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Reduction of Cavitation Damage by Surface Treatment

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ABSTRACT

It was rationalized, with limited supporting evidence, that most damage due to cavitation stems from cavities which are the consequence of outgassing nuclei growing from fissures in a body's surface. To minimize this damage, it was proposed that body surfaces be treated to reduce the number and activity of these surface faults. Vibratory cavitation damage tests of specimens treated to seal, neutralize, or compress the test surface indicated that these protective measures were inadequate for the severe conditions of a vibratory test.

Light shot peening of a work hardening stainless steel prior to cavitation exposure substantially reduced the normal rate of cavitation erosion.

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REDUCTION OF CAVITATION DAMAGE BY SURFACE TREATMENT

I. INTRODUCTION

Recent field trials with the first generation of high speed Navy hydrofoil craft have demonstrated [1,2]* serious surface deterioration of materials exposed to underwater erosion. Since these failures occurred in materials selected on the basis of an extended development program, it is apparent that future development of even higher speed naval craft may be critically dependent on improved solutions to this materials barrier. In light of these conditions, the Navy has entered into an accelerated materials development program involving several facets. Prime emphasis of the general program is the further development of protective materials with increased resistance to corrosion, impingement, and cavitation attack. The study considered in this report relates to an alternate and different approach in that protection is sought not by increased resistance to damaging cavitation but by reduction of the conditions which produce cavitation. The reduction in this case is sought through control of outgassing from the exposed surface. The following factors are considered significant to this concept and are discussed in the report together with related physical tests:

1. The occurrence of cavitation is dependent on the presence of gaseous nuclei.
2. Gaseous nuclei are presumed to occur only on solid surfaces. These surfaces may be either the flow exposed surface of a body or the surface of solid particles in the water.
3. Boundary flows tend to move particle nuclei away from a boundary.
4. Cavitation involving the vaporous expansion of a gaseous nuclei and the subsequent collapse can generate pressure conditions destructive to metal surfaces.
5. Destructive cavitation pressures can be delivered to a metallic surface only if the cavity is in fairly intimate proximity to the surface. Thus only a small fraction of the cavities which normally occur are directly involved in damage processes.
6. Gaseous nuclei which occur directly on the flow surface are considered most likely to produce damaging cavitation.

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*Numbers in brackets refer to the List of References on page 21.

7. Surface-generated nucleation and the resulting surface cavitation might be inhibited by surface sealing.
8. Improved surface sealing is sought through the employment of non-metallic films, metallic films, and surface compression.
9. Evidence indicates that the mechanisms which are involved in normal corrosion-fatigue failures of metals are very similar to the mechanisms of cavitation damage. Factors which inhibit corrosion fatigue may be useful in the reduction of cavitation damage.

In an attempt to contribute to a practical solution of present Navy problems, tests have been confined to structurally useful materials and corrective procedures deemed practical for use.

II. THE OUTGASSING OF METALLIC SURFACES AND THE RELATION TO CAVITATION

Knapp [3], among others, provided considerable evidence that the molecular structure of water virtually precluded the occurrence of cavitation unless gas-liquid interfaces were present in the form of small bubbles or nuclei. These findings have also given strength to the earlier theory [4] that these nuclei in all probability evolve from gaseous inclusions which persist in crevices, intercrystalline fissures, or pores in the surface of suspended particles in the water or on boundary surfaces in contact with the water. The persistence of these gaseous entities under pressure conditions which seemingly should lead to their complete disappearance is attributed to the powerful pressure differentials contributed by the curved gas-liquid interface occurring in the unwetted micro-scaled faults or crevices which exist on all solids. Exposure of these entrapments to pressure reductions which exceed the saturation value of the dissolved gas in the water will lead to a gas transfer from solution to dissolution across the gas-liquid interface in the crevice. Continuous exposure to either steady supersaturated pressure conditions or to pulsing pressures (rectified diffusion) can lead to continuous growth of gas in the crevice and a streaming discharge of discrete gas bubbles from the mouth of the crevice.

Tests [3] have demonstrated that strong cleaning procedures or exposure to high pressures will serve to purge the most available gas from the crevices and will temporarily reduce the ability of the crevice to discharge gas. These cleaning results are quite marked on glass surfaces but metals appear to resist any significant or persistent purging of these gassing centers.

If the surface of the solid is first wetted with an oil before exposure to saturated water, the interface wetting conditions are substantially altered and gasification is reduced or arrested. A simple demonstration of this is shown in Fig. 1. In this, four different standard rods of about 3/8 in. diameter were degreased, dried, and their lower ends dipped in oil, and drained. These were then simultaneously immersed in a beaker of chilled, freshly poured soda water. The photo of Fig. 1 was taken about ten minutes after immersion. The rods in the order of their appearance from left to right are: (1) steel with a neoprene dip coating, (2) bare brass, (3) plexiglas, and (4) a drill rod steel. The following features of the photo have pertinence:

(1) The neoprene coating appears to provide a large number of gas-evolving centers, but the rate of gas dissolution is low. Surface effects on the neoprene limit the bubbles to a small size before release. The oiling procedure employed appears to reduce the number of gas-evolving centers and the surface effect of the oil supports a larger size of bubble before release. It appears that a surface coating such as neoprene has an inherent pore structure of its own. This presumably would be true of any material which became a solid by loss of volatile solvents, and probably also for any fluid coating which crystallizes to a solid.

(2) The bare brass provides a fairly large number of gassing centers which apparently gas at a fairly high rate. The surface effects limit the bubbles to a small size. The combination of gassing rate and surface effects leads to an active buoyant streaming release of gas as evidenced by the large number of out-of-focus and elongated moving bubbles. A modest number of very slow gassing bubbles are growing on the oiled surface. Surface effects seemingly restrain the release of these until their size is large.

(3) The plexiglas rod provides a small number of gassing centers and the combined gassing rate and surface effects leads to large bubbles and very infrequent bubble release. The oil coating reduces the gassing centers to a very small number.

(4) The action on the steel appears very similar to that on the brass except that the streaming release

of gas is somewhat stronger and the oil coating appears to largely eliminate the gassing centers.

While the foregoing relates to highly supersaturated carbon dioxide and does not serve as direct evidence with regard to cavitation, it does indicate that common materials do possess large numbers of faults or gassing centers on their surfaces and that sealant materials can influence the outgassing mechanism. For the purpose of this study it is assumed that the gassing centers are some form of surface fissure. This assumption is admittedly arbitrary and unconfirmed.

In the case of flow cavitation in a natural water, which normally contains many solid particles, lowest pressures will occur, not on the boundary, but in the core of boundary layer vortices which are somewhat removed from the boundary [5]. Cavitation will, therefore, probably evolve most readily from gas nuclei occurring on solid particles in the vortices and perhaps to a lesser extent from nuclei outgassing from a body boundary surface. Water tunnel studies of cavitation on headforms in conjunction with free air measurements [6] indicate that large numbers of these transient nuclei exist in a water tunnel flow and probably serve as the principal centers of transient cavitation. Field observations [7] indicate the probability that these transient nuclei also exist in most natural water boundary layers in great numbers except in the laminar forward portions. Direct observations [8] of outgassing from a body boundary have been made in a water tunnel, but it seems unlikely that these nuclei are as numerous as those which are in the flow. In consequence most bulk evidences of cavitation in flow systems probably stem from cavities which are not directly on the body boundary.

