelerated damage has been induced by methods to be discussed later. The earliest experiments relied on visual observations and measurements of weight lost from an exposed specimen as the primary data upon which to base conclusions. Only after experimenters began to use x-ray metallography and photomicrography to examine damaged surfaces did it become possible to obtain precise descriptions of the phenomena occurring. Some of the earlier observations are of direct interest here and will be summarized before proceeding with the more recent results that clearly indicate the mechanical nature of damage associated with cavitation attack.

a. Macroscopic observations

The hypothesis of mechanical damage was first supported by results of two types of investigations, the first being experiments in which damage was produced by means which would simulate impact damage and the second by the use of materials that are chemically quite inactive. In experiments where damage was produced by the impact of water droplets on rods rotating rapidly in air, de Haller (22) demonstrated that the erosion caused was very similar in nature to the damage on the same materials in a cavitation attack experiment. He concluded that the damage was essentially mechanical in nature although he was not able, at that time, to convince himself that the pressures produced were sufficiently high for fatigue damage in the usual sense. Work by Schröter (33) and Hunsaker (34) on lead showed that a lead plate under cavitation attack suffered no loss in weight but was badly pitted -- with the craters in the metal being surrounded by protruding edges reflecting the deformation of the surface. Schröter also did a number of experiments on bakelite, rubber, glass, quartz and agate in water. On the basis of the rapid damage to these materials and the relative chemical inertness of some of them, it was concluded that the damage mechanism was essentially mechanical in nature. While these conclusions were correct for some of the materials tested, such as glass, agate, and quartz, for example, the damage to rubber involves other effects as well. Nevertheless, the conclusions that mechanical stressing was certainly sufficient to account for cavitation damage was well substantiated.

b. Metallographic observations

Important investigations using more modern techniques were carried out, among others, by Kerr (35), Mousson (36), Nowotny (37), Rheingans (38), and Leith (39) on correlation of material properties with damage behavior; and by Boettcher (40), Nowotny (37), Mousson (36), Rightmire and Bonneville (41), and in more recent years, by Ellis (42), and Plesset and Ellis (43,44) on the metallurgical aspects of the problem. The work of Boettcher and Mousson was especially important in disclosing on a sound basis of physical observation and deduction the essential features of cavitation damage, not only with respect to the initial plastic deformation and subsequent failure but also many of the important relationships between material properties and resistance to damage. The physical and metallurgical aspects of the mechanism of damage as given by Boettcher and Mousson have since been confirmed and extended by others mentioned above. From the work of these investigators, it is possible to construct a rather precise picture of the events that occur during the onset of cavitation damage.

In relatively soft materials such as nickel, the surface is observed to be deformed immediately upon application of the cavitating field with the formation of microscopic "hills and valleys" (43). In harder materials, e.g., stainless steels, slip lines become evident after very short exposures. Very hard materials such as titanium 150A do not exhibit surface deformations even after long exposures. Studies (43) of the damage to a zinc monocrystal show that application of a highly concentrated field of cavitation brings out the hexagonal structure of the crystal, Figure 9. Evidence of the plastic deformation that takes place on application of a broad cloud of cavitation to a zinc monocrystal is shown in Figure 10, where it is seen that the twin bands, cross twins and hexagonal pits appear only after the surface has been exposed. In general, severe plastic deformation of a zinc monocrystal is found in the form of twinning in a specimen exposed on a slip plane and in the form of slip when exposed on a twinning plane (43). Further evidence that plastic deformation and cold work takes place immediately upon application of a cavitation field well before any weight loss occurs has been obtained by means of x-ray diffraction patterns of damaged surfaces. Typical patterns are shown in Figure 11; these were taken of a nickel specimen exposed to cavitation in water. The deformation of the lattice structure is shown by the blurring of the Laue spots very soon after initial exposure. Similar effects were observed by Rightmire and Bonneville (41). These results indicate clearly that the initiation of cavitation damage occurs so rapidly that chemical effects must certainly be of secondary importance in materials that are not particularly resistive to repeated stressing. Even for highly resistive materials, such as those mentioned above, the physical changes after long exposure to cavitation are typical of the zinc and nickel specimens described.

Evidence of the rate and depth of penetration of plastic deformation was also obtained by Ellis (42) using the technique of electrolytic polishing, thus enabling the removal of material without introducing extraneous mechanical forces. In a typical experiment on nickel, he found the depth of damage to be greater than 0.007 cm. after 30 seconds exposure. He found that all of the spots which were clearly defined in the undamaged x-ray pictures were nearly all obliterated after exposure to the cavitation cloud. This would indicate that the damage is not a localized phenomenon such as is assumed in theories involving minute cracks. Boettcher (38) has observed that the thickness of the strain hardened layer varies with the initial hardness and with the susceptibility of the metal to strain hardening. When susceptibility is high, the layer is very thin and "quite" hard; when low, the strain-hardened layer is thicker, with correspondingly lower surface hardness Boettcher concludes that following strain hardening the energy of collapse of cavitation bubbles is absorbed in the deformation of the intercrystalline material with eventual cracking and fatigue failure. The latter is based on his observation that fatigue cracks in ordinary fatigue specimens are of the same nature as the damage in a specimen exposed to cavitation damage.

We will next discuss certain correlations with the physical and chemical properties of the liquid environment that tend to substantiate the importance of the role of mechanical effects in cavitation damage.

Effects of the Liquid Environment

Because of the complex nature of the cavitation damage mechanism and of the many variables involved in both the hydrodynamical and the metallurgical processes, investigators have gone to great lengths to find independent correlations to substantiate one or the other of the several postulates. Particularly with regard to the mechanical damage hypothesis have variations in the physical and chemical properties of the liquid received detailed attention. (In addition to our present interest in the relation of these investigations to the goal that motivated them, the results are intrinsically of some interest in connection with cavitation damage in general). We shall first discuss experiments which were designed to add evidence for the mechanical nature of initial damage by demonstrating the congruence of results in a chemically inert environment with the results cited previously. The influence of the physical properties and state of the liquid system will then be considered.

a. Chemical activity

In order to separate as well as possible the effects of mechanical action from concurrent chemical attack, investigations have been carried out in environments that were chemically inert. Two sets of results are of particular interest. Wheeler (45) has performed experiments in an accelerated damage apparatus using toluene as the liquid medium and, independently, Plesset and Ellis (41) have also reported results using toluene; however, the latter used, in addition, helium atmosphere above the toluene. Toluene was selected not only because it is chemically very inert, and therefore corrosion should be completely absent, but also because its physical properties are such that fluid dynamic pressures developed should be comparable with water under the same test conditions. Helium is, of course, a very inert gas. The experiments of Wheeler were performed with pure annealed iron while those of Plesset and Ellis were carried out on nickel and stainless steel. The results of both investigations showed clearly that the onset of damage (plastic deformation, cold work) is precisely the same in the inert environment as it is in water in an air atmosphere. While this evidence can leave no doubt as to the importance of the mechanical damage mechanism in cavitation attack, it does not exclude the possibility of chemical or electrochemical attack in later stages of the process. In fact, Wheeler found that after extended periods of exposure, the rate of damage as measured by loss of material was much greater in the water than in toluene. In addition, he reports that in toluene, beyond a certain time of exposure, no further loss occurred, and states that the same result was generally observed in tests with a number of different hydrocarbon liquids. This behavior is attributed to corrosive action in the water environment, and we shall discuss such effects separately.

b. Temperature: vapor pressure; gas content

In examining the effects of the temperature of the liquid on the damage process, account must be taken of both the vapor pressure and the dissolved or entrained gas content. The effects of temperature have been studied by Kerr (35), Rheingans (38), Nowotny (37), Mousson (36), Wilson and Graham (46), Leith and Thompson (47), and Bebchuk (48,49) among others. The results of experiments by Bebchuk are reproduced in Figure 12 as typical of the behavior generally observed. That the effects are primarily associated with the vapor pressure and gas content may be deduced from the fact that the corresponding changes in the other properties of the liquids (density, surface tension, viscosity) vary comparatively little with change in temperature. The occurrence of the peak in the damage curves may be explained as follows. At the lower temperatures, the vapor pressure is relatively low but the capacity of the liquid for solution and entrainment of gases is relatively high. Thus, the high air content provides permanent gas for "cushioning" of bubble collapse and damage is relatively slight. As the temperature is increased, gas is driven off but the vapor pressure is still not high enough to provide any cushioning effect. In fact, the higher vapor pressure may provide additional unstable nuclei and, consequently, more cavitation bubbles will be available for damaging attack. As a result, damage is rapidly increased. Finally, as the temperature continues to increase, the vapor pressure reaches high enough values to provide considerable cushioning for the collapsing bubbles and damage is again reduced.

The effects of vapor pressure on the damage process was strikingly demonstrated by Nowotny (37) in experiments on pure aluminum in water, benzin, benzol (octane-nonane mixture), and ethyl ether. He compared damage in water at 20°, 60°, and 90°C with damage in the other liquids at approximately 26°C. The vapor pressures for water at the three temperatures cited are 17, 150, and 525 mm Hg, while the vapor pressures of n-octane, benzol, and ethyl ether at the test temperature were about 16, 100, and 500 mm Hg, respectively. The damage obtained at the corresponding vapor pressures was very nearly the same. He observes further that in the ether no damage could be observed even after long exposure to attack; this behavior is typical of water near the boiling point and in highly volatile liquids in general, and was an important piece of circumstantial evidence in substantiation of the mechanical damage hypothesis for many years.

The recognition of the role of permanent gases in ameliorating cavitation damage has led to the use of air injection into cavitating machines for damage reduction; this will be discussed further in connection with methods for reducing cavitation damage.

c. Surface tension

Other factors remaining constant, the expected effect of surface tension, based on the conclusions from dynamics of transient cavities, would be an increase in damage with increasing surface tension (since collapse pressures would be higher with higher surface tension). That this is indeed the case has demonstrated by Nowotny (37), for example. Nowotny's results are shown in Figure 13, where the weight loss of a pure aluminum specimen has been plotted as a function of surface tension; in these experiments, the vapor pressure was held approximately constant.

d. Viscosity

Since cavity collapse pressures in liquids of low viscosity tend to be higher than in liquids of high viscosity, greater cavitation damage of mechanical nature would be expected in the former. This conclusion is also borne out by experiments. We cite, in particular, the results of Wilson and Graham (46), which are reproduced in Figure 14. Using mineral oils of different viscosities and glycerine-water mixtures of different composition and therefore different viscosity, they conducted experiments in two ways. In experiments on a silver-plated surface, the energy input (to a magnetostriction oscillator) was held constant and the viscosity varied. As would be expected on the basis of the remarks in the foregoing, the damage decreased with increasing viscosity. To further check the effect postulated, experiments were carried out on an aluminum surface with the energy input increased to compensate for the increase in damping of the cavitation bubbles as the viscosity of the liquid was increased. That approximately constant damage was obtained in this way further confirms the role of mechanical effects in cavitation damage.

e. Compressibility and density

A final piece of evidence which shows the correlation of mechanical effects with cavitation damage may be cited from the experiments of Wilson and Graham (46). Their experiments on the effects of compressibility and density, separately, showed generally the trends that would be expected on the basis of the behavior of collapsing transient cavities, i.e., increasing damage with increasing density and decreasing compressibility, although the scatter in data is rather large. Reasoning from the approximate Rayleigh theory of bubble collapse with account for the compressibility of the liquid, they correlated their results on the basis of the product of sound velocity and density. The results for experiments on silver surfaces in a variety of liquids are reproduced in Figure 15. Not only are these results of interest in connection with the mechanism of cavitation damage, but they will be of some interest in practical cases where a knowledge of the relative effects of various liquids will assist in design or in extrapolation of experimental results from one liquid to another.

2. Electrochemical and Chemical Effects

In view of the evidence on the mechanical origin of cavitation damage that has been gathered in the foregoing part of this chapter, it may seem surprising that there should still be controversy concerning the basic nature of the damage process. There can be no question that concurrent chemical or electrochemical activity may alter even seriously the net result and character of damage under cavitating conditions. However, there are still under way attempts to prove that the damage process is primarily of electrochemical origin with mechanical damage only incidental if present at all. Hence, two questions will be examined here: the bases for the latter view, and the more pertinent problem of the interaction of mechanical and chemical or electrochemical effects.

Observations and Theories of Electrochemical Corrosion

A number of mechanisms have been postulated at various times which involve almost all aspects of possible electrochemical activity including thermogalvanic effects, stress-induced galvanic effects, oxygen concentration cells, ion concentration cells, etc.

Largely, these hypotheses have been based on the observed effects of applied cathodic protection rather than direct observation and analysis. We shall first consider the reasoning and evidence on which these various postulates are based and then discuss recent research on the mechanism of cathodic protection as it relates to these postulates. It should be kept carefully in mind that our discussion refers to electrochemical effects associated specifically with phenomena occurring during or directly from the cavitation process and not with the more familiar galvanic effects arising with dissimilar metals in an electrolyte, for example. The fact that galvanic effects of the latter type are often present simultaneously in practical situations has indeed complicated and obscured the cavitation damage mechanism and account of these effects must, of course, be taken separately.

a. Thermogalvanic postulates

Thermogalvanic postulates require that electrochemical effects associated with temperature changes be brought about by the presence or creation of high temperatures as the primary mechanism inducing the flow of corrosive currents in a metal. The possibility of high stresses concurrent with or responsible for such high temperatures is assumed to have only a secondary effect on the corrosion process. Two sources of high temperature are generally identified in support of such theories: (i) the high temperatures that are possible momentarily in the collapsing bubbles due to compression of the contained gas, and (ii) possible high temperatures associated with the momentary stressing of the metal at the position of bubble collapse. The idea of thermogalvanic effects has been advanced by Krenn (50) on the basis of the heat flow between corroded parts and adjacent power generating equipment in machines and by Foltyn (51) and Nechleba (52) on a more rational assumption of a heat potential generated by increase of temperature of the metal due to local stressing or due to high temperatures in the cavitation bubbles themselves. Owing to this local heating, a temperature gradient is created between the heated spot and the surrounding material which causes an electric current to flow (in a conducting medium). The electrolytic corrosion presumed caused by such current flow will be directly proportional to the current. To test this hypothesis, Foltyn carried out experiments using impressed cathodic currents in which the counter current was adjusted to be just equal to the electrolytic current measured during an independent cavitation experiment. While he was able to report considerable reduction in damage, he was not able to completely eliminate the loss of material. The explanation offered for the ameliorating effects of such cathodic protection is that the potential of the "cathode" is raised above the potential level induced at the attacked point. It is interesting to note that both Foltyn and Nechleba were able to achieve reduction in damage by means of cathodic protection only with very smooth surfaces, while very little, if any, protection was observed on roughened surfaces.

b. Mechanically-induced electrochemical effects

(i) Stress-induced galvanic effects.

Closely related to the idea of the mechanism of thermogalvanic effects of the type described above is that of stress-induced galvanic effects between adjacent crystals accompanying the high local stresses associated with collapsing cavitation bubbles. This hypothesis was first announced by Petracchi (53), who also admits the possibility of (secondary) thermal effects of the type described above. The arguments and alternatives are approximately as follows. Deformation of the microcells increase their e.m.f. by altering the internal energy of the small surfaces which constitute the electrodes. Alternatively, the polarization of the microcells might be slowed down or impeded by the varying stresses. Finally, even microcells with very low e.m.f. values can give rise to appreciable effects since the corrosive effects is localized in the most highly stressed areas and in turn increases the stresses.

Petracchi assumed that the suggested mechanism is somehow related to the mechanism of corrosion fatigue and that, by the use of cathodic protection which can retain in a corrosive medium the fatigue properties of a metal in air, for example, he would be able to prevent cavitation damage. His experiments (53) indeed show considerable protective effect similar to the tests cited in the foregoing. Again, however, he was not able to prevent damage completely at currents which just balanced those measured under non-protected conditions. A more likely and now quite conclusively demonstrated mechanism of such cathodic protection is associated with the actual evolution of hydrogen at the cathode, which provides then a cushioning effect. The evidence for this statement will be discussed in a later part of this report.

(ii) Mechanically-associated galvanic effects

It has been shown by Ffield, Mosher, and O'Neil (54) that materials such as bronze in water form a protective film that may be cathodic to the underlying material; they report that such films have been observed both in their laboratory experiments and on ships' propellers. They postulate that rupturing this film will create a galvanic cell between the bare metal and the surrounding film. In view of the highly localized action of mechanical cavitation damage, it is concluded that the area relationship between anode and cathode will be favorable for very high galvanic corrosion rates. Thus, their thesis assumes that the mechanical aspects of cavitation is only the trigger which sets off a violent electrochemical effect. They point out further that, if this is indeed a primary cause of cavitation damage, the galvanic effect should be eliminated by applying cathodic protection which would immediately heal the (mechanically) damaged areas. However, no substantiating results are as yet available.

c. Other suggestions of electrolytic corrosion

A number of suggestions have been made to account for cavitation damage or cavitation-associated damage which, in one way or another, rely on a primary mechanism of electrolytic corrosion induced or accelerated by the concurrent cavitation activity. These range from very simple postulates which require that the stirring action produced by cavitation in water in which polarization has occurred assists in removing hydrogen layers (which tend to inhibit electrolytic processes) from the cathode surface to more sophisticated mechanisms associated with strain-induced anodic corrosion. Since ordinary electrolysis attack is very slow compared with observed cavitation damage, any effects of the former type cannot play a very important role. Another suggestion is based on electrolytic corrosion associated with fluctuations in the boundary between the metal, liquid and atmosphere.

(1) Strain-produced anodic corrosion.

This mechanism, which evidently embodies some of the features of corrosion fatigue and is somewhat related to the ideas set forth by Petracchi (53), has been discussed in detail by Wheeler (45). It is based on the expectation that strained portions of a metal, in which the crystal structure is distorted, will be unstable electrochemically, and the observation that cold worked iron exhibits a solution rate very much greater than annealed iron. Thus, if a previously annealed specimen is subjected to repeated plastic deformation with the formation of associated strain centers, anodic areas will be continuously created. Where the metal is stressed but not permanently deformed, the electrode potential shift will be transitory and varying with the stress. These anodic areas, adjacent to the undisturbed metal, will give rise to electrolytic corrosion if the surface is in contact with an electrolyte, and corrosion will continue until polarization prevents further flow of current or until the anodic areas are etched away. It is not known whether cathodic protection in the sense described previously can be effective here. If the specimen as a whole is made cathodic relative to the adjacent electrolyte, differences in electrode potential between strained points and undisturbed metal will still not be prevented. A previously cold-worked material, or a material in which adjacent grains have different electrode potentials (heterogeneous materials), will be immediately attacked electrolytically when placed in an electrolyte and such attack will be accelerated in the above manners when subjected additionally to cavitation activity.

(ii) Interfacial fluctuations.

Based on observations of the greatly increased cavitation damage of cast iron in (synthetic) sea water as compared with fresh water, Shal'nev (55) is willing to dismiss all evidence of mechanical damage and assign the responsibility for cavitation damage entirely to electrochemical corrosion associated with fluctuations in the metal-liquid-atmosphere interface. According to his hypothesis, the movement of the liquid-vapor (or gas) interface across the surface of the metal during cavitation attack results in momentary electrode potentials which are orders of magnitude greater than that caused by an unbroken contact between liquid and electrolyte and produces electrochemical corrosion at tremendously high rates. He cites the irregular shape of attacked regions in a magnetostriction apparatus as evidence that such electrochemical attack is associated with different modes in the growth and collapse of the cavitating mass and the irregular shape of unstable transient cavities locally. However, an explanation of the irregularities of the damage patterns in such an experiment, associated with hydrodynamic instabilities, has recently been given, and a method for completely eliminating them has been devised (these observations will be discussed in connection with the use of the magnetostriction oscillator for accelerated damage experiments). Furthermore, such a mechanism cannot, of course, account for the damage to materials which are not as active as cast iron nor to damage in non-corrosive media, although such a mechanism as a source of additional damage in some cases probably cannot be ruled out at the present time.

Observations and Theories of Associated Chemical Corrosion

Concurrent chemical attack has been observed during many experiments on cavitation damage. This has been explained variously on the bases of straightforward chemical activity in highly corrosive media and of chemical activity induced or accelerated by the production of high temperatures which either produce chemically active products in the liquid environment or render the metal itself more active.

a. Chemically-corrosive environments

Among the earliest observations of purely chemical corrosion during cavitation attack were those of Spannhake (56) and Schröter (57), and effects similar to those reported by them have been found by subsequent investigators; see, e.g., Nowotny (37). In tests in venturi tubes, after long exposure to cavitation, pronounced tarnish has been noted on brass specimens as well as various steels. Nowotny reports that, in tests carried out by Spannhake (unpublished), it was found that steel subjected to a short test had a loosely adhering film of oxide or hydroxide which was of a thickness to produce a blue interference color. However, he attributes this discoloration at least in part to the high local temperatures which are hypothesized as occurring during the collapse of cavitation bubbles. After long exposures, these films became very strong and anchored themselves into the metal. In one exceptional case, the oxide film was so thick as to cause an <u>increase</u> in the weight of the specimen. Such films are subsequently removed by the mechanical erosion of the primary (mechanical) attack. A secondary chemical effect is associated with the provision of localized micropores by mechanical attack which then act as seats for chemical action. Such corrosion is conducive to corrosion fatigue under continued stressing by the forces of the collapsing cavities. Nevertheless, from an analysis of the particles actually removed during tests of aluminum, zinc, and cadmium in water, Nowotny found that this residue was in each case composed mostly of pure metal with only a very small remainder of oxide. Tests by Rheingans (38) of steels and various nonferrous metals in sulphuric acid and hydrochloric acid also showed very little effect of the corrosive medium in comparison with distilled water in exposures of two hours. In fact, most of his results indicate less damage in the acids than in the water.