On the strength of both experimental observations and analysis [9,10, 11] it appears that vaporous cavities which form and collapse only a very small distance from a surface are damped to such an extent that damaging pressures are not delivered to the surface. In consequence, it is believed that only those cavities which collapse directly on the surface can significantly contribute to damage in flow processes.

The foregoing suggests that, in general, cavities which cause damage are probably not cavities which travel with the core flow, but are instead cavities which repeatedly grow from and collapse directly on or near the mouth of an outgassing surface fault. Substance for this view is given in an early paper by Poulter [12] in which he observed cavitation on a specimen in a vibratory apparatus under stroboscopic light. He noted that "these cavities seemed to reform in the same place on the surface of the metal rather than assuming a different random distribution for each cycle." The observed action provided both surface erosion and fatigue cracking of a cast iron specimen.

In addition to this physical concept of external gas effects, it is important to note that internal to the metal surface are other actions which may also contribute to outgassing and consequent cavitation. It should be recognized that the same cracks which serve as surface outgassing centers terminate within the metal at focal points of high stress concentration. Under repeated cycles of severe stressing the cracks propagate through the metal and contribute to eventual failure.

Under high unit stresses, failure may occur in a relatively few cycles of stressing but with most metals failures will occur at progressively lower unit stress values as the cycles of stressing are increased. Stress failure values associated with millions of cycles of stressing may be only a fraction of an initial static failure value and the former are referred to as fatigue stress values. Cavitation, a process involving large numbers of stress cycles, results in damage which is in many cases believed to be involved with a fatigue type of failure mechanism.

Most of the fatigue data acquired to date has dealt with metallic failures induced by stressing large portions of a test member rather than elementary areas as in cavitation. It is, therefore, questionable that many of the gross findings relating to conventional fatigue data can necessarily be applied directly to cavitation failures. Certain aspects of the failure mechanism should, however, be related and will be examined for pertinence.

Studies of conventional fatigue failures for most metals when conducted under dry atmospheric conditions or with moisture-sealed surfaces will normally exhibit a substantial reduction in fatigue strength with increasing cycles of exposure. If in addition the surface of the stressed member is exposed to a high humidity atmosphere or to water, the metal may exhibit an even greater reduction in strength. With some metals the latter added reduction may be approximately equal to the former and the total may constitute a reduction of two-thirds in the original static strength value. This combined action is known as corrosion fatigue.

Corrosion fatigue appears to be associated with an electrochemical action which occurs in the surface cracks due to non-homogeneities in the structure of the crack walls and to stress energy concentrations at the crack terminus. In the presence of a freely available electrolyte such as water, an accelerated electrochemical corrosive attack occurs in the intercrystalline space and crack propagation progresses. Important to the concepts of this discussion is the fact that this progression is evidently sometimes accompanied by the evolution of free gas.

Support for a relation between outgassing and fatigue failure in cavitation damage is found in recent observations [13] of hydrogen outgassing from the stressed surface of specimen in standard fatigue tests conducted in air. These tests are interesting in that a significant number of hydrogen bubbles evolved from the most highly stressed areas of the fatigue stress members. The gas evolution began after a substantial number of cycles of stress, but before any other evidence of fatigue cracking, the gas continued to evolve as cracks propagated. Gassing could be eliminated with a completely dry specimen and increased with air humidity, thus indicating that the gas evolution was associated with corrosion or electrochemical activity. Wheeler [14] has indicated the probability of a comparable anodic electrochemical activity occurring in portions of a metal strained by cavitation. Bernd [15], in studies of cavitation nuclei, found that rusting of low carbon steel involved galvanic action which produced gassing at a surface. Comparable gassing was not observed on stainless steel. It should be noted that the rate of cycling (1800 cpm) employed on the fatigue tests of Reference [13] is relatively slow compared to an accelerated cavitation test and that corrosive activity may accordingly be more evident. It is also noteworthy that in these fatigue tests hydrogen evolution was quite marked with aluminum alloys and steel but did not occur with stainless steel and titanium.

The mechanism of corrosion fatigue is not well known, but it appears that corrosion may be diminished by the use of an inhibited or less powerful electrolyte, by the use of a more noble metal, or by effectively sealing the active surface from the electrolyte. While it appears that these same factors are involved in cavitation damage mechanisms, only the use of more noble metals has generally been employed for control. It has, however, been known for a long time that pumps operating in oil, a poor electrolyte, experience much less cavitation damage than comparable pumps operating with water, which is a good electrolyte. Similarly vibratory cavitation damage tests using oil and oil mixtures have demonstrated a remarkable reduction in the damage of metals as compared to tests using water. Speculation that the differences were due to differing surface tensions, vapor pressures, and viscosities have not been proven by various tests. However, Poulter [12] rationalized that sealing the water away from the pore structure of the metal should accomplish the same beneficial effects as a complete oil environment. He confirmed the correctness of his reasoning by conducting vibratory damage tests in water using a cast iron specimen which was half bare and half coated with a heavy oil. He noted that "the treated half of the specimen seemed to be completely protected against cavitation erosion for the duration of the experiment which was for 24 hours or 500,000,000 cycles, whereas the other half of the specimen was badly eroded."

In the current study an attempt has been made to exploit these earlier protective findings of Poulter and to more specifically relate them to the concept of a surface sealing against outgassing. As a first phase, tests were conducted on a vibratory apparatus to confirm Poulter's observation of repeated cavitation at a common site.

In this study, which was conducted with procedures and apparatus generally similar to the standards of the ASME [16], the test fluid was distilled water and the test specimen a mild steel (1018). The vibratory frequency of 6100 cps approximated the ASME standard but the amplitude was 0.0003 in. or about 1/10 of that normally employed in a standard damage test. Higher amplitudes produced a large cavitation cloud which obscured the view of the specimen face and evidently produced surface flows which swept away the growing bubbles before they attained a recognizable size. By using the reduced amplitude, the two photographs of Fig. 2 could be taken. These photos taken at an interval of about 4 seconds and an exposure of about 400 micro-seconds show a peripheral pattern of gradually changing but essentially stationary small gas bubbles together with a large drifting central cloud of cavitation bubbles. Available strobe and photo techniques could not quantitatively define the oscillatory range of volume pulsations that these bubbles were experiencing but substantial pulsing could be anticipated. If pulsation does occur, then rectified diffusion may be expected to contribute to the rate of bubble growth and accumulated heat may accelerate chemical reactions in the surface fault which evolves the gas. The bubbles seemingly prefer to grow in concentric machining grooves in the surface. This is presumed due to the shelter that these relatively large valleys provide against sweep-off by the radially pulsing liquid flow.

The significant evidence from the photos is that bubbles are being progressively grown directly on the surface and then swept away after maintaining a position for a period that can be measured in tens of thousands of cycles. The photos show that, in dynamically more active regions when cavitation is occurring, a steel surface will continue to produce large numbers of surface bubbles but their size will be limited by sweep-off due to the local flow activity. It may also be assumed that the centers of outgassing constitute some sort of structural fault in the surface. Moreover it appears that, if cavitation pressures occur in the vicinity of these attached outgassed nuclei, vaporous expansion and collapse may occur directly at the structural fault and that maximum damage conditions may exist.