To reduce the contributing factors associated with chemical activity, corrosion inhibitors have been tried and used with increasing frequency. These will be summarized in connection with our discussion of methods of reducing cavitation damage.

b. High temperature chemical activity

The sources of temperature rise which have been postulated to result in locally increased chemical activity are (i) conversion of mechanical into heat energy during deformation of the material by the forces of collapsing cavities, and (ii) heating of the gases or vapor entrained in the cavitation bubbles when compressed during bubble collapse. On the basis of the explanation of work hardening as formulated by Taylor and Quinney (58), Wheeler (45,59) proposes that sufficient heat is generated to increase significantly the chemical reactivity between iron and water, for example. According to Taylor and Quinney, 85 percent or more of the work during deformation of metal by the slip process is converted into heat and the remainder into potential energy of internal stress. Work hardening is then explained by the internal stress due to very small centers of strain located at grain boundaries (or "sessile" dislocations). It is the heat formed during this process that Wheeler postulates as the source of increased chemical activity; from estimates of the amount of work done in pitting metals during cavitation attack, he estimates that momentary temperature increase of several hundred degrees Centigrade can occur, depending upon the hardness of the metal.

As already mentioned above, chemical activity observed in cavitation damage experiments has also been attributed to the production of very high temperatures in the gases within the cavities themselves. While the evidence for such temperatures in cavitation experiments where bubbles occur only once and then disappear, their place to be taken by others, is only indirect, the existence of high temperatures in bubbles in an ultrasonic field seems well documented. A number of investigations by Griffing et al (60,61) have demonstrated that bubbles in resonance with an ultrasonic field evidently produce temperatures that are of the order of hundreds and even thousands of degrees. These conclusions are based on the chemical reactions obtained, e.g., the production of H_2O_2 in irradiated water, and the observation of luminescence. Much remains to be done before it can be definitely stated whether such effects are of importance in engineering applications where damage occurs. It is not clear whether the reactions take place inside the bubbles or at the bubble walls, whether the bubble oscillation frequency is important in producing high temperatures, and whether such phenomena can occur in all liquids of engineering interest. These questions will have to be answered before the role of such phenomena in the damage process can be clearly delineated.

3. Other Observations and Postulates Concerning Cavitation Damage

There have been several other postulates of the mechanism of cavitation damage, some not unrelated in one way or another to those discussed previously. However, certain features are sufficiently different, either in physical detail or in speculative nature, to warrant separate discussions. These include other mechanical hypotheses not connected with the damage demonstrated to be produced by hydrodynamic means and certain "thermo-mechanical" and "mechano-chemical" postulates to which some of the evidence cited above also seems to apply.

a. Thermo-mechanical effects

In addition to the observations of Nowotny (cited above) of the discoloration of metals as in heat treatment, Wheeler (45) and Nowotny (37) have both remarked on the "welded" or fused appearance of adjacent crystals in metals after cavitation attack. Nowotny observes that such fusion takes place preferentially along grain boundaries. He also cites the rapid formation of amalgams of lead, cadmium and copper exposed to cavitation in mercury but the implication that high temperatures are of importance in producing the solution of one into the other is modified by the observation that the very high pressures also present might account for the observed effects. Wheeler postulates that the high temperatures associated with the Taylor mechanism of work hardening will result in welding together of deformed excrescences of the metal surface.

b. Mechanical: pressure release hypothesis

In 1942, Poulter (62) proposed the hypothesis that cavitation damage may be attributed to pressure release rather than pressure application. In a series of experiments on glass and quartz rods, he showed that breakage would occur on release of pressure slowly applied through several different liquids, and that the susceptibility to breakage increased with increased time of pressure application. Since the specimens were found to withstand greater pressures witn oil and glycerine as compared with water, alcohol, and ether, Poulter concluded that breakage depended upon the ability of the liquid to penetrate the specimen. Thus, he postulated that the damage observed in cavitation experiments is due to the penetration of the specimen by the liquid under the action of cavity pressures with subsequent fracture of particles of the material when the pressure is released. To test this hypothesis, Poulter carried out cavitation experiments with the same liquids and found indeed that the damage was greatest with the less viscous liquids. That the argument is fallaceous follows from the fact that the time of application of pressure required to obtain the effects observed by Poulter is several orders of magnitude greater than that available during the life of a cavitation bubble. Furthermore, the reasons for the difference in results for the various liquids is amply evident from the remarks in an earlier part of this chapter concerning the effects of liquid properties on cavitation pressures and damage.

c. Mechano-chemical postulates

It has been suggested by Weyl and Marbae (63) that cavitation damage in water is the result of electrical discharge phenomena occurring upon "fracture" of the water molecule with resultant dissociation of the liquid and, following, highly active electrochemical action. Others have supported the electrical discharge theory (64,65,66) but it must be remembered that cavitation in ordinary liquids originate from nuclei as discussed above, and fracture in the sense required here does not occur. A more likely explanation of the presence of hydroxyl radicals, which would also be the product of Weyl of Marbae's hypothesis, is thermal decomposition of the water as described by Griffing and her coworkers (61). Chemical reactions of this type have not been observed in liquids other than water unless some water was also present.

Another "mechano-chemical" possibility has been suggested by Wheeler (45). He cites evidence that extremely severe, repeated, shearing strains may so completely disturb the arrangement of the crystal lattice in a metal that all crystalline form is destroyed, thus rendering it amorphous and chemically more reactive. However, there is no evidence that this has actually occurred during the cavitation damage process.

4. The Role of Impressed Cathodic Currents

Although we shall later discuss cathodic protection as a means of reducing or eliminating cavitation damage, it is worthwhile to mention here the results of recent research which explains the protective nature of the cathodically applied currents cited in substantiation of many of the postulated mechanisms of damage discussed in the foregoing. It is clear, of course, that cathodic protection in a corrosive medium will assist in delaying the highly damaging effects of cavitation simply by preventing accompanying electrolytic corrosion associated with purely galvanic activity. However, in no case has it been demonstrated that the currents required for prevention of such galvanic action are sufficient to prevent cavitation damage.

It has been suggested that the mechanism of cathodic prevention of cavitation damage in water is associated with currents sufficiently high to result in hydrogen evolution (see, e.g., References 1 and 67); the hydrogen gas then acts to form a "cushion" to reduce the high pressures of the collapsing cavities. In a series of experiments, Plesset et al (68,69) has essentially confirmed the validity of this explanation. His results, which are discussed in detail in another part of this chapter, may be summarized as follows. Tests with various materials in a solution of salt in water showed a reduction in weight loss for all of the materials when the test specimen was made the cathode of an electrolytic cell and when the conditions were such that gas was evolved at the surface of the specimen. This protective effect against cavitation damage increased with increasing magnitude of the cathodic current. Similar protection was obtained when the specimen was made the anode in a test liquid of buffered distilled water. In the latter case, the gas evolved at the specimen surface is oxygen. Plesset found additional evidence for the protective effect of such gas layers 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 of the specimen; there was then no protective effect with the specimen cathodic or anodic.

In view of these results, it is questionable whether the protective effect of cathodic currents may be used in evidence for the importance of thermogalvanic and mechanically-induced electrochemical effects as sources of damage in the cavitation process. In quite another connection, however, cathodic protection of an active metal in an electrolytic environment should show significant reduction in the rate of cavitation damage in view of fatigue properties. It has been demonstrated that the resistance of metals to cavitation damage is closely related to fatigue properties because of the mechanical effects in the damage processes. Consequently, the rate of damage should be increased in a corrosive environment, since the corrosion fatigue limit is so much lower than the limit for fatigue in air. Thus, by applying cathodic protection to prevent electrolytic activity, it would be expected that the fatigue limit achieved in air can be restored. In this way, too, the damage rates in a cavitating system should be reduced proportionately. Unfortunately, there have been no experiments designed specifically to prove this point.

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5. Concluding Remarks Concerning the Importance and Interactions of the Various Damage Mechanisms

Although it is clear that damage to materials in a cavitated region can, under most conditions, be accounted for entirely by mechanical processes under the pressures produced during collapse of cavitation bubbles, there is also evidence that electrochemical corrosion is often an important factor in such regions. While there is still a tendency among investigators to attempt to show the predominant role of one to the exclusion of the other (although it is also recognized that there must be a mutually assisting process of corrosion-erosion in corrosive media), the situation is obviously more complicated than these points of view would indicate. On the basis of our previous discussion, the damage problem complex for corrosive liquid media might be summarized in the following way (70). There might be defined three regimes of interaction between mechanical and corrosive effects in cavitating flows in corrosive media: (a) flows in which the velocity and pressure fields are such that bubbles collapse far enough from the boundary or collapse in such a way that the local pressures associated with collapse are too small in themselves to cause damage -- the chemical or electrogalvanic reactions being then predominant; (b) flows in which the mechanical and corrosive actions are of the same order of magnitude; and, (c) flows in which the mechanical attack is so intense that corrosive reactions, while present, are not important in determining the rate at which damage occurs (as measured by weight loss or rate of pitting, for example), or, at most, give rise to secondary electrochemical effects.

In the first case, the flow conditions must be such that the bubbles do not reach the material surface before collapsing, i.e., the transport velocities are so small and the ambient pressures so large that collapse takes place too far from the surface for even the radiated shock waves to cause damage. (This case also includes unstable collapse and collapse in liquids containing large amounts of gas in which the pressures associated with the bubble motion are limited in magnitude and cannot cause damage even when very near or on the surface). However, the rate of corrosive damage may be accelerated in such a region either by additional mixing produced by the presence of a cavitating flow, i.e., by more efficient transport of corrosive liquid to the material, or by the accelerated removal of corrosion products, thus exposing virgin material more rapidly, through collapse pressures large enough to remove such products but not large enough to damage the virgin material. The second case implies collapse pressures large enough to produce damage directly. In this regime, mechanical, chemical and electrochemical mechanisms are mutually assisting in producing weakened and corroded material and in exposing virgin material to further attack. The third case is essentially the same as the second, but with mechanical damage rates much higher than corrosion rates, and is most likely to be attained in media that are only slightly corrosive.

We have chosen to state the situation in this highly oversimplified way in order to emphasize the possibilities of various influences in the cavitation damage process. In general, mechanical damage takes place so rapidly compared with non-mechanical reactions that there can be little doubt of the importance of mechanical damage in the initial stages of cavitation attack as well as throughout the duration of the attack. Much research remains to be done before the validity of the postulates concerning mechanically-induced electrochemical and chemical effects can be determined in detail.

III. CORRELATION OF MATERIAL PROPERTIES AND SUSCEPTIBILITY TO CAVITATION DAMAGE

PURPOSE AND SCOPE OF DISCUSSION

It is amply evident that our understanding of cavitation damage, especially in corrosive media, is far from complete. Even if the mechanism of damage were known in all detail, it would still not be possible to predict quantitatively the correlation between the properties of materials and their susceptibility or resistance to damage because of essential gaps in understanding of the behavior of materials themselves. Consequently, it is possible at present to predict in only very general terms the response of materials to cavitation attack and then only to estimate relative susceptibility or resistance. For example, on the basis of the mechanical aspects of the damage process, it might be expected that hardness would be an essential factor in determining resistance to damage. This is indeed the case for many materials but certainly not for all, and this situation seems to plague the attainment of unique correlations in general. Attempts have been made to obtain correlations between damage resistance and the mechanical, material or structural, and behavioral properties of a great number of metal and non-metallic substances. We shall examine here the phenomenological evidence of correlation with these various properties, but with no assurance that all of the pertinent characteristics have even yet been suggested. It must be recognized further that the problem is made very complicated by the difficulty of separating the influence or relations between such characteristics in any given substance.

Listings of the relative damage resistance of a great number of materials will be found in the papers of Kerr (35), Mousson (36), and Rheingans (38,71), among others. Specific materials will be mentioned here only in illustration of the relation between properties and damage resistance.

MATERIAL PROPERTIES AND DAMAGE CORRELATIONS

To bring out the essential relations between the properties of materials and damage resistance, correlations will be discussed and grouped according to mechanical properties, material properties, and behavioral or environmental characteristics. This classification should by no means be considered as the most logical one, but at the present time it at least provides a convenient reference system.

1. Mechanical Properties

a. Hardness

Harness has been shown to be an important factor in cavitation damage resistance. In general, materials with great hardness, as measured by the Brinell hardness scale for example, have better resistance to damage than softer materials. However, certain materials do not fall into the general pattern, as will be seen.

The effect of hardness will be illustrated by the results of laboratory cavitation damage tests on various metals. In Table 1 are shown the damage rates in tests of a series of cast stainless steels as determined by Rheingans (38), using a magnetostriction oscillator.

TABLE 1

CAVITATION DAMAGE RESISTANCE OF CAST STAINLESS STEELS
(After Rheingans - Reference 38)

Chrome (percent)	Brinell Hardness Number	Rate of Loss (mg. per min. in last 30 min. of test)	Total Loss (mg. in 120 min.)
12	302	0.20	20
13	302	0.26	25
13	235	0.43	49
13	241	0.39	51
12	225	0.55	54
13	229	0.46	57
13	207	0.51	70
12	167	0.73	141

Except for the small discrepancies, the order of resistance generally follows the order of hardness. Another example of the correlation of damage resistance with hardness is given in Table 2, abstracted from the results of Mousson (36) on materials tested in a venturi apparatus.

TABLE 2

CAVITATION DAMAGE RESISTANCE OF PLAIN AND ALLOYED CAST IRONS
(After Mousson - Reference 36)

Alloy	Chemical Composition (percentage)							Tensile Strength (p.s.i.)	Brinell Hardness Number	Cavitation Loss in 16 hrs. (mm.^{3})
	C[a]	Mn	Si	Ni	Cr	Cu	Note			
Cast Iron	3.18	.50	2.13				1	25,000	171	636
Cast Iron with Casting Skin	3.20	.50	2.00				2	25,000	200	396
Nickel-Tensyleran	2.54	.76	2.51	1.05			1	56,000	235	376
5 percent Nickel Cast Iron	2.93	.50	1.36	4.81			1	35,000	303	269
Ni Cu Cast Iron	3.10	1.50	2.00	15.00	1.00	7.00	2	18,000	107	837
Ni Cr Cu Iron	2.77	1.00	1.86	14.48	1.88	6.00	1	25,000	116	247
Ni Cr Cu Cast Iron	2.95	1.00	1.89	14.36	3.95	6.00	1	35,000	161	109

Notes: (1) Actual analysis. (2) Estimated analysis. (a) Total C.

The first four specimens in Table 2 are basically of ferritic type in the grain structure while the last three show an austenitic matrix. While the groups show correlation within themselves of increasing resistance with increasing hardness, there is clearly another factor which influences the comparative losses between groups. This may be attributed to grain structure and cold working properties and will be discussed subsequently.

As a final example of the role of hardness, we cite the experiments of Plesset and Ellis (43) on a number of different materials. Their results are summarized in Table 3. The criterion of damage was the depth to which a small hole was drilled by a focused cavitation cloud such as that shown in Figure 5. They point out, in addition, that nickel and brass show plastic deformation after a few seconds of exposure to cavitation, while a similar amount of deformation takes several minutes for vanadium, approximately an hour for molybdenum, and several hours for tungsten. Again, cavitation damage resistance is well correlated with hardness except for the molybdenum specimen. Thus, while the excellent resistance of titanium 150A and the stellites would have been expected on the basis of hardness alone, these results again show that hardness is not the only important factor. We shall discuss the case of molybdenum in connection with the possible role of yield lag.

TABLE 3

CAVITATION DAMAGE RESISTANCE OF VARIOUS METALS
(After Plesset and Ellis -- Reference 43)

Material (arranged in order of increasing hardness)	Composition percent	Hardness (Brinell)	Ultimate tensile strength (psi x 10^3)	Modulus of elasticity (psi x 10^6)	Depth of Cavitation Damage Hole in microns (10^{-4}cm)						
					10 sec	1 min	15 min	30 min	1 hr	2 hrs	3 hrs
Aluminum(soft)		16	16	10	10	80					
Titanium (annealed)		58	79	16			43	78			
Nickel		90	50	30			80	115			
Molybdenum		120	57	50				10	25	60	100
Brass	Cu 70,Zn 30	123	56	13		1	35	128			
Stainless Steel	Cr 18,Ni 8	163	102	29			15	28			
Titanium 75-A		203	80	16					30	66	
Steel (4130)		258	130	30					32	55	
Tungsten		350	597	51				0	0	3	
Titanium 130-A	Ti 92,Mn 7.9	351	130	16				0	3	16	
Colmonoy		400	61					0	3	18	34
Titanium 150-A	Ti 96,Cr 2.7, Fe 1.3	437	150	16				0	0	3	26
Stellite	Co 55 Cr 33, W 6	495	100	36				0	3	14	

b. Work hardening

The original hardness of materials before cavitation attack does not in itself constitute a unique correlation parameter although it may be overriding for many materials. There is clear evidence that resistance to damage is dependent upon the ability of a metal to be work hardened under repeated impact. This is well illustrated by a comparison of stainless steels which shows the excellent properties of the austenitic steels. In Table 4 are shown some results from tests by Mousson (36) in substantiation of this conclusion.

TABLE 4

COMPARISON OF CAVITATION RESISTANCE OF SOME STAINLESS STEELS
(From Mousson -- Reference 36)

Material	Tensile Strength (p.s.i.)	Yield Point (p.s.i.)	Brinell Hardness	Loss in 16 hrs (mm^3)
Stainless 17% Cr.Steel	85,000	40,000	201	67.0
Stainless Steel 18-8 Cr. Ni	75,000	30,000	145	8.8
Stainless Steel 24-12 Cr.Ni	196,000	96,000	139	8.6
Stainless Steel 26-13 Cr.Ni			161	4.1

Although the original hardness of the austentic stainless 18-8 chromium-nickel steel was lower than that of the stainless 17 percent chromium steel, the resistance of the former is far superior over the duration of the experiments. (These tests were made in a venturi-type of apparatus at much slower rates of damage than occurs in magnetostriction oscillators). The other austenitic stainless steels also exhibit similar beneficial effects of the work hardening properties of such metals. Mousson also measured the change in hardness of various metals after exposure to cavitation damage and found large increases in the zones of exposure (72) as would be expected on the basis of our previous discussion of plastic deformation accompanying cavitation attack.

c. Yield lag

No systematic research has as yet been carried out to determine the correlation of cavitation damage resistance with delayed yield properties of materials. However, from considerations of the very short times involved in the life of transient cavities (the pressure peaks have a duration of the order of microseconds while the entire life of a bubble is measured in milliseconds), it might be expected that materials which exhibit large delayed yield properties would also possess good damage resistance properties. The observations of Plesset and Ellis (43) of the behavior of molybdenum is a case in point, and they have recognized this possibility. The molybdenum specimens of Table 3 have a hardness and ultimate tensile strength of about the same magnitude as nickel and brass but exhibit damage resistance comparable to that of much harder materials. However, molybdenum is known to exhibit large yield lag under rapidly applied stress (see e.g., Bechtold and Wessel (73)), and its behavior here is in keeping with this property.

d. Ultimate tensile strength

It is very difficult to distinguish unequivocally between the importance of tensile strength and hardness since these properties are usually closely correlated for most metals. In general, materials with high ultimate tensile strength tend to exhibit high resistance to cavitation damage, as indicated in Table 3 for example. Here again, as in the case of molybdenum, yield capacity and yield lag may often override shortsomings in tensile strength. Furthermore, the results of Kerr (35) and Mousson (36) indicate that hardness is a much more sensitive parameter for comparisons of relative damage resistance (see, e.g., Table 2).

In this connection, it is of interest to refer again to the results of Plesset and Ellis summarized in Table 3. In these experiments, it was noted that plastic deformation appeared almost immediately in the soft specimens , nickel, brass, and pure titanium. These materials have ultimate tensile strengths of the order of 50,000 p.s.i.; it may therefore be concluded that the stresses induced by cavitation were at least of this magnitude. Since, however, damage developed very slowly for materials such as titanium 150-A and tungsten, which have ultimate tensile strengths of the order of 130,000 p.s.i., it might be inferred that the cavitation-induced stresses were below this value. Such results, in addition to showing the influence of tensile strength, indicate that the fatigue properties must be of importance.

e. Elasticity

In view of the nature of the mechanical forces accompanying cavitation, it has been suggested that a material with high energy absorbing capacity, or a very "elastic" material, would be highly resistive to cavitation attack. Certain materials have been tested which indeed support this view. Rheingans (38) has reported very good characteristics for thiokol rubber which apparently exhibits damage resistance comparable to metals with good resistance properties. Kerr and Leith (74) have reported similar results for a liquid neoprene although rubber and neoprene sheet were quickly burned off the test button in a magnetostrictive apparatus.

Such results would be expected with materials such as rubber provided that the rate or intensity of attack is small enough or that the heat generated internally can be conducted away rapidly enough to prevent melting or other high temperature damage to the properties of the rubber. Aside from the phenomenological observations mentioned above, there has apparently been very little research relating the properties of rubber-like materials to damage resistance with due regard for the problems of internally generated heat and required heat transfer for preservation of the properties of the material.

Because of such favorable evidence for highly elastic materials, recent research devoted to them has been in connection with their possible use as coatings to prevent or reduce damage to primary structures.

2. Material Properties

a. Crystal and grain structure

There is little evidence that cavitation damage resistance is related to crystal structure (face-centered cubic, body-centered cubic, etc.) except insofar as the crystal properties of a material are reflected in the macroscopic mechanical properties discussed above. However, there is a close correlation between damage resistance and grain structure, size, and shape, as well as the characteristics of the grain boundaries, including the properties of the intergranular material. The relation of these properties to fatigue characteristics is, of course, evident; whether there are also important effects associated with electrochemical activity of the types postulated is not known. We shall discuss grain characteristics as related to damage resistance on the basis of experimental observations; in the main, the latter indicate that resistance is determined primarily by the mechanical fatigue properties of a material.

b. Grain properties

Several authors have pointed out the increase of resistance to cavitation damage with decreasing grain size when other factors are unaltered (36,37,75). Mousson has particularly demonstrated the influence of grain size on damage resistance. For example, he compares (36) nonferrous alloys (brasses) which have almost the same mechanical properties, hardness and yield point, and very little difference in hardenability. Yet the rate of material loss differed considerably. These results are shown in Table 5.

TABLE 5

COMPARISON OF DAMAGE RESISTANCE OF TWO NONFERROUS ALLOYS
(After Mousson--Reference 36)

Alloy	Chemical Composition (percents) Cu	Zn	Mn	Ni	Fe	Al	Tensile Strength (p.s.i.)	Yield Point (p.s.i.)	Brinell Hardness	Loss in 16 hrs (mm^3)
Hy-ten-sl Bronze No. 4	68	22	4		3	3	85,000	40,000	165	43.3
Turbine Metal	56	36	2	2	1	1	80,000	40,000	166	80.2

The only real difference between these two specimens was in the grain size, the first specimen having a much finer structure than the second. Similar results were found for a number of nonferrous alloys.

Such behaviour would be expected when failure occurs in the form of transcrystalline cracks, as they did in Mousson's experiments. The progress of fatigue cracks tends to be arrested at grain boundaries if the boundaries are not also attacked separately.

c. Grain boundaries

It is clear that, while the grain boundaries may act as arresters of propagating cracks in polycrystalline materials, the properties of the grain boundaries themselves will be of importance in determining the overall susceptibility to damage. Since grain boundaries represent a discontinuity in the structure of a metal, intense strain centers may be located there. (Wheeler (45) points out that such strain centers will also tend to exist at dislocations in the grain body and will act in a manner similar to boundaries.) Consequently, the effect of severe straining due to impact will be especially severe at such boundaries. These effects will be of relatively great importance if the intercrystalline substance is much weaker than the grains or if the thickness of the intercrystalline material is very large so that it does not provide adequate "support" for the adjacent crystals. Thus, damage may not only occur first in these regions but the boundaries will not act as efficient crack arresters. Conversely, very thin grain boundaries will be very much more favorable to damage resistance, and such thin boundaries are usually observed to accompany small grain structure. It has even been suggested that the primary mechanism of cavitation damage is associated with failure first in the grain boundaries because of these effects (76).

d. Inclusions

In discussing inclusions in the undissolved state, we refer here to substances which are either impurities or nonmetallic inclusions added to change the chemical composition in such a way as to achieve specific characteristics in the metal. For example, Mousson (36) reports the adverse effects of adding sulphur to a stainless steel to improve its machinability. In spite of the greater hardness of a specimen containing 0.40 percent S compared with a specimen containing only 0.025 percent S, (Brinell hardness 157 and 142, respectively), the latter showed a loss of 46.7 mm^3 compared with 72.3 mm^3 for the former in a 16 hr test. Photomicrographic analysis disclosed that the sulphur existed in the form of flakes which formed ideal centers of stress concentration and positions for nucleating fatigue cracks. Similar effects were observed in forged stainless chromium steels in which carbide-ridge areas seemed to permit quick development and propagation of fatigue cracks.

As a further example of the adverse effects of inclusions, Ackeret and de Haller (21) showed that the relatively high susceptibility of cast iron to cavitation damage is associated with the presence of free graphite. The weak graphite fails almost immediately with subsequent removal of large pieces of iron.

They have also demonstrated the detrimental effects of slag inclusions which form centers of high stress concentration in much the same way as the free sulphur in Mousson's experiments.

e. Alloy constituents

The effect of alloy constituents seems mainly to be in their influence on the resulting grain size and, through this effect on damage resistance. Results of experiments by Mousson (36) may again be cited to illustrate this point. By successive additions of molybdenum and nickel to Cr stainless steels, he showed that increased resistance to damage was obtained, Table 6. In each case, the primary effect appeared to be associated with the decreasing grain sizes obtained with the addition of these alloying constituents. The high losses with the nickel alloys in spite of their great hardness was the result of a still very course grain structure which was improved as the nickel content was increased.

f. Metallurgical structure--general

All of the effects discussed above combine in varying degrees to determine cavitation damage resistance, and the predominant characteristic depends upon the actual preparation (heat treatment, impurities, alloy constituents, etc.). Furthermore, the properties of materials are so interdependent that even the attempt made here to separate out the individual influences leads to comparisons and correlations that distinguish between these influences in a far from unique manner.

TABLE 6

EFFECT OF ALLOY CONSTITUENTS ON DAMAGE RESISTANCE
(From Mousson--Reference 36)

Alloy	Chemical Composition (percentages)								Tensile Strength (p.s.i.)	Brinell Hardness	Loss in 16 hrs (mm^3)
	C	Mn	P	S	Si	Ni	Cr	Mo			
Stainless 12 percent Cr Steel	.06	.43	.015	.028	.38	.17	12.88		99,000	206	24.6
Stainless 12 percent Cr Ni Steel	.08	.49	.016	.021	.48	1.53	12.44		126,250	281	6.3
Stainless 13 percent Cr Mo Steel	.10	.47	.014	.027	.33	.12	12.88	.58	123,750	275	9.5
Stainless 14 percent Cr Ni Steels	.06	.39	.016	.021	.33	.98	14.72			238	85.5
	.05	.32	.016	.021	.35	1.14	14.48			302	32.0
	.05	.36	.018	.019	.31	2.02	14.30			321	12.9
	.07	.35	.016	.015	.40	3.36	14.30			352	9.8

As a general observation of the role of metallurgical structure, an example of the results of experiments on materials in which all the factors so far discussed are evident in some degree is shown in Figure 16, reproduced from Leith and Thompson (47).

3. Behavioral and Other Properties

a. Fatigue and corrosion fatigue

Based on the mechanical nature of cavitation attack and the observed plastic deformation that takes place initially, it is apparent that the fatigue properties of a material will be important indicators of its resistance to the repeated impacts of a cavitating zone. In a corrosive environment, the pertinent parameter would be expected to be the corrosion fatigue limit. So far, there is only one piece of evidence of the correlation between corrosion fatigue limit and cavitation damage, and that very indirect, although there can be little doubt of its importance. Leith (39) has compared the length of the incubation time, converted to number of cycles of stress application (apparently taking the number of cycles of oscillation of the specimen in a magnetostriction apparatus over the duration of the incubation period), with the corrosion fatigue limits given in the Corrosion Handbook (77). His results are reproduced in Figure 17. Leith has plotted the number of cycles in the incubation period versus the corrosion fatigue limit after 10^7 cycles for the four metals that he tested. All that can be said about this plot is that there appears to be a linear relation between the number of cycles in the incubation period and the corrosion fatigue stress level.

Otherwise, it is not clear that these results can be taken as evidence of the relation between incubation period and corrosion fatigue properties.

It is of interest that an "incubation period" occurred only for the rolled metals in Leith's experiments. He observed immediate loss of material for cast irons. He observed further that the amplitude of oscillation of the specimen in the magnetostriction oscillator had no effect on the incubation period, but was of importance in the later stages when material was actually removed. Thus, the significance of the comparison of Figure 17 is further in doubt since the stress level might be expected to be a function of the vibration amplitude. It is clear that a great deal remains to be done to define in detail the relations between corrosion fatigue and cavitation damage.

b. Temperature dependence; melting point

In support of his conjecture that high temperatures, which may occur during the collapse of cavities, are a factor in the failure of materials under cavitation attack, Nowotny (37) has compared the loss of material in accelerated damage tests with the temperature dependence of their strength properties and with their melting points. His results are reproduced in Table 7 for 10-minute exposures to cavitation of pure annealed metals in a magnetostriction apparatus. Nowotny recognizes, however, that the tensile strength and hardness follow trends similar to the temperature dependence and that other factors such as grain size may play an important role in determining resistance to damage.

TABLE 7

RELATION OF DAMAGE RESISTANCE TO TEMPERATURE AND MELTING POINT PROPERTIES

(After Nowotny--Reference 37)

Material	Volume Loss (mm^3)	Melting Point (°C)	Tensile Strength (kg/mm^2) At 20°C	Tensile Strength (kg/mm^2) At 500°C
Lead (fine-grained)	10	327	1.35	-
Cadmium (fine-grained)	0.7	321	6.40	-
Magnesium (coarse-grained)	1.4	650	17.00	0.50
Aluminum (Medium fine-grained)	0.5	658	14.30	0.60
Brass, 65 percent Cu (coarse-grained)	0.003	850	50.00	6.00
Carbon steel (fine-grained)	0.01 and smaller	1150 to 1500	54.00	27.00

c. Surface roughness

While several authors have remarked on the adverse effects associated with surface roughness, no definitive or quantitative data have been forthcoming. Generally, there is not observed an incubation period for "rough" surfaces and the initial rate of attack is higher than for "polished" surfaces. Unfortunately, no measure of such roughness has been given when such effects were observed. That this result might be expected is not surprising, of course, since the presence of initial cracks, pits, and other deformations make available active sites for both mechanical and electrochemical attack.

IV. METHODS OF PROTECTION AGAINST CAVITATION DAMAGE

NATURE AND TYPES OF PROTECTION

Protection against cavitation damage may be considered from several points of view: (i) elimination of the problem at the source; (ii) use of highly resistant materials in zones of expected cavitation attack; (iii) use of artificial means in which protective devices are employed as adjuncts to the system; and, (iv) combinations of the latter two methods. Elimination of the problem at the source and the use of specially resistant materials either in the primary structure or as coatings for the primary structure may be considered as methods of reducing the effects of cavitation by primary design. The use of methods which are essentially added or imposed on the system as adjuncts following the basic design but are not part of the structure itself may be considered as imposed protection. Thus, we shall consider the various methods of protection in these terms.

PRIMARY DESIGN

1. Hydrodynamic Design

It is beyond the scope of this treatise to discuss in detail the question of elimination of cavitation in a hydraulic system by means of hydrodynamic design considerations. Comments on this problem will be found in Reference 4. We can give here only some general observations on some of the factors to be considered in hydrodynamic design and especially on those that might otherwise escape attention. It is clear, of course, that it is essential to avoid low pressure regions where the pressures may fall to levels required for cavitation inception. In general, this means regions of high velocity and low ambient pressure. However, the efficient operation of many machines depends just on this ability to induce high velocities at low pressures; requirements for weight saving and small size in hydraulic machinery also imply operation at high velocities and low pressures. In addition to these factors, which are usually considered in some detail in the design of hydraulic machines, a number of other flow conditions may exist that are conducive to low pressures and the onset of cavitation. Of particular importance are separated flows in which the local turbulent pressure fluctuations and the low pressures induced in the vortical flow associated with such regions may lead to cavitation at ambient pressures higher than would be expected for cavitation onset. Examples of such situations are stalled rotors in hydraulic machinery and the flow about roughness elements on a surface that otherwise has pressures nowhere low enough to cause cavitation to occur. Further discussion of the problem and nature of cavitation in separated flows and about roughnesses will be found in References 3, 4, 78, 79 and 80.

Very often, for reasons of efficiency or weight reduction, or because a machine must operate under cavitating conditions for only limited periods during its life, it may actaully be advantageous to allow operation with cavitation and try to reduce the adverse effects by structural design or imposed protective systems.

2. Materials for Primary Structures

From the examination of correlations between material properties and resistance to damage, there are evident certain characteristics desireable for primary structures which must withstand the effects of cavitation. Without regard to other requirements that a material must possess, such as machinability for example, the most highly resistant materials are those with a tough, homogeneous, fine-grained structure, a high tensile strength, high hardness, good work hardening properties, and high fatigue and corrosion fatigue limits. The stainless steels generally possess these properties in a good measure as do aluminum bronzes. An outstanding material is stellite, but its poor machining qualities (because of great hardness) and high cost make it unattractive for many applications. Materials such as molybdenum, tungsten, and titanium alloys possess very attractive properties but have not yet come into engineering use in this connection. The relative merits of other metals and alloys will be found in the References cited previously, particularly Rheingans (71,38), Mousson (36), and Kerr (35).

Where materials are used for primary structures that are not particularly suitable for damage resistance, it has become a growing practice to use overlays of highly resistant metals or other coatings.

3. Special Coatings

In an attempt to ameliorate the destructive effects of cavitation, either in a new machine or when repairing damaged surfaces, several metallic and nonmetallic materials have been investigated for use as coatings. These take the form of welded overlays, sprayed metallic or nonmetallic coatings, and bonded nonmetallic coatings.

Welded overlays of stainless steel or aluminum bronze are excellent for protection as might be expected from their general behavior under cavitation attack. There are a number of other welding alloys that are suitable and have good damage resistance qualities (see e.g., Rheingans (71)); selection of such materials will, however, be governed by their grinding and machining properties as well as their cavitation damage resistance.

Sprayed metal coatings are attractive because of the ease of application and low cost. However, difficulties may be encountered unless the sprayed metal is also fused to the base metal. Rheingans (7) has given data on the characteristics of various sprayed metal coatings both fused and unfused; his data from accelerated damage tests are reproduced in Table 8.

TABLE 8

CAVITATION DAMAGE RESISTANCE OF SPRAYED COATINGS
(After Rheingans--Reference 71)

Alloy	Weight Loss in 2 hrs.- mg
UNFUSED	
High Chromium Stainless Steel (Metcoloy 2)	72
18 Cr-8 Ni stainless steel (Metcoloy 1)	98
13 percent Cr stainless steel	192
Molybdenum	358
FUSED	
65 to 75 Ni-15 to 20 Cr-2.7 to 4.7 percent B(Colmonoy 6)	8
75 to 85 Ni-8 to 14 Cr-2 to 3 Percent B (Colmonoy 4)	30

He points out that the resistance of unfused coatings is not very good, mostly because of the difficulty of obtaining a good bond between the coating and the base metal. The fused metallic coating shown in Table 8 were prepared by spraying on a specially prepared base and then heating to 1850°F. Rheingans remarks that although these coatings exhibit good resistance qualities they are limited in usefulness by high cost and by the distortion produced in the base metal during fusion.

Among the nonmetallic materials that have been tested as coatings are natural and synthetic rubbers and a number of plastics. Examples of materials tested for this purpose are Thiokol rubber, Neoprene, nylon, phenolic resin, and Teflon. Neoprene appears to have exceptionally good qualities (74,81). Plastics generally exhibit poor resistance characteristics compared with Neoprene (81). An example of the relative merits of some of these materials is shown in Table 9. Other data will be found in References 71, 81, 82 and 83. Major difficulties with such coatings arise because of poor bonding between coating and base material; the entire coating may be torn away from the base material by the violent action of cavitation before the coating itself is damaged.

TABLE 9

CAVITATION DAMAGE RESISTANCE OF NONMETALLIC COATINGS
(After Rheingans--Reference 71)

Coating	Volume Loss in 2 hrs, mm^3	Weight Loss in 2 hrs, mg
Nylon	7	8
Phenolic resin on fabric base	20	26
Rubber, flame sprayed on mild steel	29	33

It is clear that development of adequate methods of bonding to base metals must be achieved before these materials can be used, or even evaluated successfully, as protective coatings.

IMPOSED PROTECTION

1. Air Injection

Perhaps the earliest method of artificially protecting hydraulic machinery against cavitation damage was the use of small amounts of air injected into the cavitating region. It is not known how this suggestion came out; however, it is not unlikely that the idea originated from observations that cavitation damage was reduced in large turbines during seasons when the air content of the reservoir water was high. Ackeret (14) was perhaps the first to point out on theoretical grounds that a permanent gas in cavitation bubbles would greatly reduce the collapse pressures (although he also decided that the temperature of such gas must increase greatly). In any event, air injection has been used with success in reducing or even eliminating cavitation damage (84,85), and the mechanism of its protective action is clearly the "cushioning" effect produced during compression by the collapsing cavitation bubbles. As pointed out in a previous part of this chapter, the fact that such air injection does reduce or eliminate cavitation damage also substantiates the observations that cavitation attack is primarily a mechanical effect.

Experimental observations of the effectiveness of air injection have been recorded by Mousson (36) and Rasmussen (32,86). Some results of Mousson on a copper bus bar in a venturi apparatus are shown in Figure 18a; the effect of air injection on the damage sustained by an aluminum alloy in experiments by Rasmussen using a rotating disk apparatus is shown in Figure 18b. The air content in Mousson's experiments is given in percent of discharge (volumetric flow rate) while that of Rasmussen's experiments is given in parts per thousand. In each case the ameliorating effects of relatively small quantities of air is strikingly demonstrated.

It is of interest to note that the introduction of air does not seem to produce adverse effects on most metals as far as corrosion is concerned--the reduction of primary mechanical damage being so much greater and more rapid than any adverse chemical effects. Only in one case has there been observed such adverse chemical effects. In Rasmussen's experiments on cast iron, the increase in chemical corrosion was just about balanced by the protective action of the air bubbles. The reduced pressures of the bubbles were still sufficiently large or the water motion itself enough to remove the oxide layers formed very rapidly on the iron.

2. Cathodic Protection

There has been so much controversy and conjecture concerning the mechanism of cathodic protection as applied to prevent cavitation damage that it is worth devoting some detail to a discussion of this subject. Perhaps the best series of experiments designed specifically to disclose the mechanism of cathodic protection in this connection are those performed by Plesset and his colleagues (68,69). In their experiments, the specimen was made one electrode of an electrolytic cell with the second electrode a platimum wire insulated from the liquid except at its tip; the liquid was a 3 percent solution of NaCl in distilled water (see Figure 25). Tests were made at constant current under both cavitating and non-cavitating conditions in a specially-designed magnetostriction apparatus. Under cavitating conditions, the circuit had an inherent back e.m.f. due to electrolytic action which was subtracted from the external voltage measurements. With the onset of cavitation, the voltage between electrodes was observed to decrease appreciably, presumably because of the disturbance and partial removal of poorly conducting layers of hydrogen gas at the cathode. Experiments were also made to confirm the latter point and to determine that a large fraction of the current flows to the face of the specimen while cavitation is occurring.

Results of the experiments on 4340 steel are shown in Figure 19a. The effect of the impressed cathodic currents is clearly demonstrated. Tests were also made on copper of high purity in order to compare the above results with those for relatively inactive metal. Figure 19b is the summary of the average results for the latter experiments as reported by Plesset (69). Thus, similar trends were found for both the steel and copper specimens. It is emphasized that in all of the experiments in the salt solution hydrogen evolution was observed on the specimen surface even at the lowest cathodic current of 1 milliamp. Considering the range of materials tested, these results indicate that the protective effect against cavitation damage is associated with the cushioning provided by the evolved hydrogen (in much the same way as the protective effects of injected air described in the foregoing). A further substantiation of this conclusion is the general result that the loss in weight decreases monotonically with increasing rate of hydrogen evolution (or increasing cathodic current). That full protection was not obtained over the range of currents used is attributed to the removal of the hydrogen gas layer through agitation produced by the cavitated zone.

In further substantiation of the conclusion that such protection is associated with the cushioning effects of evolved gas, a series of experiments was performed by Plesset (69) in which the specimen was the anode of an electrolytic cell but in such a way that, at the same time, gas evolved at the specimen surface. This was done by using stainless steel in distilled water buffered to pH 8. One electrode of the cell was again platinum, and the other 17-7 PH stainless steel. Two sets of experiments were performed. In the first, the specimen was the cathode of the cell, and damage was determined for cathodic currents of 20, 50, and 100 milliamps; for all of these values, hydrogen gas was observed to be evolved at the specimen. The results are summarized in Figure 20a. In the second series, the specimen was made the anode of the cell and damage was measured for anodic currents of 40, 100 and 200 milliamps. The gas evolved in the latter case is oxygen with a valence twice that of hydrogen, so that double the current is required to evolve comparable amounts of gas for purposes of direct comparison. A summary of the latter results is shown in Figure 20b. A comparison of the results of the two types of experiments shows that the protective effect in each case is of the same order of magnitude; this result would be expected if the protection provided is indeed attributable to the cushioning effects of evolved gas.

To take account of the anodic weight loss which is entirely independent of the cavitation damage, Plesset also compared the relative protection provided by the two methods with the second series corrected for the weight loss produced by electrolytic solution of the anode material. Figure 21 illustrates such a comparison for comparable amounts of evolved gas. It is clear that there is a large protective effect in either case.

A final series of tests made by Plesset is of interest in this connection. An attempt was made to observe the damage at current levels so low that no gas was evolved. This was not possible with the cathodic specimen in salt, since gas was evolved at the lowest currents practicable. However, in the case of both the cathodic and anodic specimens in buffered water, no observable gas evolution occurred at a current of 2 milliamps. Under these conditions, no protective effect against cavitation damage could be obtained.

Other investigators have reached essentially the same conclusions. Leith and Thompson (47) have applied cathodic protection to cast steel in sea water and found that the current density necessary to fully protect this metal is about 3 amps per square inch, clearly a level at which large quantities of hydrogen must be generated. Their results are shown in Figure 22. For such metals, there is probably also some protection provided by the cathodic currents in reducing normal electrolytic solution.

While the application of cathodic protection against cavitation damage in actual installations is still in the experimental stages, it has already been suggested that it may be necessary to observe caution with steels that are subject to hydrogen embrittlement. This problem has been the subject of discussion in connection with normal cathodic protection when hydrogen gas is evolved and will certainly be raised again in the present context. So far, there is no evidence of adverse effects due to hydrogen embrittlement in the experiments reported on protection against cavitation damage. However, the possibility of such effects probably should not be overlooked. Discussions of the problem of hydrogen embrittlement in steel from the viewpoint of the basic mechanisms and application of cathodic protection for prevention of normal electrolytic corrosion will be found in References 87 and 88.

With regard to the application of cathodic protection, a basic question in the design of a practical system will be that of the current and voltage levels required to achieve specified degrees of protection. It is clear that much greater amounts of evolved gas will be required where cavitation is very "intense" than where it is relatively "light". Furthermore, it will not be possible to shield exposed surfaces completely from at least occasional exposure because of either the nonuniformity of the hydrogen layer or the displacement of the evolved gas through the agitating action of the cavitation zone. These remarks apply equally, of course, to all cushioning systems--air injection, for example. Thus, it would be of great interest in this connection to have some measure of the expected intensity of cavitation in a machine for which such protection is to be provided. A definitive characterization of cavitation intensity is not likely to be available for many years to come because of the great complexity of the cavitation process. However, some attempts have been made to obtain such a measure in connection with the prediction of the amount or rate of damage to be expected; these suggestions, which are discussed later, may have interest in the present connection as well.