The above-described mechanism for intimate surface outgassing and consequent cavitation damage is not necessarily confined to the environment provided by a vibratory cavitation mechanism but may also occur in the large moderately damaging type of pulsing separation cavity observed by Knapp [17]. Based on analysis of high-speed motion pictures and pitting evidences observed on an axisymmetric body with a separation type of cavitation, Knapp concluded that the pulsing reentrant jet at the after portion of the large cavity caused a stagnation pressure point which repeatedly moved forward and aft along the body surface. He attributed the resulting surface damage to the collapse of discrete transient cavities which were swept into this stagnation region on the body.

The current study of outgassing suggests an alternate damage concept involving the growth of a cavity over a gassed surface fault during the low pressure phase accompanying the recession of the reentrant jet and a collapse of the cavity when the reentrant jet sweeps the stagnation point forward. This concept permits placement of the damaging cavity directly on the surface rather than in the body of the flow and further provides an environment in which pressure oscillates from near vapor to stagnation at moderate frequencies and with very steep gradients. It should be noted that a very similar reentrant jet mechanism occurs in the large pseudo-steady separation cavity which provides the damage mechanism in the rotating disk cavitation apparatus employed by the Naval Applied Science Laboratory [18].

It may also be noted that structural members downstream of cavitating propellers are exposed to the sweep of tip vortex cavities which cause a periodic pressure cycling on their surface. This pressure cycle also continuously oscillates from vapor to stagnation pressure at moderately high frequency and could well support gassed-fault damage as well as direct impingement damage.

The foregoing attempted to demonstrate that outgassing can occur on metallic surfaces as a result of both external and internal physical and electrochemical mechanisms and that such outgassing may significantly contribute to cavitation damage.

III. SURFACE TREATMENT FOR SUPPRESSION OF OUTGASSING

A. General Considerations

The foregoing discussions support the concept that most useful solid surfaces contain minute fissures and that such fissures outgas under pressure cycling either as a result of electrochemical activity or because local supersaturation of the liquid is promoted in the non-wetted apex of a fissure. If this concept is tentatively accepted, it would appear that cavitation damage on surfaces might be reduced if surface outgassing could be reduced. The following are methods which are considered capable of influencing outgassing from solid surfaces: applied non-metallic films, chemical treatment of metallic surfaces, physical treatment of metallic surfaces, and applied metallic coatings on metallic substrates.

In the discussion which follows, more detailed consideration is given to each of the above methods of surface treatment. These considerations have as a prime objective the determination of remedial methods which might be reasonably practical for application under normal naval fabricating conditions. The methods considered are, moreover, restricted to practically available materials and those which might reasonably endure under severe cavitation conditions in a salt water environment.

B. Applied Non-Metallic Films

Poulter's earlier tests demonstrated that a simple adsorbed oil film could serve to protect a readily erodible material (cast iron) in a low intensity cavitation exposure. Preliminary tests with standard ASME cavitation procedures under the current program established that adsorbed oils could not provide protection. Hence the specific problem here is to determine whether practical, thin, protective films can effectively protect against the high intensity damage exposures which are common today. Since screening tests for film effectiveness were to be conducted in a vibratory cavitation apparatus, it was obvious that the films would, in addition to other properties, have to be of a very tenacious character to endure for even a limited life.

In view of the large numbers of surface films that might be conceived, consultations were held with chemical specialists to isolate a limited number of materials for cavitation testing. As a result of these consultations five specific materials were ultimately tested. These materials and their properties are as follows:

Minnesota Mining and Manufacturing Company, FC-75

> This is a fluorochemical inert liquid of excellent high temperature stability in the presence of metals and an excellent dielectric. It is insoluble in water and wets and penetrates all surfaces with ease. A degreased and heated cavitation specimen of C 1018 mild steel was soaked for two hours and then allowed to air dry before testing.

Minnesota Mining and Manufacturing Company, FX-161

> This is a fluorochemical surfactant. It forms a tenacious, monomolecular, corrosion resistant barrier film of good heat and chemical stability. A degreased and heated specimen of C 1018 mild steel was soaked in an acetone solution of the surfactant for two hours and was then air dried and oven baked to 265°F before testing.

Minnesota Mining and Manufacturing Company, L-1495, L-1541

> These are special fluorochemical surfactants somewhat similar to FX-161 and were handled similarly except they were not oven baked.

Northstar Research Institute, Penton

> A very thin film of water-supported Penton was transferred to the prepared face of a C 1018 mild steel specimen and thoroughly dried before testing.

C. Chemical Treatment of Metallic Surfaces

It appears rather generally accepted that cavitation damage is in most cases primarily due to excessive mechanical or physical stressing and secondarily due to electrochemical activity involving corrosion. The relative importance of the electrochemical activity seemingly varies widely from that of little influence to very substantial influence depending on the conditions of exposure or test. A number of points were made earlier showing that outgassing is probably involved with this electrochemical activity and separate discussions are given to the manner in which this activity might be inhibited with non-metallic sealing films and metallic overlays. This particular discussion gives consideration to inhibiting the electrochemical activity and consequent outgassing by chemically pretreating the substrate metal to produce a new surface of more noble character. Many proprietary rust preventive treatments of this nature have been developed and are widely and effectively used in industrial practice. These include such treatments as Parkerizing, Bonderizing, passivation, etc. Most of these systems produce some form of surface film of insoluble and stable oxide or salt.

A review of available treatments of this type indicated that the films could provide a substantial amount of static corrosion protection but might be of questionable durability in severe dynamic exposures. For the current program an arbitrary choice of test specimen was selected to include a cold drawn mild steel with a commercial black oxide rustproofing treatment and a 304 stainless steel with a nitric acid type of passivation treatment [19]. The chemical treatments were further combined with physical treatment by shot peening the specimen.

D. Physical Treatment of Metallic Surfaces

It has been pointed out that the boundaries of metallic surfaces are normally provided with fissures which may serve as centers for outgassing. These fissures seem to be an inherent product of the crystallization and thermal and flexural stressing to which the surface has been exposed in its initial formation and subsequent handling. It seems apparent that fissuring is, in general, the result of a tensile condition in the surface of either a local or general character and that a revision of stresses to provide compressive conditions should materially reduce the size or number of fissures. Any reduction of fissuring should then reduce outgassing both by reduction of unwetted gassing centers and by reducing the stress concentrations at the apex of the fissures. As was mentioned earlier, it has been postulated by others that the stress values at a fracture apex are very high and in dynamic stressing are probably accompanied by high thermal, electrical, and chemical activity leading to further propagation of the fissure. These mechanisms are believed to contribute to fatigue failures. Harris [20] on the basis of fatigue tests concludes that tensile stresses in the boundary lower the internal electrode potential while compressive stresses tend to ennoble the metal and reduce corrosion. While there is no available evidence to show that provision of compressed surfaces will promote improved cavitation damage resistance, there are a number of instances where the useful life of metallic structures and fatigue test members [21] have been materially extended by surface compression.

Among the more common subjects for such treatment are flexure springs and drill rods for rock drilling. These have been given compressed surfaces to reduce fatigue crack propagation from the surface. Compression in this case is provided by peening the exterior with small shot propelled by compressed air. The theory is that the impacting shot locally expands the surface metal. The internal layers resist this expansion in biaxial tension which balances the exterior biaxial compression. The compressive stresses may exist in only a superficial film or penetrate as much as 1/4 in. depending on the velocity, weight, and hardness of the shot and the character of the metal surface. The compressive stresses achieved by this action may approximate 50 per cent of the yield strength of a steel [22]. Standard fatigue tests of materials which have been peened show higher allowable stresses or an increased life.

Comparable compressive skin stresses have also recently been achieved in the manufacture of ball bearings by heat treatment processes. Bearings produced thus are reputed to show a life at least three times the former rating when run in standard fatigue life tests.

Since shot peening is commonly employed for other uses in shipyard practice, it was deemed a practical means of pretreating ship members subject to cavitation damage. In consequence, the cavitation damage studies described later include specimens which had been shot-peened to establish the influence of compressed surfaces. The shot peening in this case consisted of two complete passes in front of an air blast gun using hardened steel shot of ≈0.05 in. diameter with blast pressures varying from as low as 10 psi to as high as 75 psi. In some instances the higher peaks of the dimpled surfaces were removed by surface grinding prior to cavitation testing. These peaks were presumed to be uncompressed.

E. Applied Metallic Coatings on Metallic Substrate

The use of metallic overlays that have protective characteristics greater than those of the structural substrate metal is probably the most effective procedure currently available for retarding cavitation damage in prototype installations. Few structures exposed to cavitation can afford fabrication entirely of the expensive substrate materials which are resistant to cavitation damage nor is this necessary where the surface area subject to cavitation is only a small percentage of the total. It is, therefore, more practical to fabricate with a metal which is an economic answer to the structural or corrosion needs of the device and locally provide additional protection where cavitation damage is anticipated.

Numerous attempts have been made to provide the desired protection with solid and elastomeric non-metallic overlays as well as metallic overlays. None of the solid non-metallics studied to date appear to have adequate resistance to damage for severe exposure conditions. Some of the elastomeric coatings have shown excellent resistance in laboratory studies but appear to fail under field conditions. The field failures are associated with the bond between the coating and the substrate rather than with the coating itself. Metallic coatings when of adequate thickness and properly anchored or bonded exhibit protection consistent with the inherent resistance of the coating material. For the better materials, these overlays afford protection which is adequate for most current exposure problems. For moderately severe exposures, good protection is offered by such materials as stainless steel and aluminum bronze. For severe service, various tool steel and hardfacing alloys of iron, nickel, borium, silicon, cobalt, chromium, tungsten, molybdenum, and titanium are required to resist the damage. In a few instances, these resistant materials have been applied as sheet overlays with mechanical fastenings or cementing but difficulties with forming, edge fairing, attachment, corrosion, etc. do not make such procedures generally practical. Attempts [23] have also been made to apply these resistant materials by metallizing or spraying but inadequate bond is developed unless atomic fusion is achieved by the use of high temperatures. This is in effect a welding process.

The most practical overlay procedure to date is the brazing or welding of the alloy to the substrate. In the case of structural assemblies which are weldments, the overlay may be applied either before or after the forming of the piece. It is generally more practical to do this after the assembly but for complex shapes, the necessary fusion temperature (>1800°F) may lead to excessive stressing and distortion of the body. Moreover, the resistant weld overlay is inherently rough and required surface grinding to achieve a suitable hydraulic smoothness. For stainless steel and alloys of similar hardness, grinding is practical but for the more resistant alloys, grinding is impractical.

The foregoing considerations of the use of metallic coatings to enhance cavitation resistance has related primarily to a substantial coating which has inherent resistance characteristics suitable to the needs. Apparently little has been done to determine the effectiveness of thin coatings intended for modification of the chemical rather than the structural character of the surface. Such a coating should be an inherent corrosion protector for the substrate and should additionally reduce the chemical activity of the substrate with respect to outgassing. If its inherent strength and deformation characteristics are low, it should be capable of transferring mechanical stress to the substrate without failure of its attachment bond. A review of methods of applying such coatings to metals indicated that electroplating might offer a practical solution and that zinc might be a preferred metal. The reasons for this are:

1. Electroplate deposition of metal is a well developed technique about which considerable is known.
2. Most plating relates to small parts handled in special shop vat procedures. There are, however, techniques (the Dalic process) which will permit quality field plating of large structures without submersion baths.
3. Standard fatigue tests have shown that plating of a steel surface with chromium or nickel will usually markedly lower the fatigue strength. On the other hand, zinc plated surfaces, while providing only a modest reduction in standard air fatigue test values, are very beneficial in corrosion fatigue tests on

steel [24]. Since both stress fatigue and corrosion fatigue are believed to have an involvement in cavitation erosion, plated zinc would appear to have merit as a coating.

4. Unlike chromium or nickel plate which results in a high tensile stress and small inherent cracks in the plating, zinc plate is generally compressive and uncracked.

5. Zinc plating affords full protection against saline corrosion for a reasonable time. In the event of mechanical damage to the zinc coating and exposure of the base steel, galvanic protection of the steel will continue with sacrificial loss of the surrounding zinc as an anode. If a metal more noble than the steel is used, accelerated corrosion of the steel would occur at any breach in the coating.

6. In proper zinc cleaning and plating processes, the bonding of the zinc to the steel is approximately atomic in character and the work may be formed and bent without scaling of the plating.

7. Zinc plating yields a relatively gas impermeable cover and presumably harbors fewer crevices for outgassing origin.

In view of the favorable features of zinc plated surfaces, such surfaces have been included in the comparative damage resistance tests which are described later. The tests also included samples exposed to both plating and shot peening, a combination which has shown distinct advantages in fatigue tests [24]. It is to be noted that the available cyanide type of zinc plating which was used does not provide as good film compression as other types of plating procedures [20].

IV. EXPERIMENTAL TESTS

The cavitation tests were conducted in general accord with the ASME standard procedures [16] using a vibratory apparatus with an amplitude of 3.4×10^{-3} in. and a frequency of 6100 cps. The tests were conducted either with distilled water or with a 3 per cent solution of NaCl in distilled water as a variation in electrolytic values. In one instance mineral seal oil was used.

The test specimens were made of either C 1018 cold drawn mild steel or a work hardening type of non-annealed cold drawn 304 stainless steel. The exposed ends of the test specimen were lathe turned in a common manner which resulted in a spiral small groove finish. In some instances the specimens were surface ground approximately 0.002 in. either to remove the machine tool marks or to remove the bulk of the dimple ridges resulting from shot peening.

The various surface treatments applied to the specimens were detailed previously and the various combinations of specimen and treatment as tested are listed in Table I. Typical quantitative evaluations of the damage are shown by weight loss curves in Figs. 3, 4, and 5. In several of the weight loss tests the influence of the applied surface treatment appeared to be insignificant. For these materials no comparative curves have been shown.