3. Corrosion Inhibitors

The employment of corrosion inhibitors has been suggested as a means of reducing cavitation damage, and such compounds are in general use in diesel engines, for example, to aid in protecting the water side of cylinder liners. It is, of course, apparent that chemical attack can be controlled by such additives, but it is not clear just what their role might be as specifically related to cavitation attack. In fact, there seems to be conflicting evidence of the usefulness of additives in preventing or reducing cavitation damage per se. Presumably, the prevention of chemical corrosion will tend to preserve the original properties of materials so that combined effects of cavitation erosion -- chemical corrosion are delayed. Otherwise it is difficult to see that corrosion inhibitors should have any other direct effects. On this basis, it might be expected that corrosion inhibitors would show little or no effect in accelerated damage tests since the mechanical damage proceeds so much more rapidly than the usual types of chemical activity; on the other hand, in machines, over very long periods of time, it might be expected that the beneficial effects of corrosion inhibitors in reducing chemical attack would be reflected to a larger extent. These conclusions are borne out, at least partly, by the few data available. Rheingans (38) has reported experiments with several different concentrations of a solution of water treated with chromate (Na_3CrO_4), one of the more widely used additives. He found no effect of the chromate in accelerated damage tests on low-alloy gray cast irons and austenitic cast irons, except in one case of heat treated gray cast iron. However, in the latter case, the difference in hardness between the test specimens was the likeliest explanation of the effects found. Speller and LaQue (89) point out, too, that corrosion inhibitors seem to be more effective in practice than in the laboratory experiments. Whether this observation is due to the effect, postulated above, of the duration and intensity of attack is not known.

Peculiarly enough, there appear to be optimum concentrations of inhibicor for maximum protection against cavitation damage, and this has never been explained. This may be illustrated by the results of experiments by Margulis, McGowan, and Leith (90), shown in Table 10; these are for accelerated damage tests of alloy cast iron (of a type used in diesel cylinder liners) in water treated with various additives. The temperature and ambient pressure conditions were maintained at the levels encountered in practice: $170^{\circ}F$ and 20 psig.

TABLE 10

EFFECT OF CORROSION INHIBITORS ON CAVITATION DAMAGE
(After Margulis, McGowan, and Leith--Reference 90)

Inhibitor Concentration (ppm)	Loss in grams in two hours			
	Chromate	Boron-Nitrate	Soluble Oil	Gelatine
500	0.026	0.026	0.026	0.026
1000	0.015			0.025
2000	0.009	0.023		0.025
2500	0.0008			0.024
3000		0.019	0.013	
5000 (0.5%)	0.015			0.024
10000 (1%)	0.020	0.020	0.009	0.024
20000 (2%)		0.016	0.011	

Unfortunately, in none of the investigations found has any attempt been made, apparently, to correlate the damage with the physical properties of the solutions used. Whether sufficient differences do exist in the characteristics of the solutions to account for the behavior just mentioned can only be determined by experiments in which the actual properties of the solutions (surface tension, density, etc.) are measured.

V. EXPERIMENTAL FACILITIES AND METHODS IN CAVITATION DAMAGE RESEARCH

EXPERIMENTAL FACILITIES

The experimental facilities that have been used for investigations of cavitation damage may be grouped into two categories: those that depend on inducing low pressures as a result of high velocities in flowing liquids, or motion through a stationary liquid, and those that produce cavitation by means of local, periodic, accelerations in an otherwise stationary liquid. The first group includes devices such as venturi tubes and rotating discs while the second depend on alternating pressure fields such as are produced by acoustic or other acceleration producing devices. In addition to such equipments, other types of "impact" producing devices used in the past include liquid jets impinging on specimens and single shock waves in a bar in contact with the liquid.

Such devices may also be grouped according to the relative rates of damage production. In general, flow devices approximate field conditions while, for laboratory use, methods have been developed to produce damage at an accelerated rate. We shall discuss the principal devices that have been or are now being used; many modifications have been suggested but the basic ideas are represented in the present survey.

The relative merits of these equipments will be evident from their description. The question of the relations between the results in different devices and extrapolation of results from one to another and to field conditions will be considered in connection with our discussion of methods of analysis.

1. Flow Devices

a. Venturi tubes

Venturi sections were among the first flow devices used in the study of cavitation damage. These are simply convergent-divergent nozzles of the type shown in Figure 1. Such venturi sections are made part of a closed system in which the liquid is pumped around the circuit. The pressure in the test section is then controlled by the velocity through the test section and the ambient pressure imposed on the entire closed system (see Equation [1]). The pressure along the test section will drop as the liquid is accelerated through the position of minimum area and increase as it proceeds into the diffusing section where the area is increasing. Cavitation then occurs when the pressure drops to the order of vapor pressure, and the extent of the cavitating zone will be increased in length as the speed increases, or the ambient pressure is lowered, and vapor pressure is reached by points further and further along the section. The cavitation zone collapses in the diffuser where the pressure increases; it is just at this position and in the wall of the venturi that test specimens are placed so as to be exposed to the collapsing cavities. Very often, the cavitation zone will surround a central core of liquid that cannot be fully vaporized during its passage through the length of the low pressure region. In this case, there will be agitation due to turbulent mixing of the "jet" with the condensed liquid in addition to the violent action of the collapsing cavity. Further discussions of the cavitating flow in such nozzles and their use in damage experiments will be found in References 4, 6, 36, and 82.

Since many machines operate under conditions of high velocity flow similar to that described here, the venturi section is considered to be quite representative of field conditions. However, as in the field, measurable damage proceeds at rates that require long periods of exposure (sometimes of the order of hours as in the tests reported by Mousson, Tables 2, 4, 5, and 6). Consequently, emphasis on laboratory equipment has been directed toward methods of producing accelerated damage.

b. Cavitation tunnels

Cavitation damage tests have also been performed in large cavitation tunnels which operate on principles essentially similar to the venturi section described above. However, these may take a number of different forms including closed sections in which the section flows full (as in the case above), open sections in which a high speed jet discharges into a water filled section maintained at low ambient pressure, and free jets in which a high speed jet discharges into an evacuated space It is beyond the scope of our discussion to describe the details of such tunnels and the methods whereby they are operated and controlled. It is only necessary to point out here that for cavitation damage tests, the test specimen is placed on a carrier vehicle, such as a body of revolution or a hydrofoil, on which cavitation is produced by the combination of high tunnel speeds, low ambient pressures, and high velocities induced on the test body as a result of its particular shape. Descriptions of some typical cavitation tunnels will be found in References 91 and 92, and a description of cavitation damage experiments carried out in recent years in such a tunnel in Reference 93.

Such tunnels are seldom used for damage tests because of the expense of operation, the relatively complicated procedures required in installing experiments, and the length of time they must be in operation to obtain measurable weight loss.

c. Rotating disks

A device that has been used in recent years for studies of cavitation damage is a rotating disk on which cavitation is induced in a separated flow region. We have already discussed how cavitation occurs in such regions in connection with some principles of hydrodynamic design to avoid cavitation. Basically, such devices consist of a disk with holes at the periphery, rotated at high speeds in a chamber in which the ambient pressure can be controlled. Because of the unstable flow within the hole, a separated region is formed and a cavitating wake is shed downstream of the opening. The test specimen is placed in this wake so that the cavitating zone collapses at the position of the specimen. Such devices have been used and described by Rasmussen (86) and by Lichtman et al (82). A sketch of the disk used by Rasmussen is shown in Figure 23. The test chamber is normally designed with fixed stilling vanes on either side of the disk to damp the induced circulation of the liquid. Rotation speeds as high as 3200 rpm have been used (82) with a disk 12-inches in diameter.

From the standpoint of labroatory testing, the rotating disk apparatus also suffers from the difficulty that damage rates are relatively low. As with the venturi types of apparatus, it also requires rather elaborate auxiliary equipment, requires long periods of continuous operation, and considerable time for installation of experiments.

d. Hydraulic jets

Although the impact of water drops is not a cavitation damage testing device, the use of such impact tests was important in early examinations of the mechanism of cavitation damage and is therefore mentioned here. In order to examine the question of whether the mechanism of cavitation damage was indeed associated with mechanical erosion, de Haller (22) ran experiments in which small rods fastened to the periphery of a wheel rotating at a high rate of speed, were passed through a high speed water jet. While he could not account for the pressures thought necessary for such damage in either type of experiment, and was puzzled by the fact that damage was observed in all cases as long as enough impacts were sustained, he did conclude that the damage in a cavitation test is of the same nature as that observed in the drop impact tests. Thus, as was discussed earlier, he came to the view that cavitation damage is primarily mechanical in nature.

2. Accelerated Damage Devices

a. Magnetostriction oscillators

The expensive and time consuming experiments that, of necessity, result with the types of equipment discussed so far has led to the development of laboratory devices for accelerated damage experiments. Of these, the most important has been the magnetostriction oscillator, which is still the most widely used device and therefore merits rather detailed description. Such transducers possess the attributes of compactness, precise control, comparatively low initial cost, and economy of operation.

(i) Characteristics and principles of operation

Magnetostrictive effects are exhibited by the ferromagnetic materials, which respond to a magnetic field by a change in physical dimensions, or, conversely, show a change in magnetic properties when their dimensions are changed by an external force. The type of oscillator used for cavitation damage investigations makes use of the Joule effect, the change in length along the axis of an applied magnetic field when the field is varied. The first magnetostriction oscillator constructed specifically for cavitation tests was developed by Gaines (94) who utilized a nickel rod in a concentric alternating field. In addition to pure nickel, materials suitable for this purpose include nickel alloys, invar, and monel metal with a trace of silica or iron. The test specimen is fastened to the end of the rod, and the high frequency oscillations of the specimen in the test liquid are adjusted to induce accelerations high enough to produce cavitation on the face of the specimen. Since all ferromagnetic materials are temperature-sensitive, the temperature must be held below the Curie point (where all magnetic properties cease to be exhibited) by external cooling of the rod or tube which holds the specimen.

The basic magnetostriction apparatus now in use consists of a high-frequency oscillator operated at the resonant frequency of a nickel tube in an alternating magnetic field. A schematic diagram of a typical oscillator is shown in Figure 24. Considerable effort has been devoted to the development of standardized procedures for tests with such equipment in order to insure uniformity of comparisons between different laboratories. Typical recommended configurations and operating conditions include (95):

(i) a transducer capable of a peak-to-peak amplitude of sustained vibration of 0.004 inch in a test liquid at a frequency of 6500 cps ±100 cps; (ii) a power supply of about 500 watt output; (iii) a tube of commercially pure Grade-A nickel, 12 inches in length, 5/8-inch in diameter, and 1/32-inch wall thickness, cold drawn and stress equalized with Rockwell 15T hardness of 90-95. Other recommended details of the tube itself and of the driving equipment will be found in Reference 95, and descriptions of similar, representative, equipment used by various investigators since the first Gaines oscillator are available in References 35, 37, 40, 74, and 81.

(ii) Modifications and improvements

The basic magnetostriction oscillator has been modified for special investigations, and improvements have been suggested to increase its efficiency of power utilization. To investigate the effects of ambient pressure in such experiments, Leith (39) has constructed equipment to enable pressurization of the liquid container; the basic setup is as shown in Figure 24; the container was, however, made of stainless steel for safe pressurization. Other refinements possible with such equipment include the use of inert atmospheres, nitrogen (39), helium (43), etc., above the test liquid.

An improvement in the efficiency of equipment based on the principle of the magnetostriction oscillator has been devised by M. S. Plesset and A. T. Ellis of the California Institute of Technology, reported in References 68 and 69. This design makes use of the characteristics of exponential horns in amplifying imposed vibrations. A sketch of the horn and test arrangement is shown in Figure 25. Alternating current is applied to the nickel transducer stack and the resulting vibrations are amplified by the solid steel horn. The motions of the horn are such that the resulting vibrations in the cylindrical specimen holder at its end are almost entirely in the axial direction. Further details on such horns will be found in Reference 96.

Figure 25 also illustrates the use of the magnetostriction oscillator equipment for tests of cathodic protection of cavitating specimens. This is the arrangement used by Plesset et al in the experiments mentioned previously.

As we have mentioned, considerable effort has been expended on standardization of methods of testing and of test specimens, and recommendations have been forthcoming from a number of sources on the size, shape, and finish of test specimens. These have generally specified flat surfaces, although tests have also been carried out with specimens having concave surfaces. The damage observed on such specimens has usually had a very nonuniform appearance, the patterns often showing a roughly starlike radial pattern. Reasoning that this phenomenon is associated with a type of hydrodynamic instability inherent in a system of fluids of different densities accelerated one toward the other (Taylor instability (97)), Plesset (68) proposed to decrease the accelerations of the growing and collapsing bubble cloud by providing a small raised ledge or rim around the periphery of the specimen (the so-called "dished" specimens of Figures 19-21). He confirmed that the damage patterns with these dished specimens are very uniform over the entire surface and that the experimental results were much more repeatable and consistent within themselves than with flat-faced specimens. Whether this result will be observed in all magnetostriction equipment is not clear. As explained above, the Ellis horn differs from the usual apparatus in that the motion of the face of the specimen must be more nearly rectilinear than in the normal nickel tube arrangement. In the latter case, radial as well as other modes of vibration will certainly be induced so that various patterns of damage would be expected. It is not known, of course, which of these factors, Taylor instability or vibration mode, are controlling under these circumstances; it would be of interest to investigate this point by testing "dished" specimens in a standard tube-type of oscillator.

b. Acoustic field generators

A convenient way of producing cavitation in a liquid is by imposing a focused acoustic field; cavitation occurs in the regions of maximum pressure amplitude. A distinct advantage of such systems for accelerated cavitation damage testing is that damage can be obtained on specimens without introducing extraneous stresses associated with magnetostrictively-induced vibrations.

A very economical cavitation generator using barium titanate transducers to produce an acoustic field in a resonant container has been developed by Ellis (42). Ellis' transducer is illustrated in Figure 26. The barium titanate ring is forced to expand and contract by a sinusoidal voltage of as much as 200 volts applied to a conductive coating on its inner and outer surfaces. The operating frequencies used in this experiment were 18 kcs and 24 kcs depending upon the characteristics of the beaker used. The rubber ring is used to permit better coupling to the normal modes of the system. An approximate theory is given by Ellis from which the characteristic frequencies for cylindrical containers can be easily computed.

Another type of acoustic field generator, operating at frequencies from 400 to 1000 kilocycles, has been used in experiments by Lichtman et al (82). This equipment produces a high-frequency vibration of a piezoelectric ceramic transducer bowl comprising part of a liquid container. Cavitation is generated at the focal point in the coupling fluid. In spite of the higher powers used in this apparatus, the rate of damage is evidently much lower than that in the barium titanate system designed by Ellis.

METHODS OF MEASUREMENT, ANALYSIS, AND CORRELATION

It is beyond the scope of this treatment to discuss all of the methods that are used for various types of analysis and measurement in cavitation damage experiments, nor is it necessary to discuss them all. It is the purpose here to examine some of the special methods that are of interest especially in two respects: firstly, the question of stresses and damage actually induced by cavitation during both the incubation period and the post-incubation period when material losses occur; and, secondly, the question of the meaning of certain measurements in relation to the problems of comparison of one situation with another, and of extrapolation and prediction of damage or damage rates for field installations from laboratory results. The latter problem is of interest also in determining whether imposed protective systems should be used and, if so, in deciding upon specifications for such systems, e.g., air injection, cathodic protection, etc. Consequently, it will be recognized that the selection of some of the methods to be discussed in connection with the first question was made on the basis of their relevency to the second.

1. Some Special Methods in Cavitation Damage Experiments

a. Weighing and counting

The most widely used criterion of cavitation damage is, of course, the rate at which material is removed from the test specimen. Clearly, such methods do not take account of the initial damage that occurs with materials that exhibit an incubation period. Nor is there presently any way in which to characterize the length of the incubation period for purposes of extrapolation; the only suggestion made so far is that of Leith (39), discussed previously, and the uniqueness and validity of his correlation, Figure 17, are still not clear. In view of our very incomplete knowledge of the relation between cavitation damage and fatigue and corrosion fatigue, not to mention the other correlating properties, it seems unlikely that a simple, unique, criterion of damage rates in the incubation period will be forthcoming in the near future.

While weight loss can give some measure of the rate of corrosion only following the incubation period, very soft materials, such as lead and pure aluminum, are pitted very quickly under cavitation attack long before actual weight loss is observed. Consequently, some attempts have been made to characterize damage and obtain an "index" of erosion rate by counting the pits or depressions formed during this period. The latest observations of this type are those of Knapp (93), who tested soft aluminum and compared the rate of formation of pits with the velocity of the fluid in his experiments. It is clear that this technique is applicable only to the very soft metals. Furthermore, to relate the rate of damage on such materials to the damage rates on hard materials would obviously be a most formidable task.

All of the attempts to characterize cavitation damage for purposes of extrapolation and prediction must be related somehow to the "intensity" of the cavitation produced in the laboratory and occurring in the field. These investigations have generally sought to find a relation between weight loss (47,82) or pitting rates (93) an the flow velocity or the amplitude of vibration of magnetostriction oscillators and to discover a "threshold" for the onset of measurable loss. The details of such investigations and the significance of the observations will be discussed in connection with correlation of laboratory and field experiments.

b. Radioactive tracers

Another method of measuring the intensity of cavitation erosion makes use of radioisotopes applied to a sample or to a part of a machine in the region of cavitation. Details have been given by Rosenberg (98), who is evidently the first to develop a specific method, and by Kerr and Rosenberg (99). Rosenberg's method consists of using a radioactive paint prepared with 5 grams of radioactive arsenic (As 76), having a total activity of 750 mC, in a vehicle of Manila copal cement used as the base for a coating material. Other details of the composition of the final coating material, as well as of the techniques and precautions to be observed in actual application, are given in Reference 99. This development was motivated particularly by a need for a simple method to be used in field installations.

To determine the effects of cavitation, the activity of the coating is measured as a function of time. The decrease in activity, corrected for the natural decay in radioactivity, is then taken as a measure of the cavitation intensity. An example of the data obtained by Rosenberg on turbine blades is shown in Figure 25, in which the measured radioactivity in micro-curies per hour, used as the cavitation erosion index, is plotted as a function of the axial velocity at the runner.

c. Electrical resistance change

By measuring the change in electrical resistance of a material with change in physical dimensions as it is corroded or eroded, it is possible to obtain a measure of the rate of damage. Such methods have been in use for some time as detectors of chemical and electrochemical corrosion (100), and recently have been suggested for use in measuring the weight loss in cavitation damage. The method consists simply in measuring the change in electrical resistance of one arm of a bridge, which is the exposed specimen, as the specimen loses material. In the instruments now in use as corrosion detectors, an insulated arm is used as the reference and for temperature compensation. The successful application to weight loss detection in cavitation damage should provide a more convenient and accurate method than weight loss measurements.

It would also be interesting to examine the use of such methods in determining the events during the incubation period. If the electrical properties of metals vary sufficiently with the amount of hardening and stress application, such changes may be detectable during an actual cavitation experiment and would give a measure of the rate of damage during the incubation period.

d. Photoelastic methods

The great difficulties associated with measurement of the pressures produced in a cavitating zone, evident from our previous discussions, led Ellis (101) to study the possibilities of using photoelastic techniques to study this question. The advantage of a successful photoelastic method lies in the fact that the actual stress produced would be measured rather than an integrated pressure as obtained with standard piezoelectric transducers. Additionally, with simultaneous use of high-speed photography, it might be possible to identify the relations between bubble motions and position relative to a specimen and the resulting strain waves. Both the latter measurements and the measurements and observations of the strain waves require ultra-high-speed photography and such photographic methods have also been developed by Ellis, particularly in this connection. The principal feature which allows the very short exposure times in Ellis' system is a Kerr cell electro-optical shutter with which he has obtained exposure times of the order of 10^{-7} second. Using a rotating mirror driven by an air turbine, he has obtained sequences of as many as 700 pictures at a rate of a million frames per second. Details of this development and of the principals of operation of the Kerr cell shutter as well as the lighting problems will be found in Reference 101. Of particular interest here is the development of the photoelastic technique which was carried out in detail by Sutton (25).

The essential problem in developing a satisfactory photoelastic technique arose from the little known dynamic characteristics of ordinary photoelastic materials. Consequently, the dynamic properties (Poisson's ratio, internal damping, stress wave speed) of a common photoelastic plastic CR-39, mentioned previously, were studied in some detail. CR-39 is a thermosetting polymer of allyl-diglycol carbonate; the method of manufacture is described in Reference 25. Sutton found that this plastic exhibits strain birefringence (rather than stress birefringence) and that its strain-optic constant is independent of the rate of loading. Consequently, together with the high speed photographic techniques previously developed, it was possible to study the strain waves produced by cavitation. It was with this type of material that Sutton deduced that cavitation may produce stresses as high as 200,000 p.s.i. It was estimated that the duration of the pressures in his experiments was about 2 microseconds and the area affected by the cavitation pressure had a diameter of about 0.001 inch. Further development of such techniques will be useful in obtaining quantitatively accurate information of the behavior of materials under cavitation attack; such methods will complement the important methods of x-ray metallography.

2. Correlation of Laboratory and Field Damage Rates

a. Damage rate in flow experiments

Experiments in flow facilities such as water tunnels and rotating disk equipment have shown that certain minimum velocities are required before measureable damage is observed. This has led to the suggestion that there is a "threshold velocity" for cavitation damage below which no damage can occur. Furthermore, correlations of damage rate as a function of velocity have been obtained and attempts made on the basis of the results to infer universality of such dependence. Knapp (93) found in his experiments on bodies of revolution in a cavitation tunnel that the pitting rate varied roughly as the sixth power of the flow velocity; the test specimen, soft aluminum, formed a portion of the surface of the body. Below a speed of about 45 feet per second no pitting was observed, and it was concluded that this speed might be taken as the "threshold" velocity for damage in cavitation zones formed in flow fields, at least for soft aluminum in fresh water. Lichtman et al (82) also found a lower "threshold" speed for various materials including soft aluminum in both a rotating disk apparatus and in cavitation tunnels. In the rotating disk experiments, the threshold speed was about 80 feet per second regardless of the material. In two different water tunnels, threshold speeds of 70 feet per second and 60 feet per second were observed in either fresh or sea water except for mild-steel and STS steel which exhibited damage in salt water at velocities of 48 feet per second.

Such effects have been observed from the very beginning of cavitation damage testing, and the question was discussed over a decade ago by Nowotny (37), among others. We shall consider these results in greater detail after first reviewing some observations on the rate of damage in accelerated damage experiments and in full scale installations.

b. Damage rate in accelerated damage experiments

Depending upon the frequency and amplitude of vibration of magnetostriction oscillators or acoustic cavitation generators, the intensity of cavitation will vary, becoming increasingly severe with increasing amplitude of the pressure fluctuations. This has, of course, been widely recognized and has motivated development of procedures for standardization of damage testing in magnetostriction equipment. Nowotny (37), using aluminum specimens, was perhaps the first to make systematic tests of the effects of amplitude of oscillation on rate of damage. These effects are now again the subject of investigation. Some recent results, reported by Leith (39), are reproduced in Figure 27. In the case of accelerated damage experiments with equipment of this type, no "threshold" amplitudes have been reported, even the smallest amplitude of vibration at which cavitation occurs at all being observed to produce plastic deformation.

c. Damage rate in field experiments

Aside from the purposes of correlating the damage behavior of specific materials with the "intensity" of cavitation and of searching for the so-called threshold of damage, a most important goal of such correlation is the ability to predict the behavior of materials under field conditions from measurements of damage rate in accelerated laboratory tests. Measurements on cavitating hydraulic turbines in the field have been made by Knapp (102) using the technique of a soft aluminum specimen wrapped around the leading edge of a runner blade and by Rosenberg (98) with the coating of radioactive paint mentioned previously. Knapp was able to run the full scale tests at only one velocity. He states, however, that the pitting rate in the turbine was the same as that in the water tunnel tests on a body of revolution. On the other hand, his actual data seem to show that only the minimum pitting rate for the turbine falls in line with the tunnel tests, and then only in the zone of maximum damage, while the maximum pitting rate in the turbine is perhaps double that in the tunnel. Rosenberg's results are shown in Figure 26; his data appear to vary, on the average, with the fifth power of the velocity although slopes of his curve (as pointed out in the authors' closure to the discussion of Reference 99) vary from 5.8 for the lower four points to about 8 for the upper points.

It should be recognized that each of the full scale tests mentioned here were made with the purpose of obtaining a measure of the "intensity" of cavitation and not of the damage to the material in the machine, although the ultimate goal is to discover a means to predict the rate at which the material would be damaged.

d. Comments on cavitation "intensity" and damage rate determinations

Some confusion seems to have arisen in the attempts to develop correlation procedures for cavitation damage between the so-called intensity of cavitation, the rate of damage to construction materials, and the rate of damage to materials used as damage indicators. Firstly, there has been no real attempt to define what is meant by the intensity of cavitation, the term having a vague meaning associated with the rate and amount of damage produced. Evidently such a definition should be descriptive of the pressures produced and of the rate at which such pressures are applied. So far, the only correlations have been on the basis of velocity dependence. However, the flow conditions vary so greatly from machine to machine and the properties of the liquid vary so greatly that it would indeed be surprising if there were a universal velocity dependence. The number of cavitation bubbles will depend not only upon the type of cavitation flow but also upon the air entrainment in the liquid and thus upon the number of nuclei available for growth. There have been no critical studies of this point -- only the empirical results discussed above. Studies of the motions of convected, collapsing bubbles in the pressure gradients of the types of flow field in the experiments mentioned can be made analytically and would quickly disclose whether universal laws can be found.

Secondly, it should be carefully recognized that the methods used for measurement of "intensity" depend upon the corrosion of materials other than those in which the primary interest centered.

In this respect, very little was gained directly in achieving methods of prediction except perhaps for those materials that happen to behave similarly to the test material (aluminum or radioisotope) in their response to cavitation attack. Until more is known of the exact sequence of events in any liquid environment and the response of various materials as a function of their properties (resistance to mechanical erosion as well as electrochemical corrosion), recourse to such methods may be the only way in which some measure of the rate of damage can be obtained quickly and thus whether difficulties must be anticipated.

Finally, none of these methods are yet developed to the point where a judgment can be made of whether imposed protection must be considered either in the initial design or after a machine has been in operation under cavitation conditions.

CONCLUDING REMARKS

It is clear from our discussions of cavitation damage and the various hydrodynamical, metallurgical, and electrochemical factors involved that the process is a very complicated one. Qualitatively, much is now known about the mechanism of cavitation damage. Quantitatively, much remains to be learned, especially with regard to the interaction of mechanical and electrochemical effects. In particular, little is yet known about the scaling laws of damage with respect to comparison of events in different flow environments and extrapolation of events from one cavitating system to another. Not only is such information important in determining the best material to be used in a given situation (from the standpoint of the most economical choice), but also in deciding whether protective systems should be used to achieve most economical design for optimum life; and to enable the specification of the protective system when it is indicated. Thus, further progress will depend upon more detailed understanding of the hydrodynamics of cavitation and of the behavior of materials in corrosive media, both of which must be understood before the interactions can be evaluated fully and quantitatively.

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FIGURE I– CAVITATION IN A VENTURI SECTION
[*FOTTINGER (6)*]

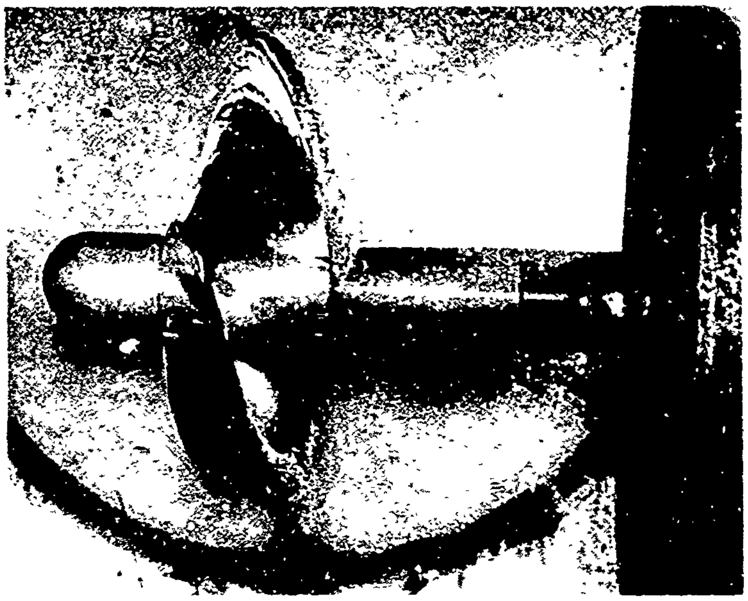

FIGURE 2— CAVITATION ON A MODEL PROPELLER SHOWING "STEADY" CAVITATION NEAR THE TIP OF THE UPPERMOST BLADE

(DTMB, U.S. NAVY)

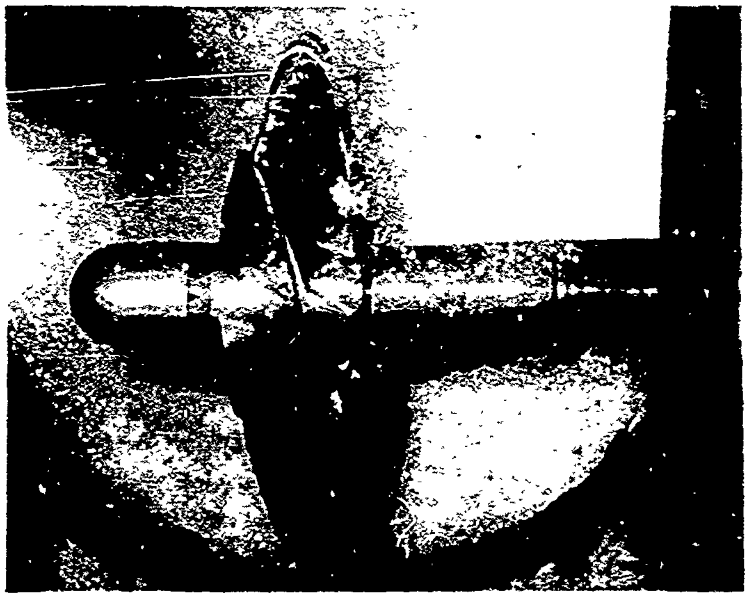

FIGURE 3— "TRANSIENT" CAVITATION ON A MODEL PROPELLER

(DTMB, U.S. NAVY)

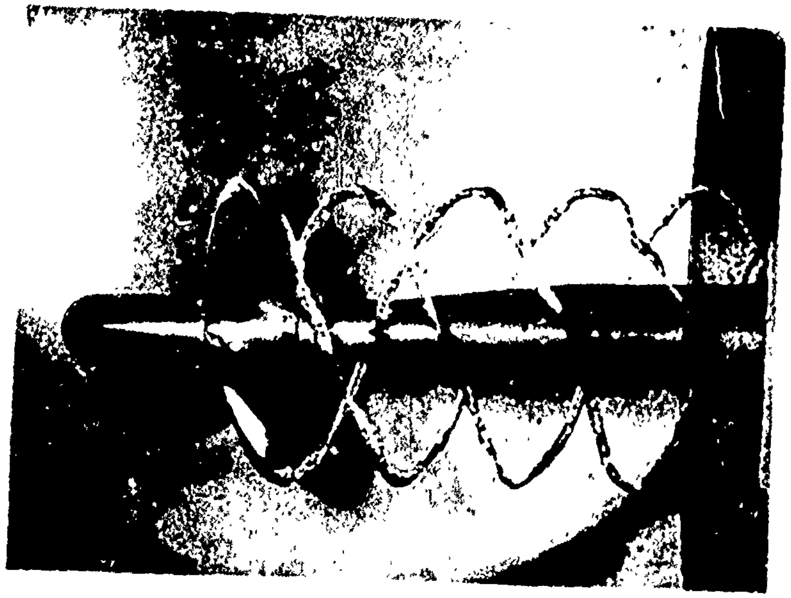

FIGURE 4— CAVITATION IN THE TIP VORTICES OF A MODEL PROPELLER
(DTMB , U.S. NAVY)

FIGURE 5— CAVITATION CLOUD AT TWO DIFFERENT POINTS OF A PRESSURE CYCLE IN A BARIUM TITANATE APPARATUS
[ELLIS (8)]

FIGURE 6a– "STEADY" CAVITY BEHIND A DISK. EXPOSURE TIME 2 SECONDS
[*EISENBERG AND POND (29)*]

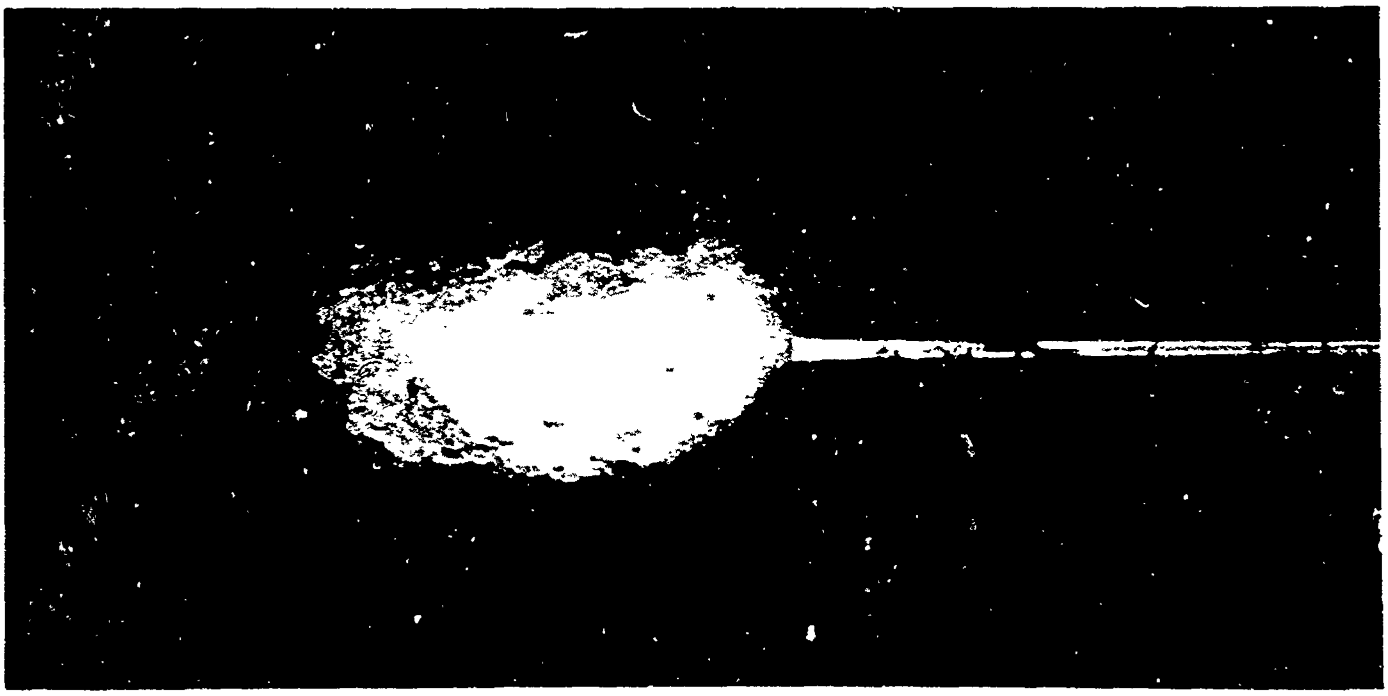

FIGURE 6b–"STEADY" CAVITY BEHIND A DISK. EXPOSURE TIME 1/10,000 SECOND
[*EISENBERG AND POND (29)*]

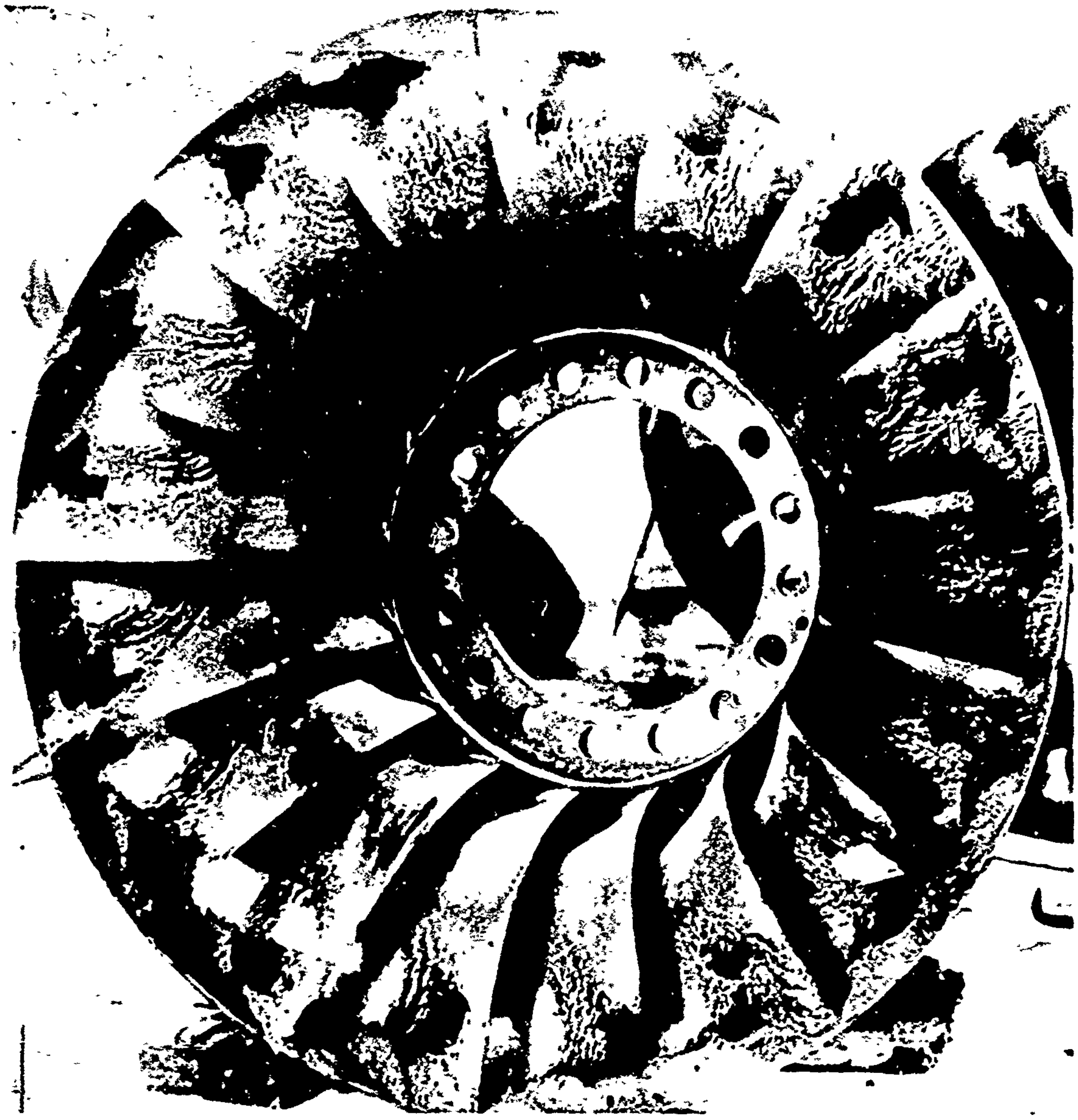

FIGURE 7– EXTENSIVE CAVITATION DAMAGE TO THE RUNNER OF A FRANCIS-TYPE HYDRAULIC TURBINE
[*W.C. LEITH, DOMINION ENGINEERING, LTD*]

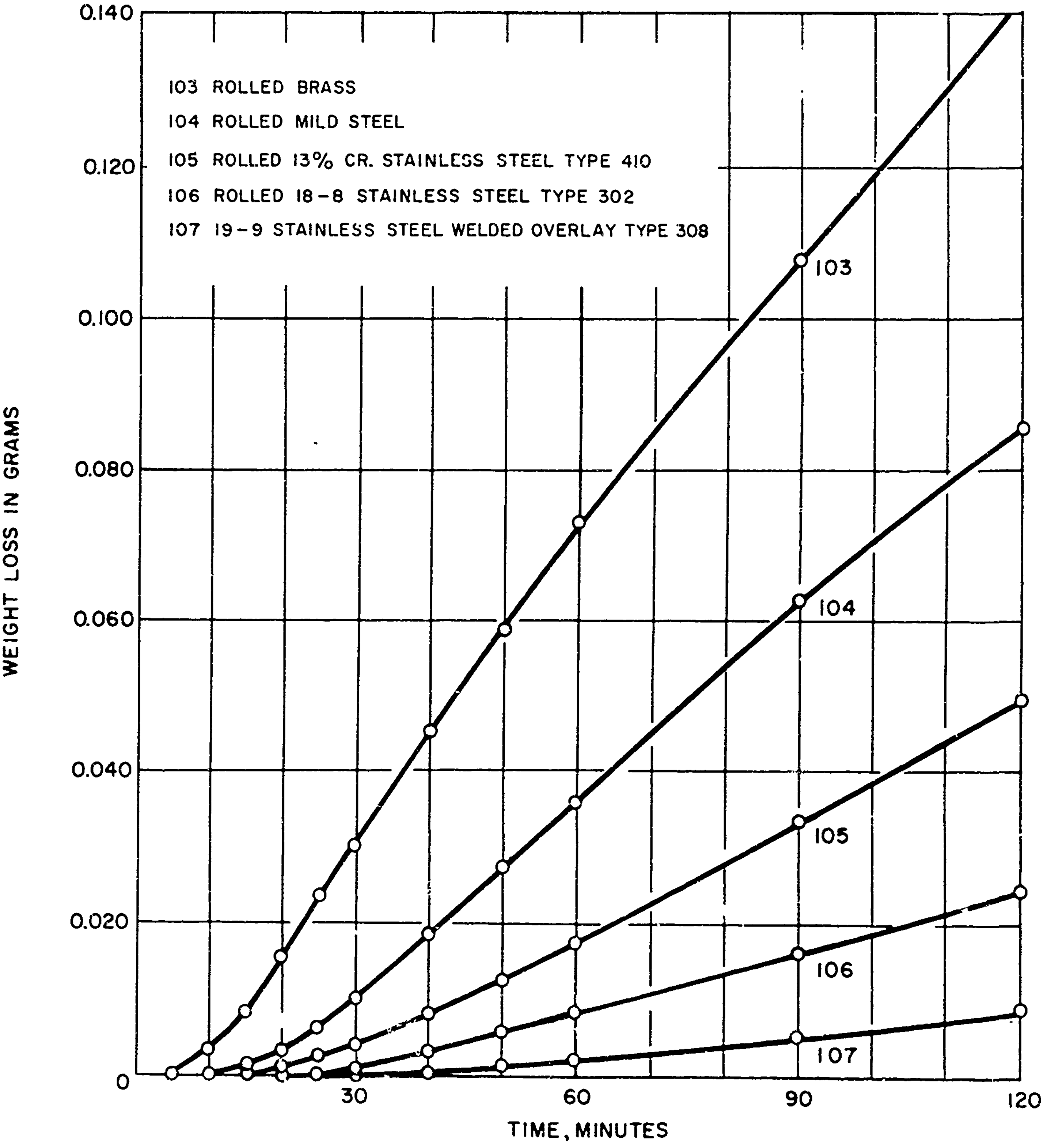

FIGURE 9— ILLUSTRATION OF THE SO-CALLED "INCUBATION PERIOD" IN TESTS OF ACCELERATED CAVITATION DAMAGE

(COURTESY OF W.C. LEITH, DOMINION ENGINEERING, LTD.)