V. DISCUSSION OF TEST RESULTS

A. Influence of Non-Metallic Thin Films

None of the five thin film materials which were used contributed significant benefits in terms of weight loss erosion in a standard vibratory cavitation test. Limited evidence indicated that the films were in all probability removed in the very early stages of exposure to cavitation. This is seemingly contradictory in that if the films were effective in sealing the surface against outgassing and cavitation, there presumably should be no damaging forces to remove the protective film. Unfortunately, a vibratory apparatus, unlike most flow generated cavity mechanisms, permits repetitive pressure cycling on unsealed water-borne particulate near the boundary and the cavitation continues despite any depressive characteristics of the specimen itself.

Thus the standard vibratory cavitation test may serve as a practical means of evaluating the very longtime merit of the films but failed to establish the influence of outgassing on the failure mechanism or to establish the rates of loss in a more real flow generated cavitation environment.

Figure 3 shows the greatly reduced damage when using oil rather than distilled water or salt water on cavitation erosion. It emphasizes the potential values that lie in obtaining a better understanding of the role that oils and films must play in erosion control. This is true despite the fact that the current vibratory tests failed to disclose an adequate type of film.

Figure 3 indicates that ground specimen X-2 sustained somewhat more weight loss than the standard machined specimen X-1.

Table I

SUMMARY OF EXPERIMENTAL TEST CONDITIONS

Specimen No.	Material	Surface Treatment	Fluid	Figure
X-1	C 1018	Plain	Distilled	Fig. 3
X-2	C 1018	Ground after machining	Distilled	Fig. 3
11	C 1018	Ground after machining	3 per cent NaCl	Figs. 3,5
12	C 1018	Peened at 10 psi	3 per cent NaCl	Fig. 3
13	C 1018	Black oxide	3 per cent NaCl	-
16	C 1018	Zinc plated	3 per cent NaCl	Fig. 3
17	C 1018	Zinc plated and peened at 10 psi	3 per cent NaCl	Fig. 3
19	C 1018	Peened at 20 psi, then ground	3 per cent NaCl	-
27	C 1018	L-1495	Distilled H_2O	Fig. 5
28	C 1018	FC-75	Distilled H_2O	Fig. 5
29	C 1018	L-1541	3 per cent NaCl	Fig. 5
31	C 1018	FX-161	3 per cent NaCl	Fig. 5
30	C 1018	Plain	Mineral seal oil	Fig. 3
NS1	C 1018	Penton	3 per cent NaCl	-
25	SST 304	Plain	3 per cent NaCl	Fig. 4
21	SST 304	Peened at 10 psi	3 per cent NaCl	Fig. 4
22	SST 304	Passivated	3 per cent NaCl	Fig. 4
24	SST 304	Peened at 10 psi and passivated	3 per cent NaCl	Fig. 4
32	SST 304	Peened at 75 psi	3 per cent NaCl	Fig. 4
33	SST 304	Peened at 75 psi, then ground	3 per cent NaCl	Fig. 4

B. Influence of Chemically Treated Surfaces

Neither the black oxide treatment of mild steel nor the passivation treatment of a stainless steel appeared to significantly influence the cavitation erosion of these materials.

C. Influence of Physically Treated (Shot Peened) Surfaces

Light (10 psi) shot peening of a mild steel appeared to have relatively little influence on the rate of a subsequent cavitation erosion. A somewhat heavier (20 psi) shot peening of a mild steel followed by surface grinding to remove the dimples also failed to significantly change the rate of erosion when compared to an untreated specimen. It is inferred from this that creation of a compressed surface by shot peening does not in itself materially influence the cavitation erosion characteristics of a mild steel in salt water.

Light (10 psi) shot peening of a work hardening stainless steel drastically reduced the normal rate of cavitation erosion. However, heavy (75 psi) shot peening drastically increased the normal rate of erosion. Heavy shot peening followed by surface grinding of the dimples produced an even greater erosive loss than heavy peening alone. It is inferred from this that low level peening or working of a work hardening stainless steel upgrades the hardness or stress values beneficial to erosive protection but high level peening overworks and degrades the structure. It has long been known [25] that cavitation itself upgrades and hardens a material of this type but the evidence of additional upgrading due to prior selective shot peening as evidenced in Fig. 4 is believed to be new. Table II gives related hardness values for specimens 21, 25, 32, and 33 whose characteristics are given in Table I and whose erosive properties are given in Fig. 4.

Table II

HARDNESS EVALUATIONS FOR PEENED AND CAVITATED STAINLESS STEEL 304

Specimen No.	Surface Treatment	Test Location: Back	Test Location: Front Where Eroded	Test Location: Front Where Not Eroded
21	Peened at 10 psi	90.5	94.4	94.3
25	Plain	-	88.6	91
32	Peened at 75 psi	-	93.9	95.8
33	Peened at 75 psi, then ground	-	93.4	95.3

Note: All hardness values were measured with a Rockwell 15-T test procedure and the values shown are the average of either five or six separate tests. The specimens were treated in accord with Table I and the hardness tests were run after the complete cavitation exposure shown in Fig. 4.

D. Influence of a Zinc Plated Surface

A mild steel specimen with zinc plated surface experienced a slightly greater cavitation erosion rate than an unplated specimen. The increased rate is believed to be mainly due to the early removal of the relatively soft and erodible zinc rather than to any basic change in the rate of erosion of the substrate.

VI. CONCLUSIONS

A rationale and selected experimental evidence supports the tentative conclusion that surface outgassing may contribute significantly to erosive damage in metals exposed to cavitation. It is further indicated that suitable surface treatments might materially reduce this surface outgassing and consequent cavitation damage. Unfortunately none of the surface treatments investigated under this program provided significant cavitation protection in tests conducted on a standard vibratory apparatus nor did this type of apparatus permit a clear determination of the role played by surface outgassing.

Although this investigation in general failed to find suitable means for reducing cavitation damage, it has afforded an opportunity to re-expose certain aspects of the cavitation mechanism which have been long observed but little explored. The marked reduction in cavitation damage in oil systems remains a challenging mystery.

The tests did clearly show that a work hardening type of stainless steel could be very substantially improved in resistance to cavitation erosion by suitable shot peening of the surface.

It may be concluded that the protective cavitation damage evidences disclosed earlier by Poulter when using an oil film and a low intensity test facility are not effective for materials exposed to high intensity vibratory cavitation.

VII. ACKNOWLEDGMENT

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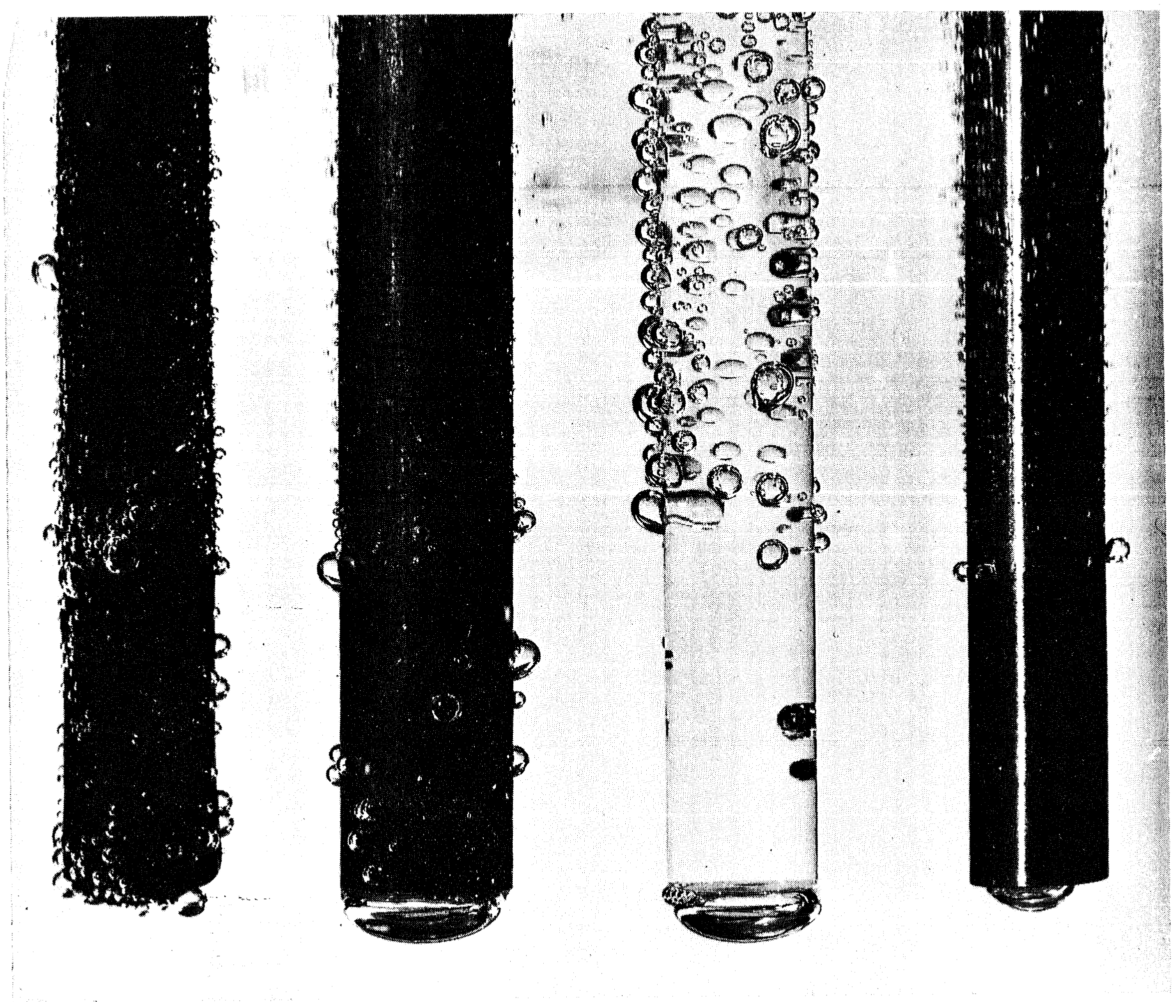
F I G U R E S

(1 through 5)



a b c d

Fig. 1 - Outgassing From Solid Surfaces

The solids shown are: (a) neoprene coated steel, (b) bare brass, (c) plexiglas, and (d) steel drill rod. The lower ends were dipped into Texaco Waylube G oil prior to immersion in soda water.