FIGURE 9— CENTER OF DAMAGED AREA ON (0001) PLANE OF A SINGLE ZINC CRYSTAL AFTER 10 MINUTE EXPOSURE TO A 1/16 DIAMETER CAVITATION BUBBLE CLOUD — MAGNIFICATION 38X

[*COURTESY OF M.S. PLESSET (43)*]

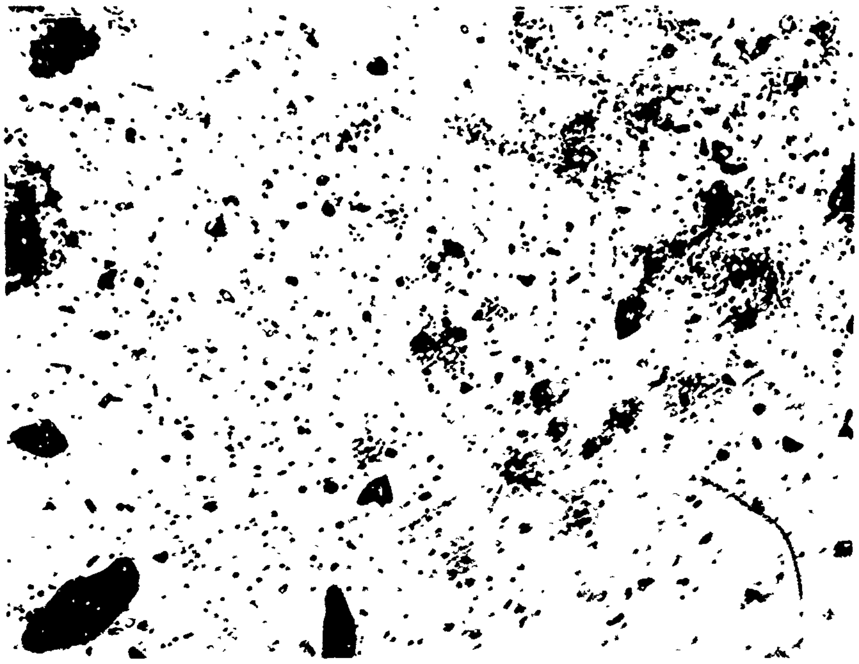

FIGURE 10a- UNDAMAGED SPECIMEN

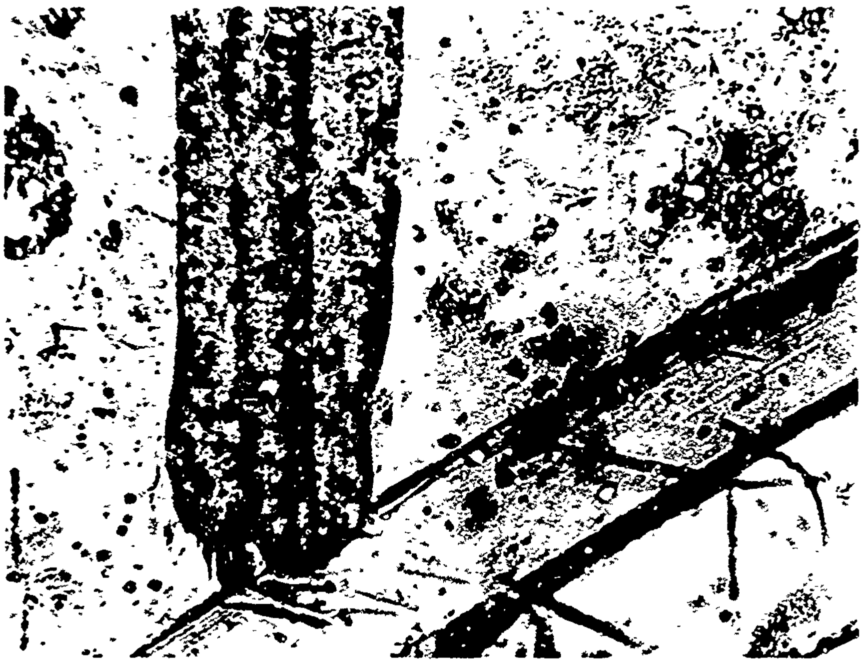

FIGURE 10b- AFTER 15 SECOND EXPOSURE TO CAVITATION CLOUD

FIGURE 10— ANNEALED SURFACE OF ZINC MONOCRYSTAL CLEAVED ALONG A BASAL PLANE — MAGNIFICATION 250X

[COURTESY OF M.S. PLESSET (43)]

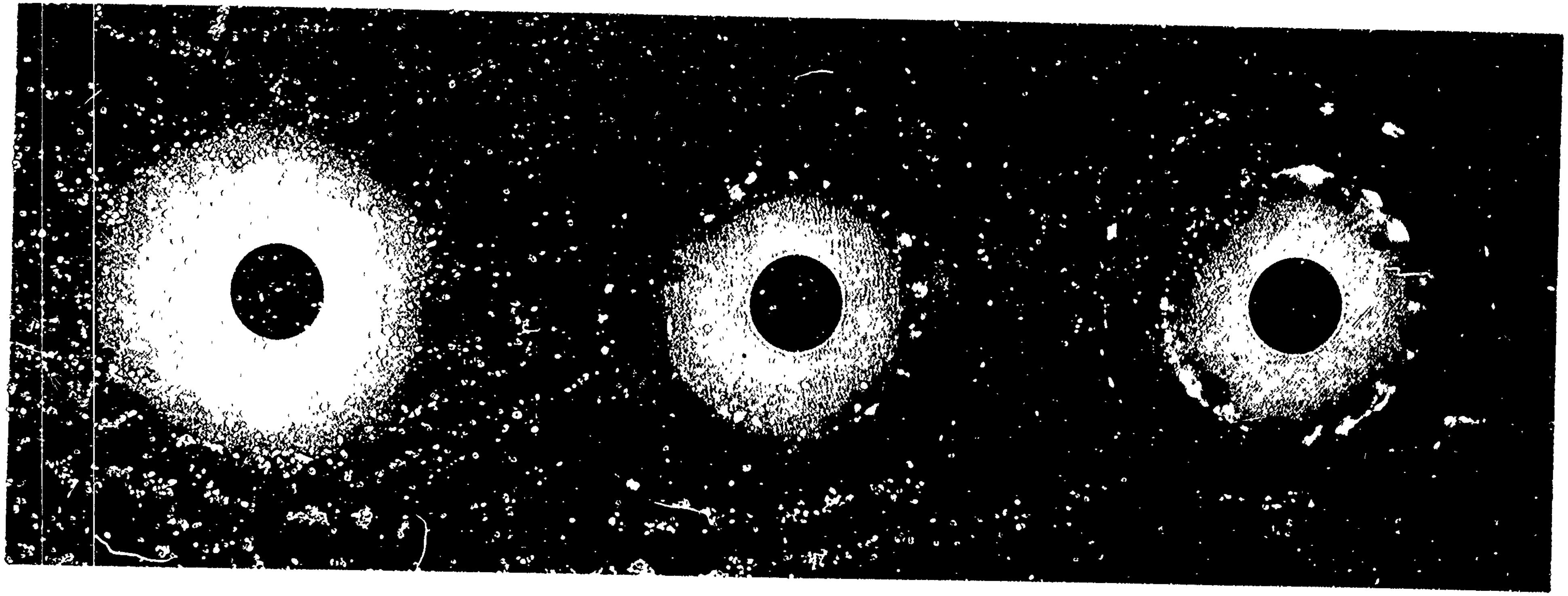

FIGURE 11— X-RAY DIFFRACTION PATTERN OF NICKEL SPECIMEN SHOWING RAPID ONSET OF COLD WORK ON EXPOSURE TO CAVITATION IN WATER : (a) BEFORE EXPOSURE , (b) AFTER 2 SECOND EXPOSURE,(c) AFTER 10 SECOND EXPOSURE

[*COURTESY OF M.S. PLESSET(43)*]

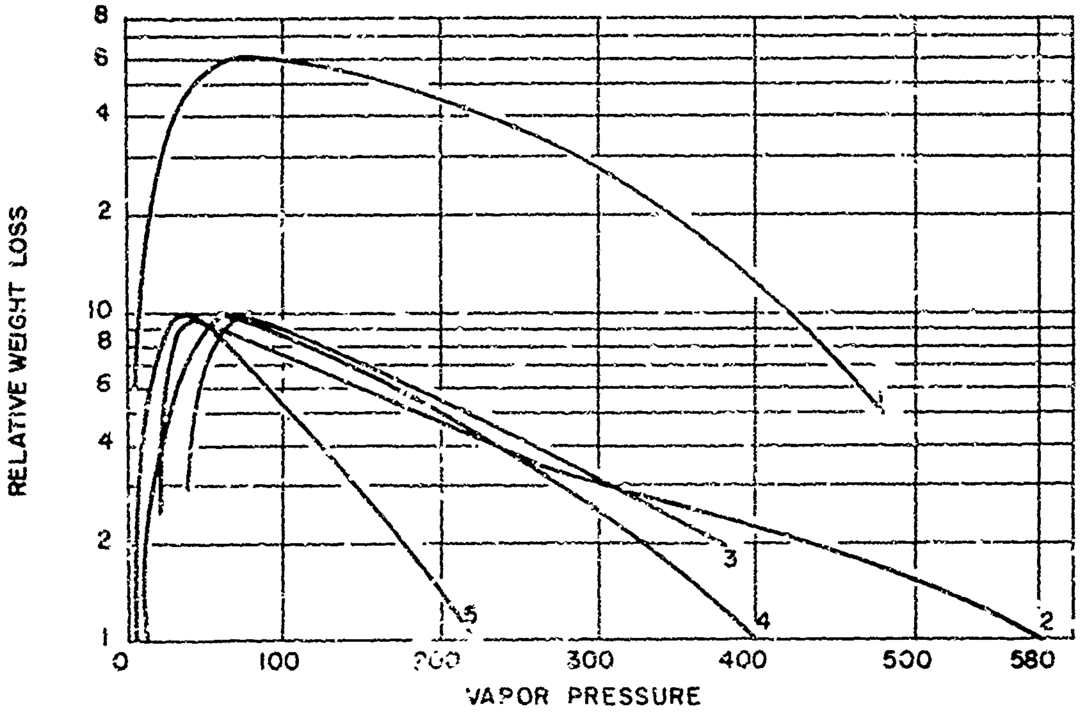

FIGURE 12– DEPENDENCE OF CAVITATION DAMAGE ON SATURATED VAPOR PRESSURE OF: 1. WATER, 2. ALCOHOL, 3. ACETONE, 4. TRICHLOROETHYLENE, 5. CARBON TETRACHLORIDE [*BEBCHUK (48)*]

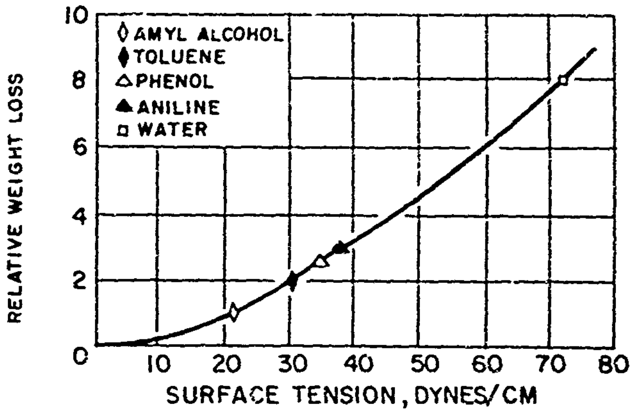

FIGURE 13 – DEPENDENCE OF WEIGHT LOSS OF ALUMINUM SPECIMEN ON SURFACE TENSION. [*NOWOTNY (37)*]

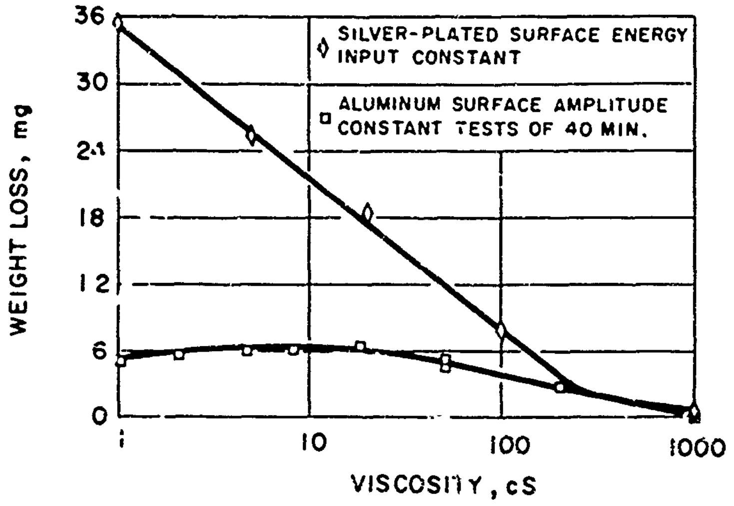

FIGURE 14– EFFECT OF VISCOSITY OF LIQUID ON CAVITATION DAMAGE [*WILSON AND GRAHAM (46)*]

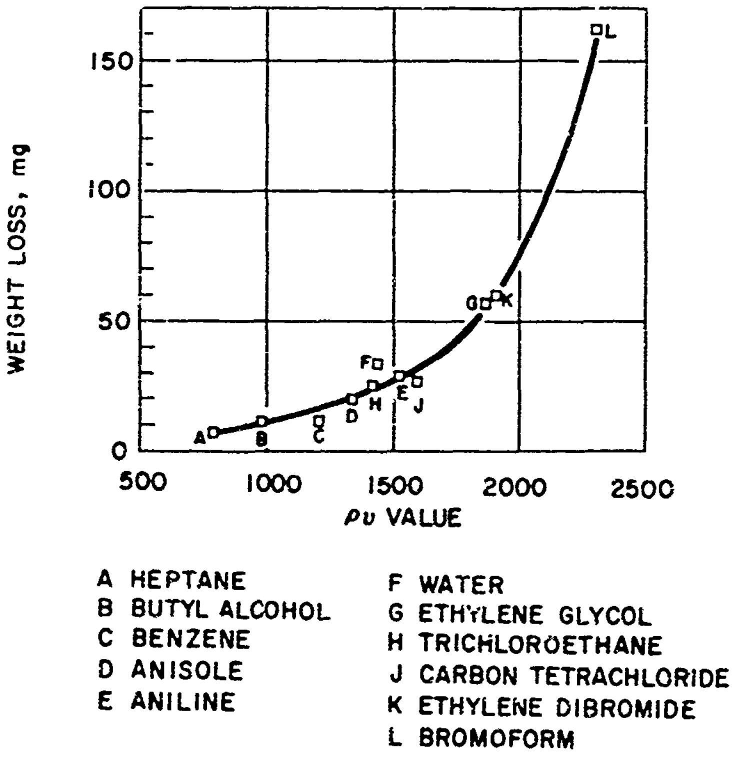

FIGURE 15– CORRELATION OF CAVITATION DAMAGE WITH PRODUCT OF LIQUID DENSITY AND SOUND VELOCITY [*WILSON AND GRAHAM (46)*]

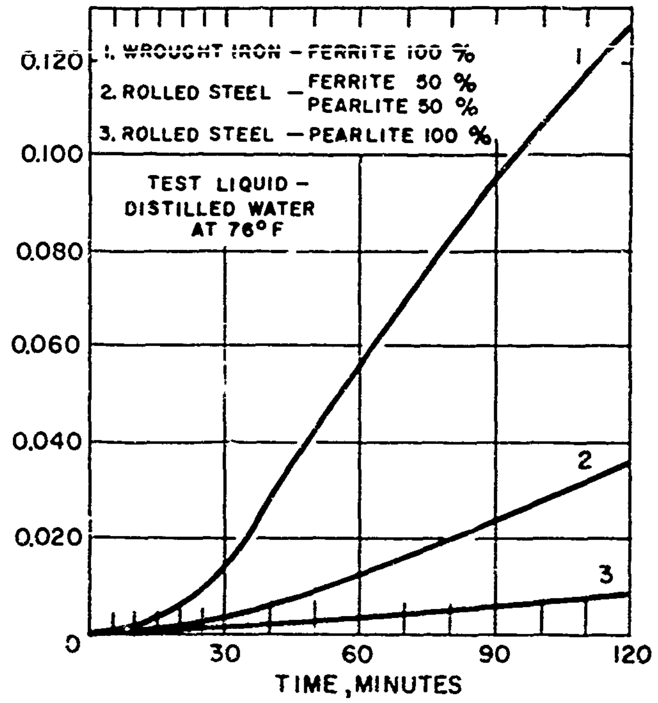

FIGURE 16a – CARBON STEELS

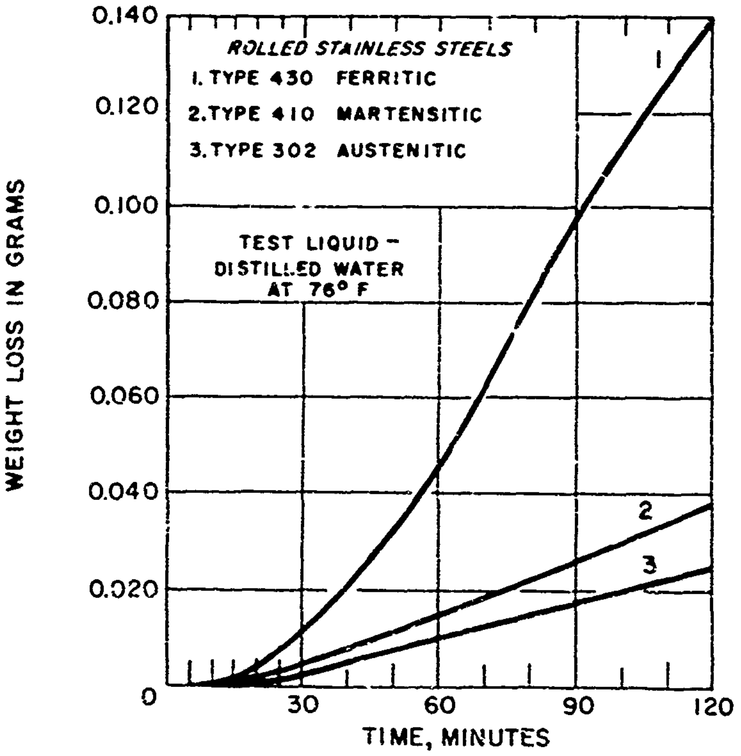

FIGURE 16b – STAINLESS STEELS

FIGURE 16 – DEPENDENCE OF CAVITATION DAMAGE RESISTANCE ON METALLURGICAL STRUCTURE
[*LEITH AND THOMPSON (47)*]

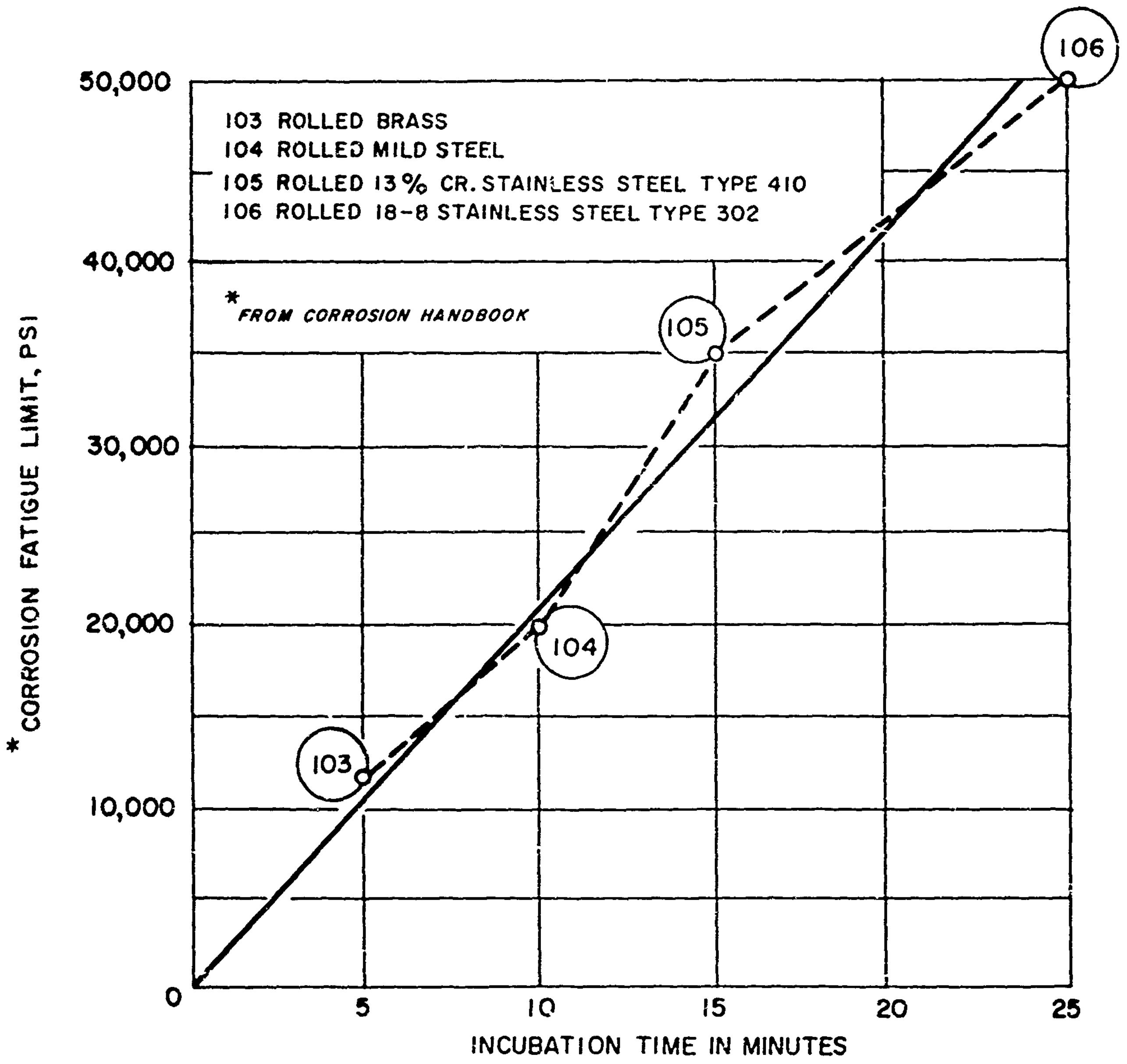

FIGURE 17– CORROSION FATIGUE LIMIT AND INCUBATION TIME

[*LEITH (39)*]