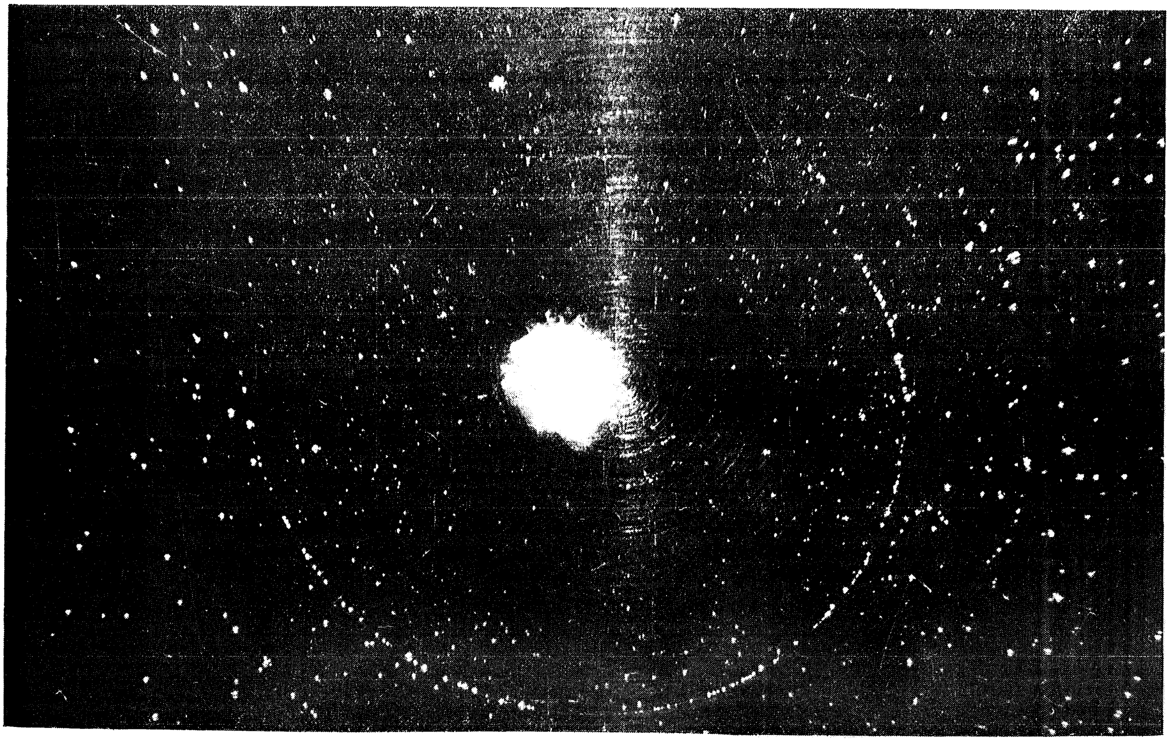


Photo 1 - Time = 0 sec

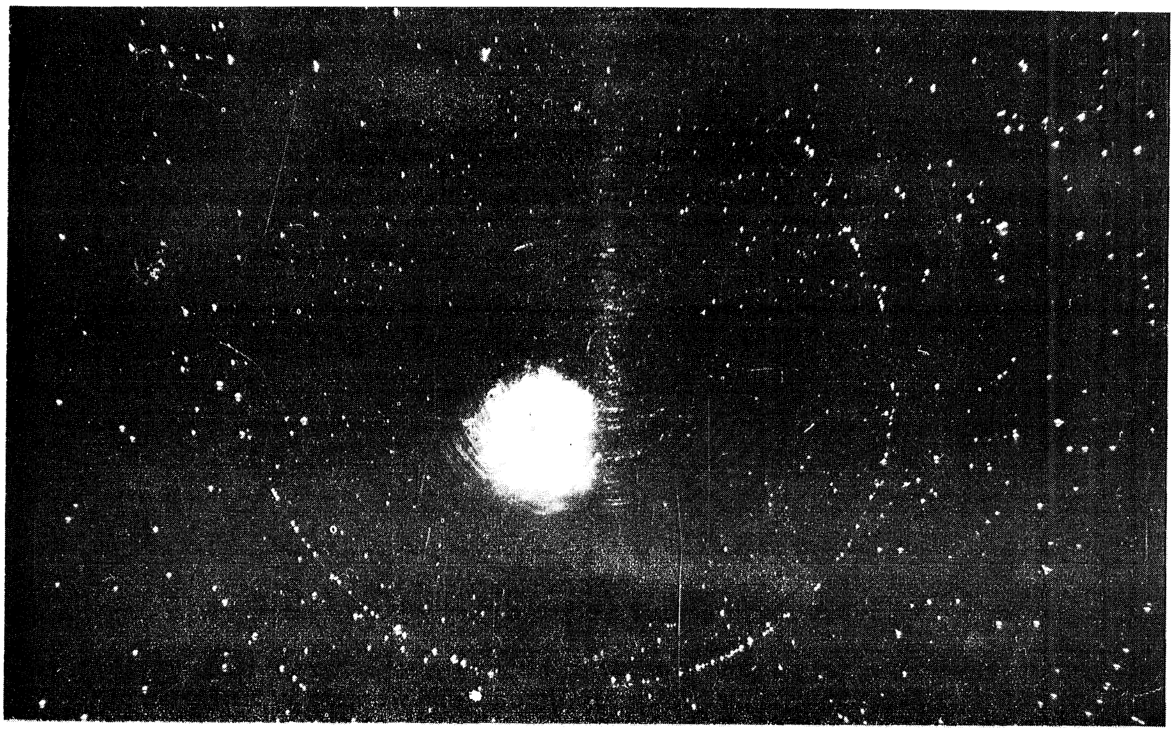


Photo 2 - Time = 4 sec

Fig. 2 - Outgassing Bubbles on the Face of a Steel Specimen Vibrating at 6100 cps with an Amplitude of 0.0003 inch (each picture height represents about 1/4 inch in full scale)

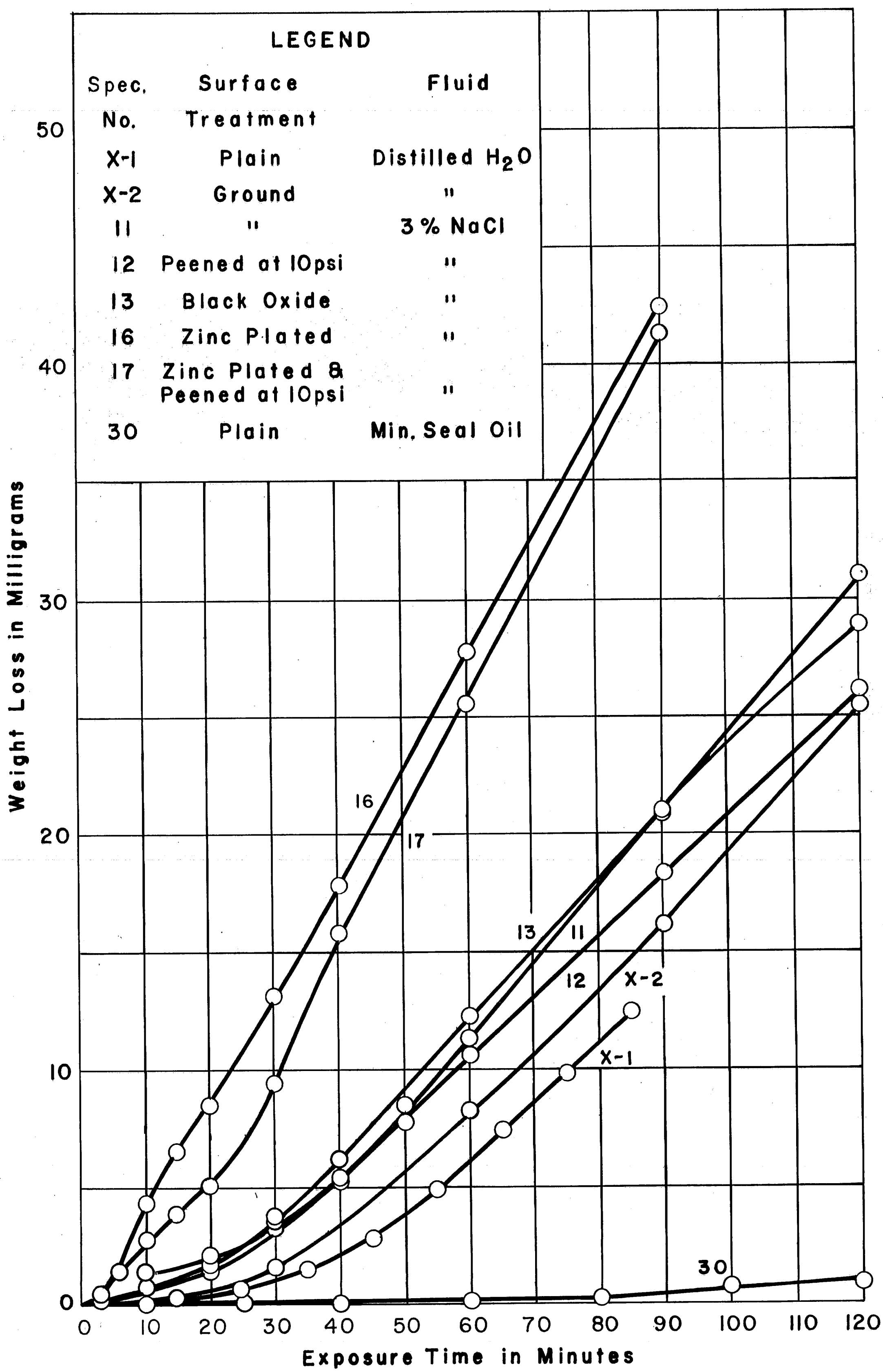


Fig. 3 - Erosive Weight Loss as a Function of Cavitation Exposure Time for Mild Steel, C 1018, with Various Liquids and Plain, Oxidized, Peened, and Plated Surfaces

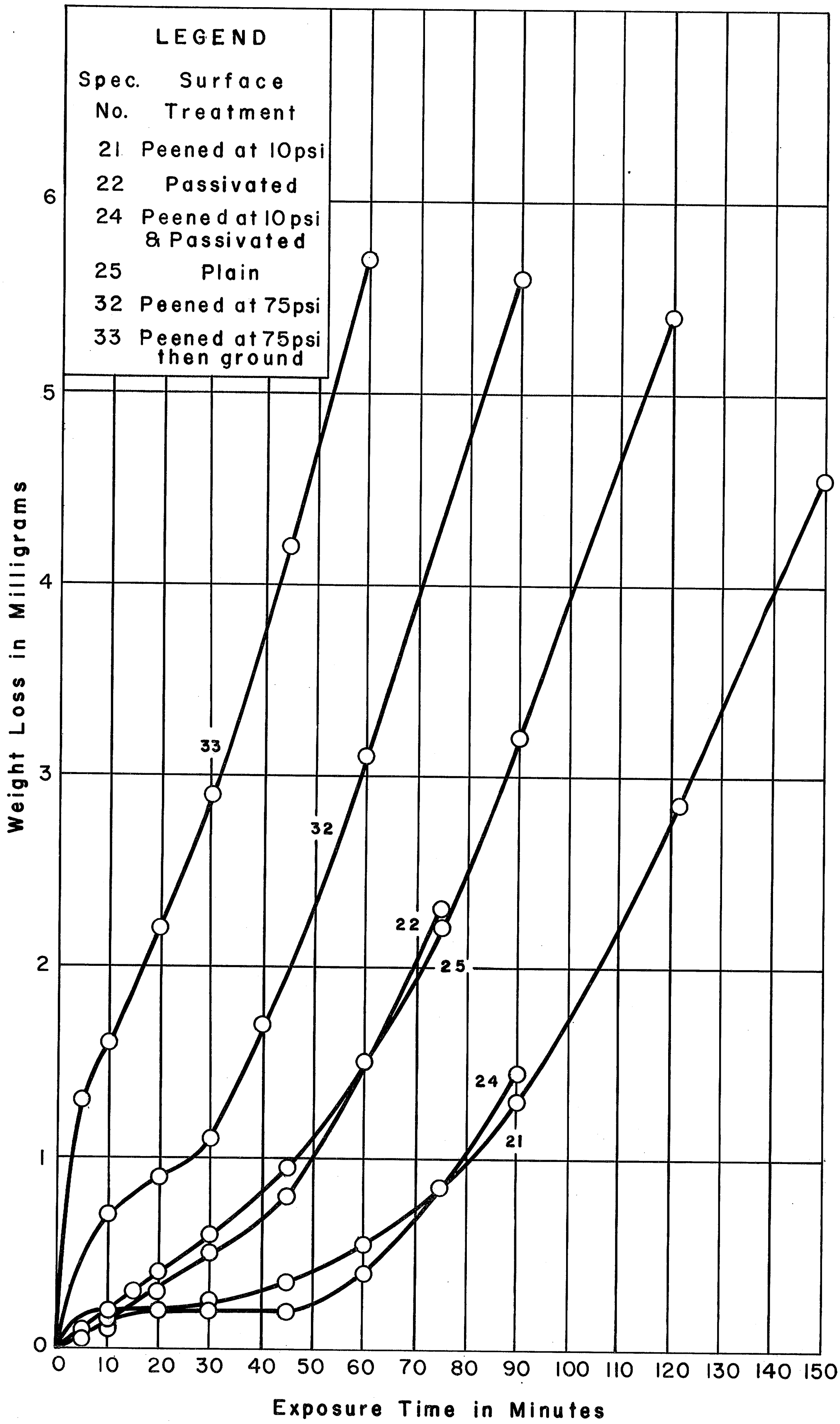


Fig. 4 - Erosive Weight Loss as a Function of Cavitation Exposure Time for Stainless Steel 304 in Salt Water with Various Surface Treatments

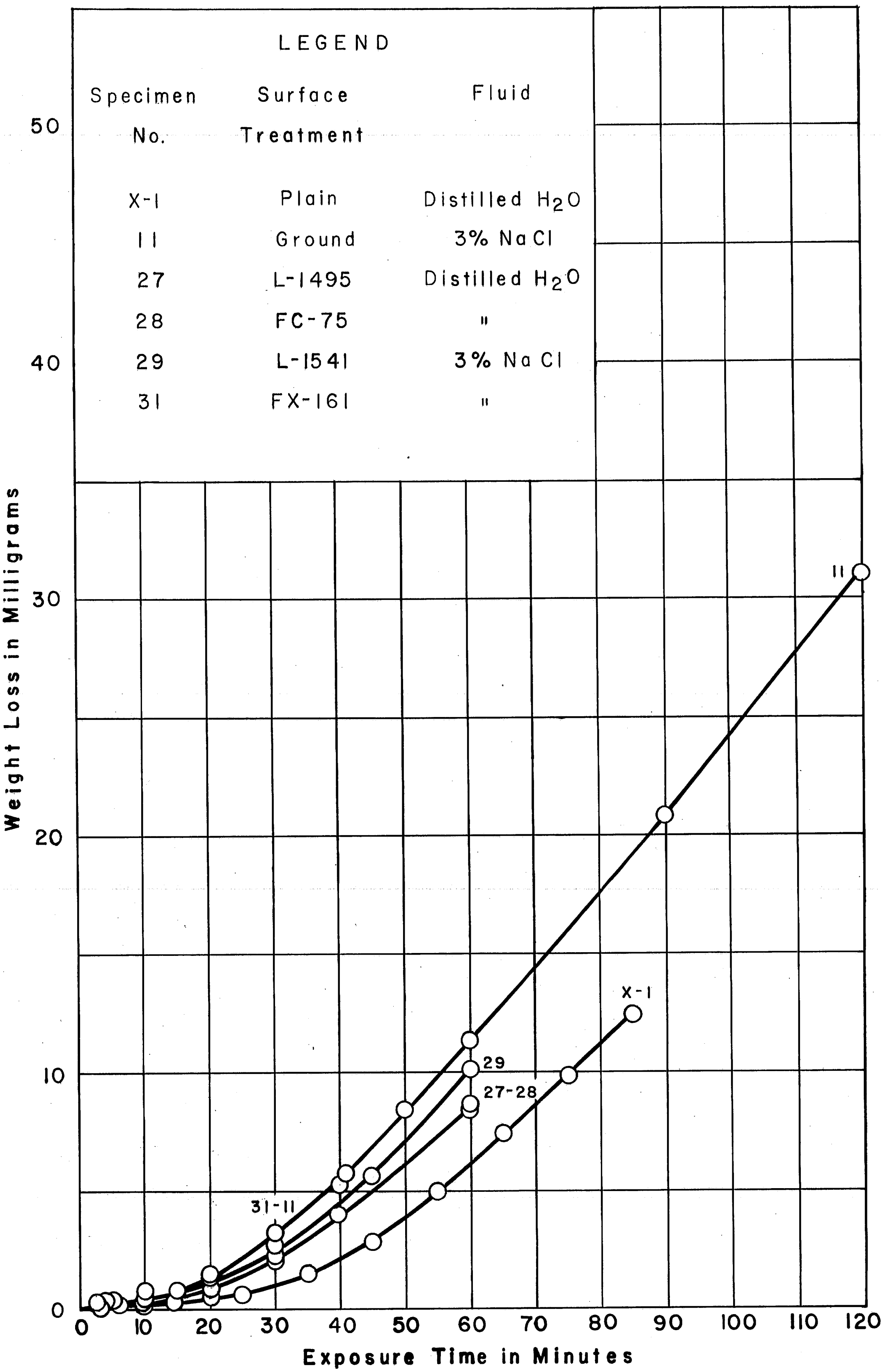


Fig. 5 - Erosive Weight Loss as a Function of Cavitation Exposure Time for Mild Steel, C 1018, with Various Liquids and Plain and Non-Metallic Films

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A rationale and selected experimental evidence indicate that surface outgassing may contribute significantly to erosive damage in metals exposed to a cavitation environment. The possibility of inhibiting outgassing and consequent cavitation erosion by suitable surface treatments is experimentally examined. Tests of various surface treatments on an ASME type vibratory test apparatus failed to disclose significant benefits except in the case of a work hardening steel treated by shot peening.

It is concluded that Poulter's earlier findings on protective films do not hold for metals exposed in a high intensity cavitation test facility.

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