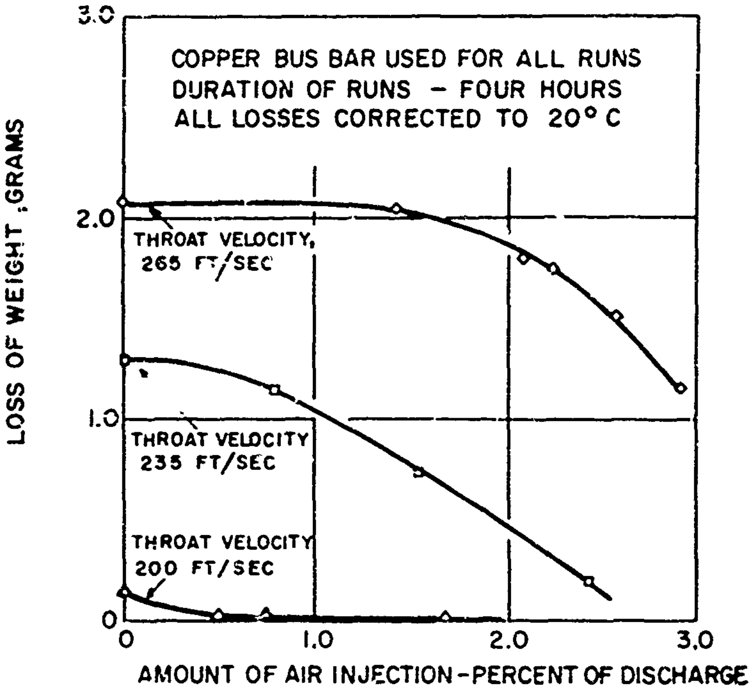

FIGURE 18a– COPPER BUS BARS IN VENTURI APPARATUS
[*MOUSSON (36)*]

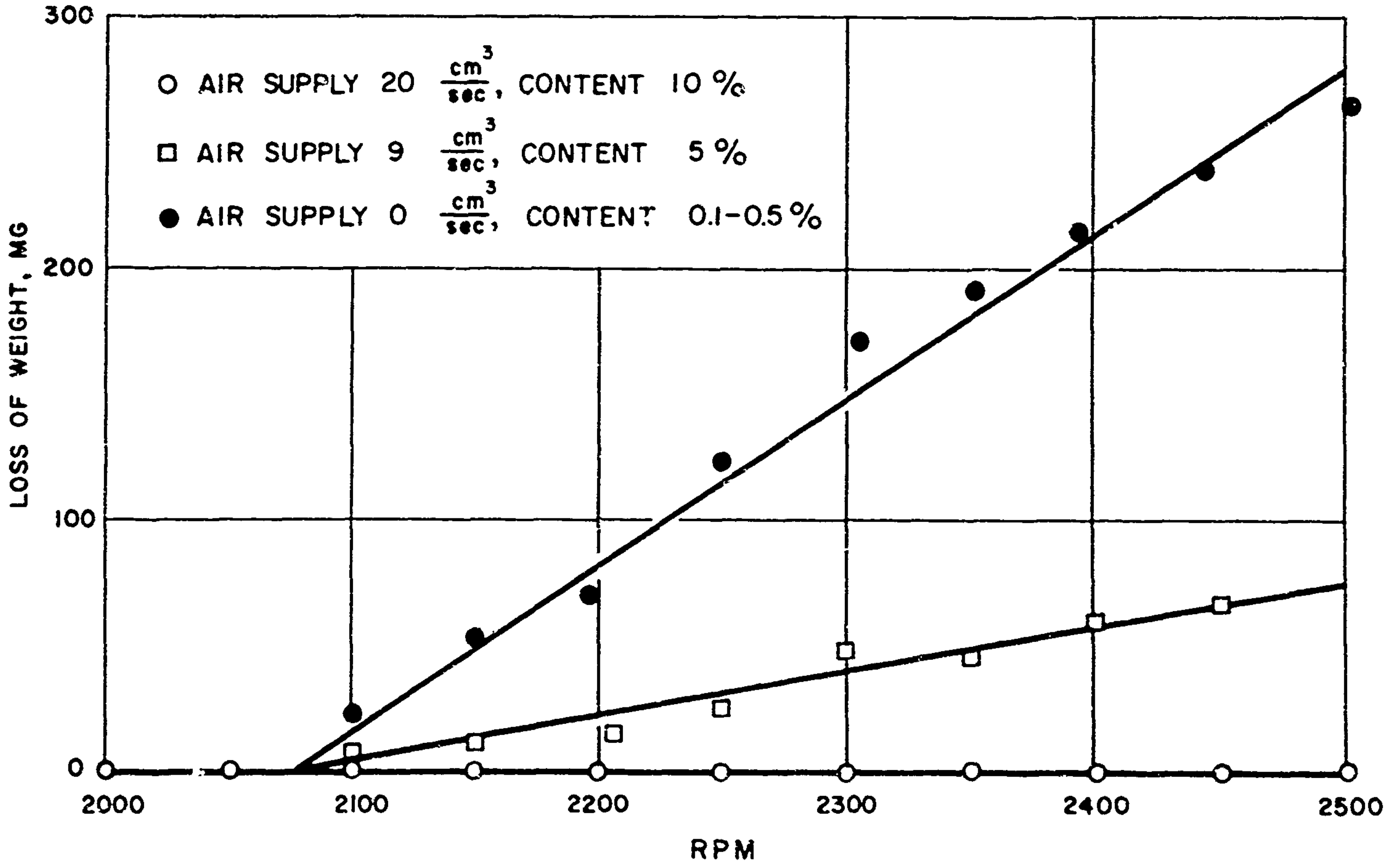

FIGURE 18b– ALUMINUM ALLOYS IN ROTATING DISK APPARATUS
[*RASMUSSEN (86)*]

FIGURE 18– EFFECT OF AIR INJECTION ON CAVITATION

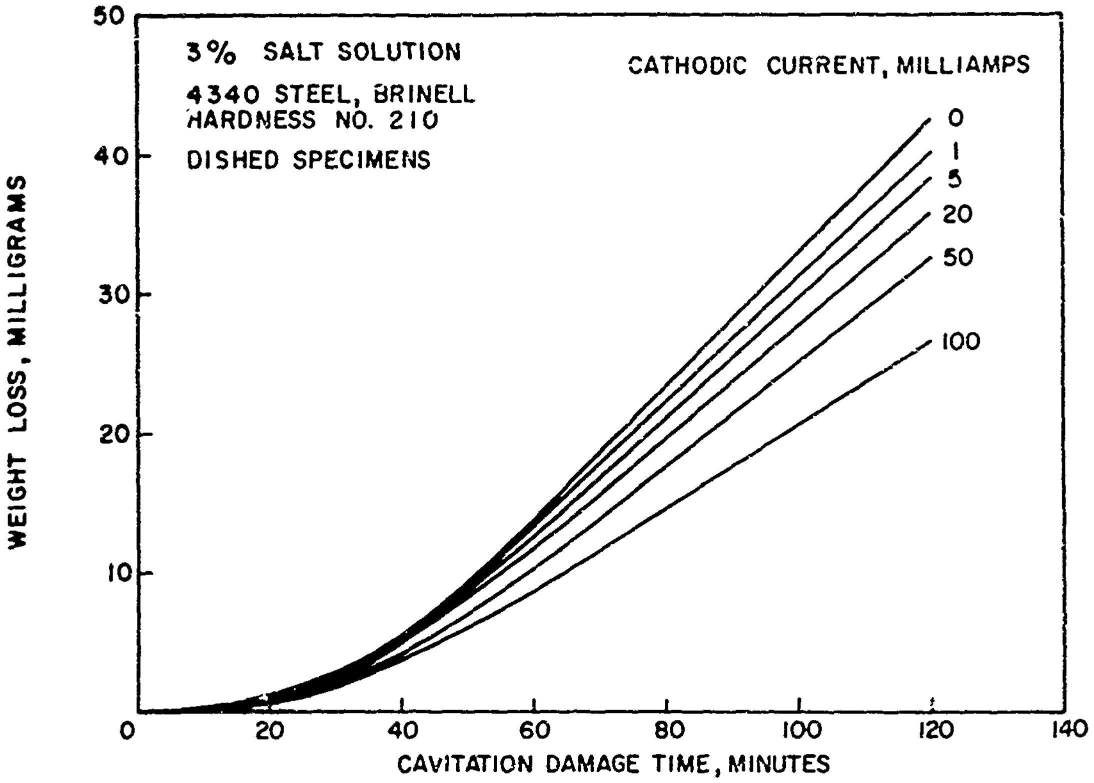

FIGURE 19a— 4340 STEEL

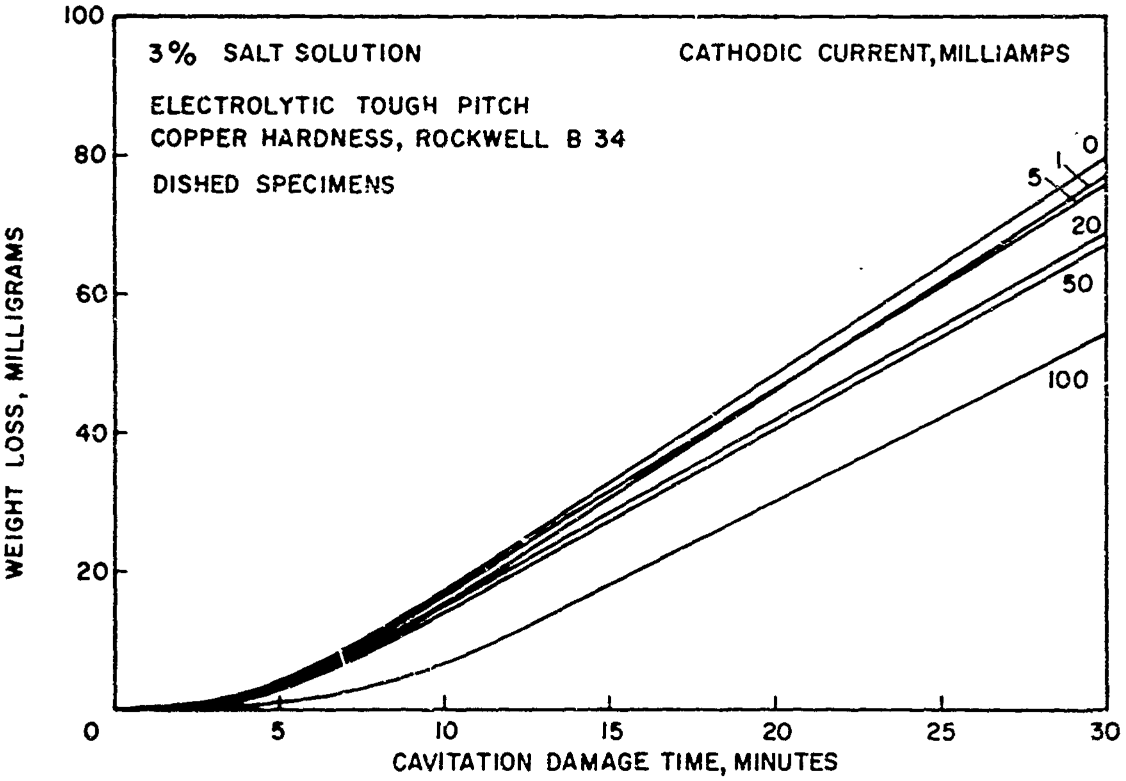

FIGURE 19b— PURE COPPER

FIGURE 19— AVERAGE CURVES OF CAVITATION DAMAGE LOSSES OF STEEL AND COPPER SPECIMENS IN 3% SALT SOLUTIONS AS A FUNCTION OF CATHODIC CURRENT

[*PLESSET (69)*]

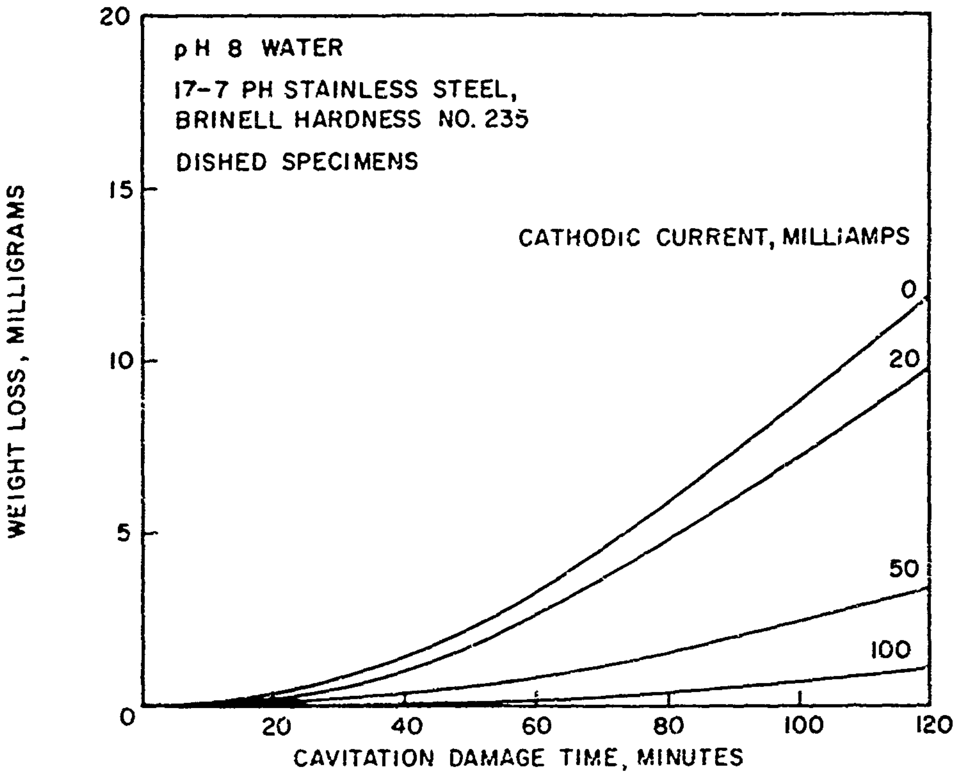

FIGURE 20a– SPECIMEN CATHODIC

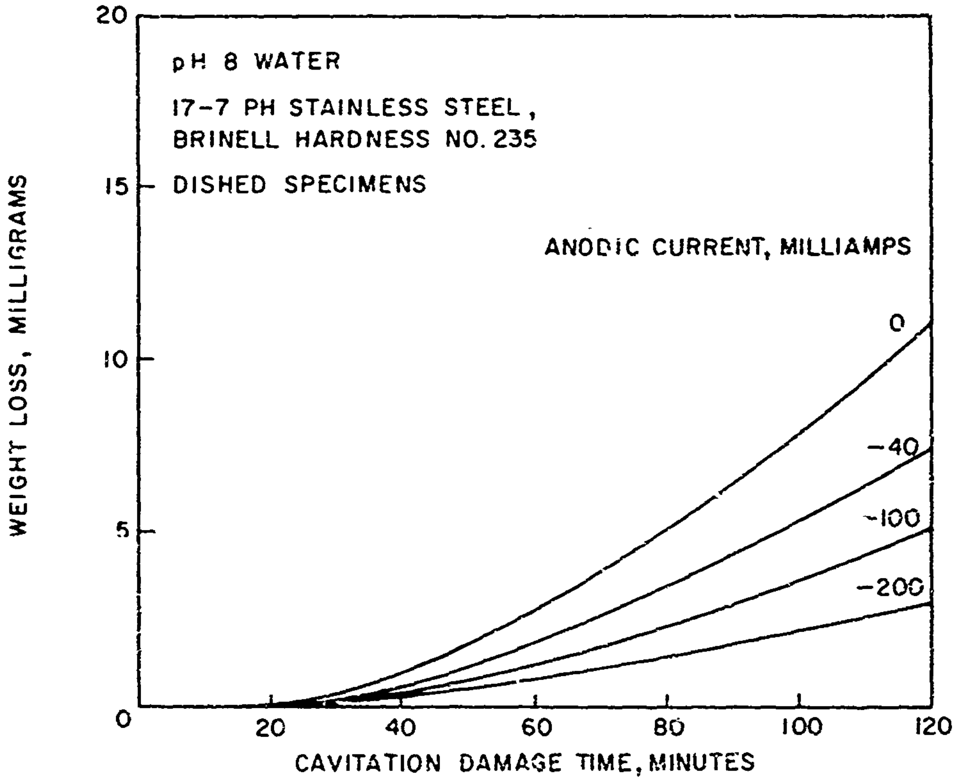

FIGURE 20b – SPECIMEN ANODIC

FIGURE 20 – AVERAGE CAVITATION DAMAGE LOSSES OF 17-7 STAINLESS STEEL SPECIMENS AS CATHODES AND ANODES IN BUFFERED DISTILLED WATER

[*PLESSET (69)*]

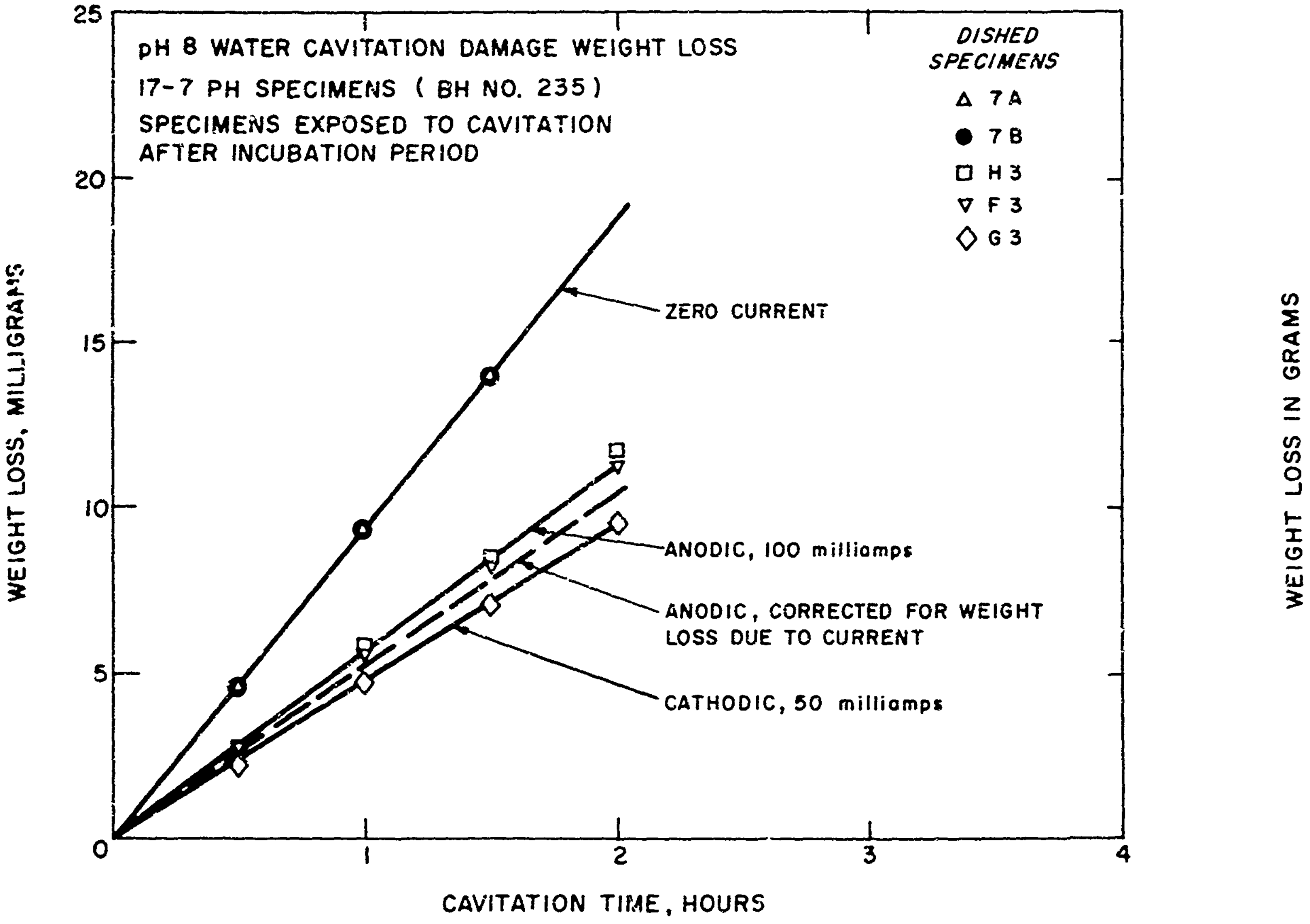

FIGURE 21– COMPARISON OF CAVITATION DAMAGE LOSSES OF 17-7 STAINLESS STEEL IN BUFFERED DISTILLED WATER WITH THE SPECIMEN ANODIC AND CATHODIC (ANODIC RESULTS CORRECTED FOR WEIGHT LOSS DUE TO ELECTOLYTIC SOLUTION)

[PLESSET (69)]

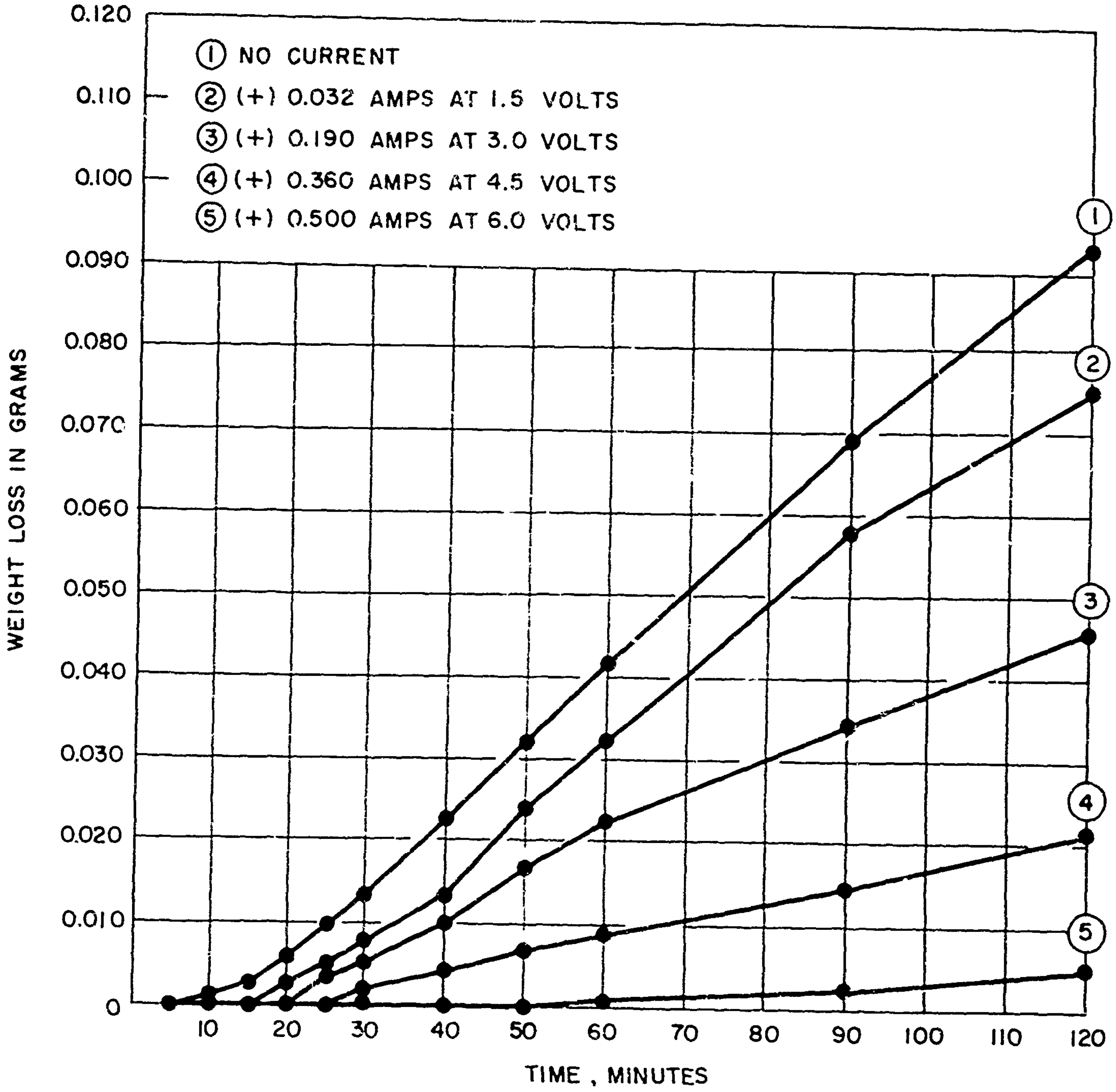

FIGURE 22– CATHODIC PROTECTION OF CAST STEEL IN SEA WATER
[*LEITH AND THOMPSON (47)*]

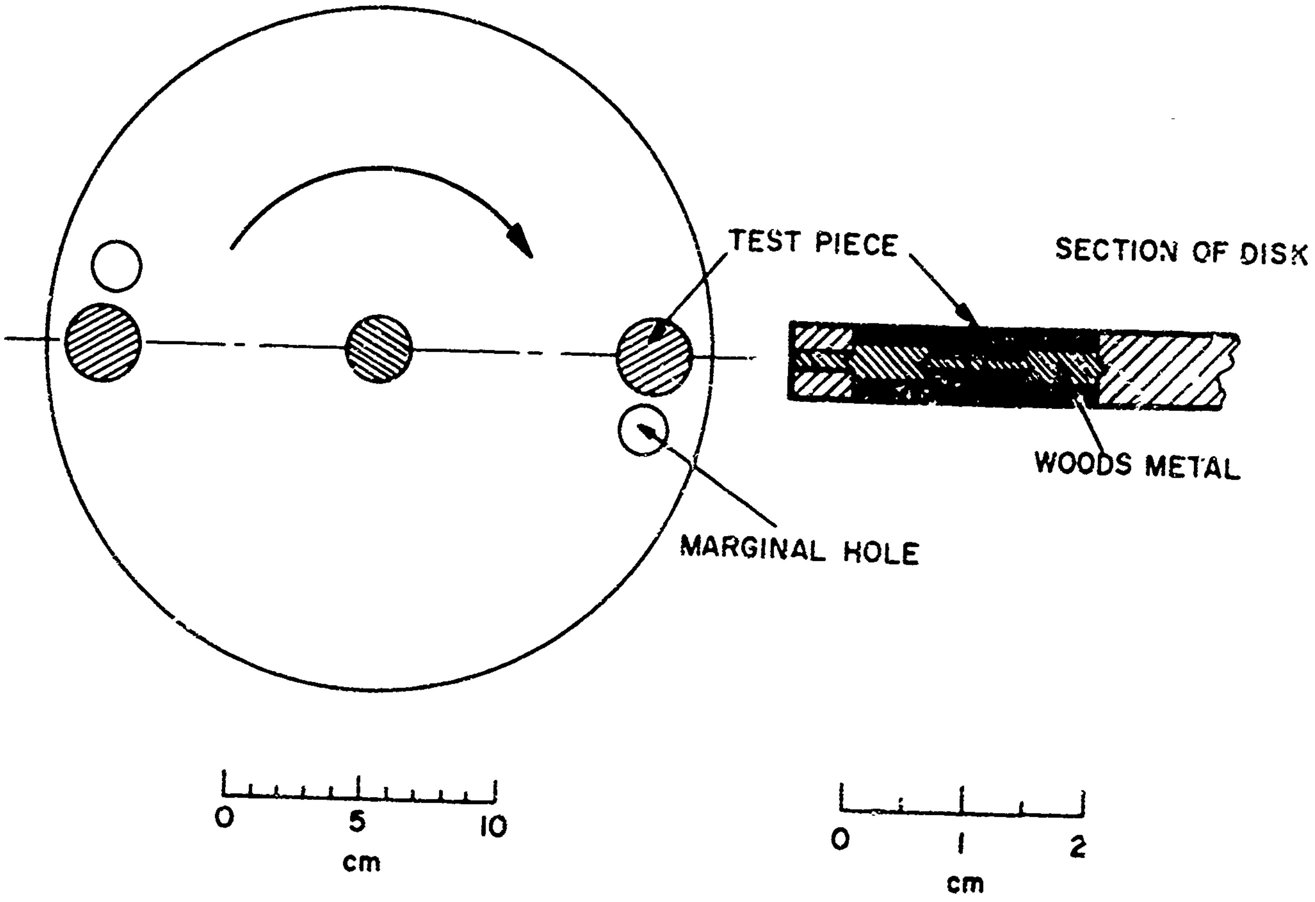

FIGURE 23– ROTATING DISK FOR CAVITATION DAMAGE EXPERIMENTS
[*RASMUSSEN (86)*]

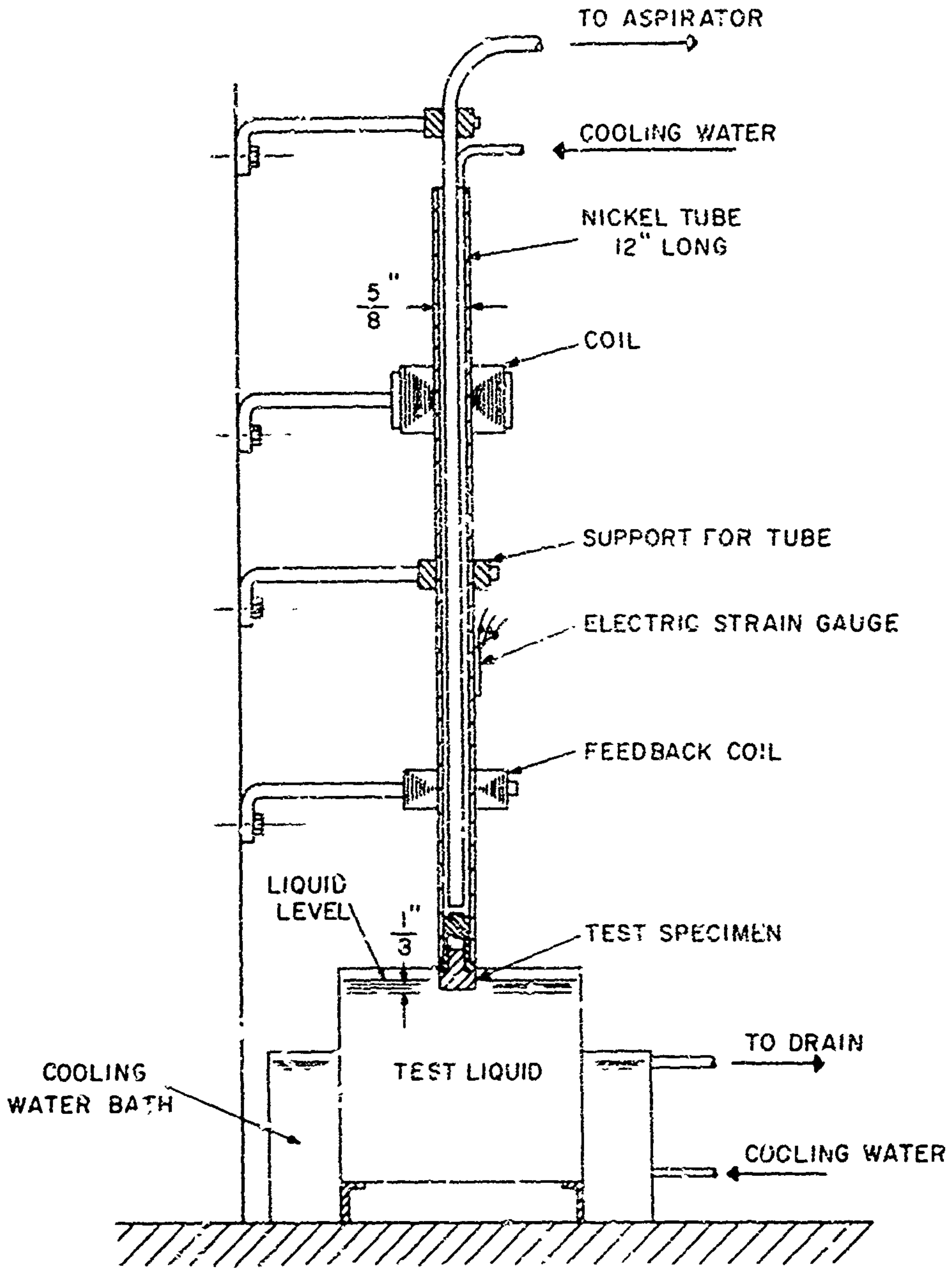

FIGURE 24 - SCHEMATIC DIAGRAM OF MAGNETOSTRICTION APPARATUS FOR ACCELERATED DAMAGE TESTS

[LEITH (39)]

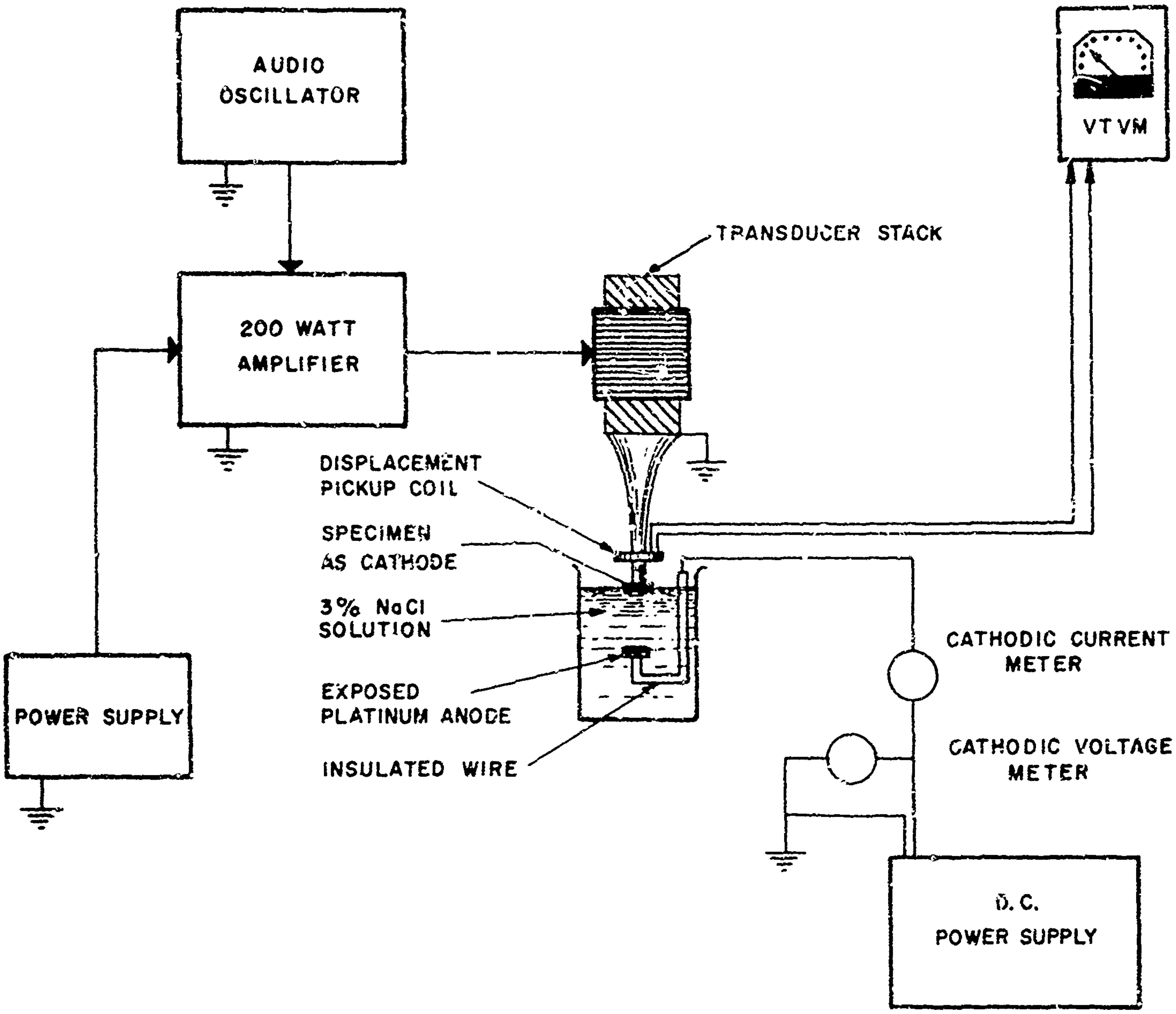

FIGURE 25– MAGNETOSTRICTION APPARATUS WITH EXPONENTIAL HORN AMPLIFIER AND ARRANGEMENT FOR TESTS OF CATHODIC PROTECTION. [*PLESSET ET AL, (68)*]

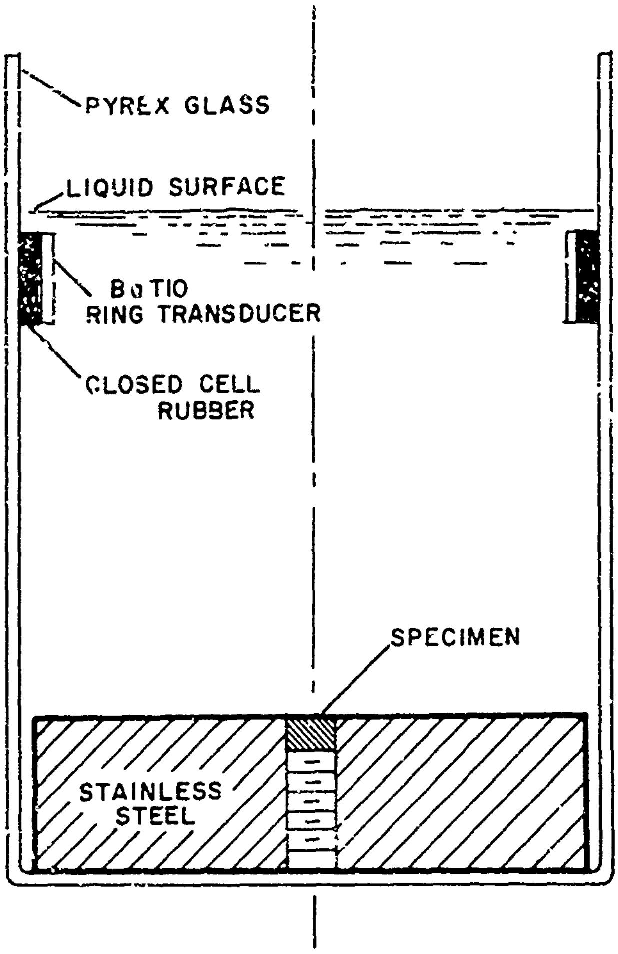

FIGURE 26– BARIUM TITANATE TRANSDUCER SYSTEM FOR ACCELERATED CAVITATION DAMAGE EXPERIMENTS
[*ELLIS (8)*]

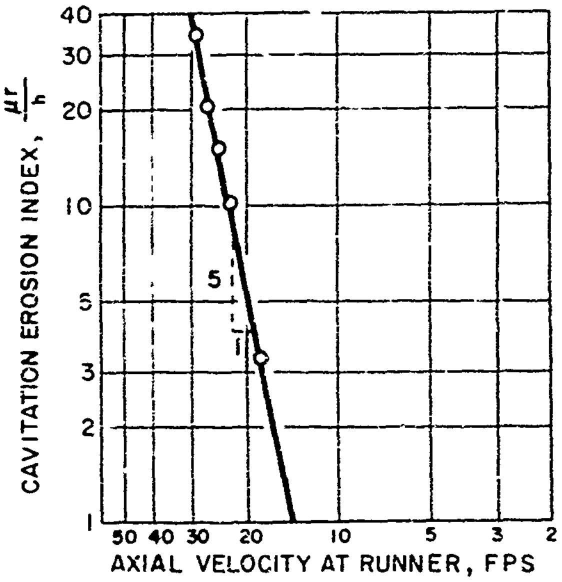

FIGURE 27– CAVITATION EROSION AS MEASURED BY CHANGE IN RADIOACTIVITY IN MICRO-CURIES PER HOUR, AS A FUNCTION OF AXIAL VELOCITY AT A TURBINE RUNNER
[*KERR AND ROSENBERG (99)*]

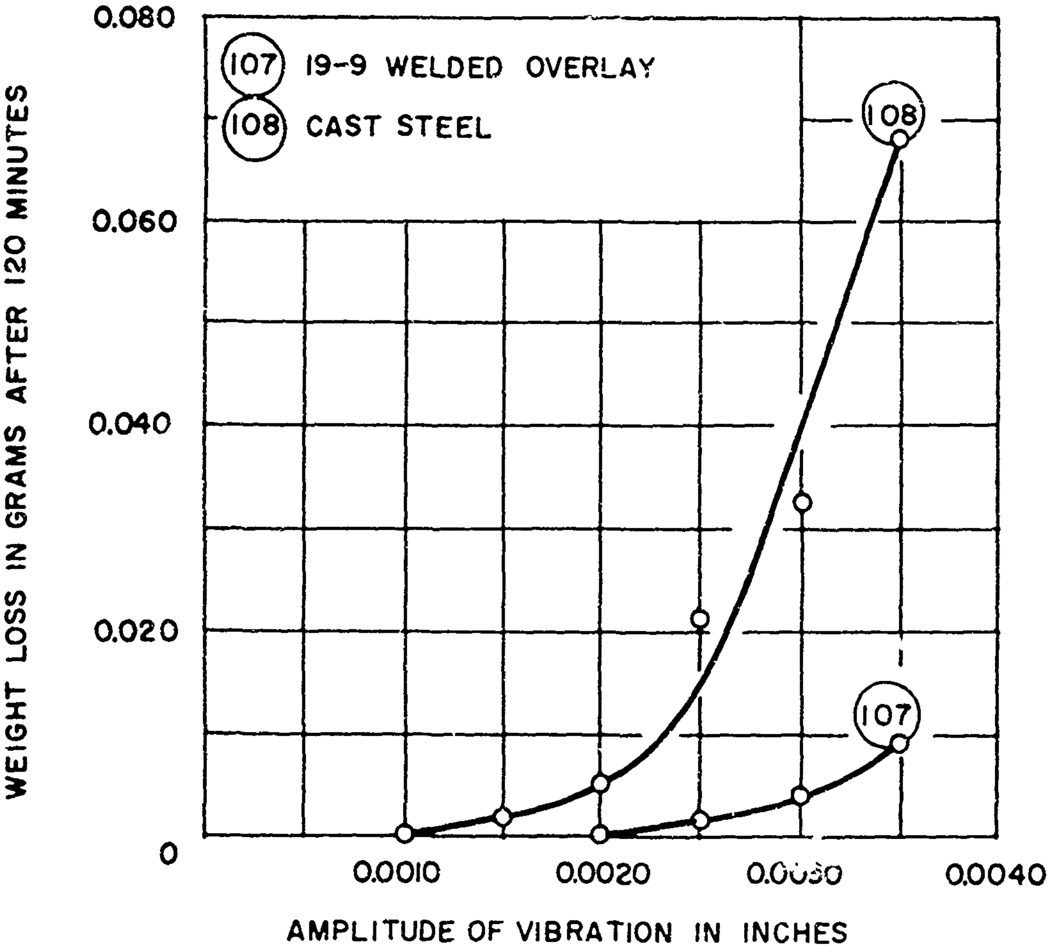

FIGURE 28– CAVITATION DAMAGE RATE AS A FUNCTION OF MAGNETOSTRICTION OSCILLATOR AMPLITUDE

[LEITH (39)]

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