NBS SPECIAL PUBLICATION 394

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

The Role of Cavitation in Mechanical Failures

MFPG

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The Role of Cavitation in Mechanical Failures

Proceedings of the 19th Meeting of the
Mechanical Failures Prevention Group,
held at the
National Bureau of Standards,
October 31, November 1 and 2, 1973,
Boulder, Colorado 80302

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t. Special publication no. 394

The 19th meeting of MFPG and these proceedings were sponsored by the Office of Naval Research, the National Aeronautics and Space Administration, and the Institute for Materials Research of the National Bureau of Standards.

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

Issued April 1974

Library of Congress Cataloging in Publication Data

Mechanical Failures Prevention Group.
The role of cavitation in mechanical failures.

(National Bureau of Standards Special Publication, 394)
Papers presented at the meeting, held Oct. 31-Nov. 2, 1973 in Boulder, Colo.
Supt. of Docs. No.: C 13.10.394
1. Erosion of metals--Congresses. 2. Cavitation--Congresses. I. Shives, T. R., ed. II. Willard, William A., ed. III. Title. IV. Series: United States. National Bureau of Standards. Special Publication, 394.
QC100.U57 no. 394 [TA460] 389'.08s [620.1'6'6] 74-7057

National Bureau of Standards Special Publication 394
Nat. Bur. Stand. (U.S.), Spec. Publ. 394, 183 pages (Apr. 1974)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1974

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.10:394). Price $2.25

FOREWORD

The 19th meeting of the Mechanical Failures Prevention Group was held October 31 and November 1 and 2, 1973, at the National Bureau of Standards in Boulder, Colorado. Under the chairmanship of Professor Elmer E. Klaus, the MFPG technical committee, Mechanisms of Failure, organized the program for the meeting. We commend Professor Klaus, the session chairmen, and especially the speakers for an excellent program.

In addition to the abstracts of the talks, which are presented as submitted except for very minor editing in a few cases, these "Proceedings" include the discussions of the talks. These discussions were recorded at the meeting and have been edited to improve readability.

Special appreciation should be extended to Mr. T. R. Shives and Mr. W. A. Willard of the NBS Metallurgy Division for their editing, organization, and preparation of the "Proceedings", Mr. Kenneth Armstrong of the Boulder Special Activities Office of NBS for the meeting arrangements, Mr. H. C. Burnett of the NBS Metallurgy Division for general coordination, and the entire staff of the Metallurgy Division and the Institute for Materials Research for their assistance in many ways. Special thanks are accorded Miss Bronny Evans of the Metallurgy Division for her diligent efforts in transcribing the recorded discussions.

ELIO PASSAGLIA
Executive Secretary, MFPG

Chief, Metallurgy Division
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TABLE OF CONTENTS

ABSTRACT

These proceedings consist of a group of sixteen submitted papers and discussions from the 19th meeting of the Mechanical Failures Prevention Group which was held at the National Bureau of Standards on October 31 and November 1 and 2, 1973. The central theme of the proceedings is the role of cavitation in mechanical failures.

Key words: Bubble collapse; cavitation; cavitation damage; cavitation erosion prevention; erosion; surface roughness.

SESSION I

Chairman: E. E. Klaus
The Pennsylvania State University

PHYSICS ASSOCIATED WITH CAVITATION INDUCED MATERIAL DAMAGE

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The role of cavitation in mechanical failure is extremely complex and in many aspects is very imperfectly understood. Some of the most common types of material damage associated with the presence of cavitation are surface material removal, delamination and structural vibration. This occurs in external flows such as on propellers, hydrofoils, and high speed non-lifting surfaces. In internal flows, pipe bends, inlets, constrictions, pumps and turbines are typical. Nominally nonflowing liquids are also susceptible in, for example, strong acoustic fields and high energy particle detectors.

For flowing systems, Bernoulli's equation shows how a local pressure is reduced as the fluid's velocity is increased. At sufficiently high velocities, a tension can actually develop and this has, in fact, been demonstrated experimentally. Once the pressure is reduced below the fluid vapor pressure a vapor cavity can be nucleated. Various aspects of this process are simply shown by considering the flow over a lifting surface. When the flow is completely unseparated, cavities will be generated in the low pressure region and will translate along the surface. These cavities are frequently quite large and can produce material damage. If the flow is separated then a stationary cavity is produced which remains fixed on the surface. When this fixed cavity becomes sufficiently large the downstream portion breaks up into many small vapor cavities and these nominally spherical cavities then collapse in the high pressure region. It is this process that typically can produce very intense erosion, noise and vibration. It should be noted, of course, that this separated flow can be the result of both gross boundary layer separation and isolated local roughness elements on the body. When the cavity length is increased to the point where the collapse occurs downstream of the body, then damage will typically occur only on a downstream surface that is in the collapse region. The basic ideas just discussed can be applied to both internal and external flows with only minor modifications for most situations.

Cavitation in acoustic fields is to some extent similar to the unseparated flow situation just discussed because both require a continuous supply of "weak spots", or nuclei, to produce the cavities. Herein lies one of the key aspects with regard to the extent of material damage for various fluids in cavitating systems. If separated flow exists, one nucleus may be all that is required to produce a fixed cavity and the subsequent generation of many smaller vapor cavities. Once this fixed cavity is formed, the local flow properties of the system are changed and the cavity can be eliminated only by a significant increase in system pressure or a decrease in flow velocity (i.e., a hysteresis effect). Conversely, when many nuclei are present, and the flow is unseparated, then very little hysteresis is experienced.

There are many methods by which cavities in a fluid can be nucleated. Some of the most common would include, noncondensable gas bubbles in the liquid, noncondensable gas trapped in particulate matter or in cracks on a solid surface, a solid with low surface-free energy, and high energy particles. If microbubbles are present, then their path in both an acoustic field or a flowing system will be influenced by the local pressure gradients. In a flowing liquid, this is the so called "screening" effect. If a microbubble is subjected to fluctuating pressures due to turbulence or an acoustic field, then a dramatic increase in bubble volume is possible. This is possible since at low pressure the surface area is greater than during the high pressure phase and thus there is a net diffusion of gas into the bubble (rectified diffusion). In addition, nonuniform pressure fields develop microscopic flow around the bubble and change the diffusion potential across the bubble wall (microstreaming). Thus, it is seen that the position and size of a bubble can be highly dependent on the time and pressure history of the liquid. When these microbubbles enter a region of local pressure equal to or less than the liquid vapor pressure, their size will determine their stability and thus the nucleation process.

Of particular importance in water is the role of hydrophobic particles that contain some noncondensable gas. It has been shown by several investigators that this particulate can be produced de novo in the water and will be stabilized and of essentially neutral buoyancy. (Summarized in ref. 1).

In the special case of water, nucleation should be relatively easy unless extreme purification measures are taken.

In both hydrodynamically and acoustically generated cavitation it has been experimentally verified that cavities can be nucleated on the solid surface bounding the fluid. This process can be initiated by, for example, noncondensable gas trapped in a crack, gas generated from electrochemical activity, external addition of heat, regions of low surface-free energy, or the previous collapse of a cavity on the surface that left a small quantity of gas or particulate matter.

Certainly with all of these various mechanisms available to nucleate a vapor cavity it is not difficult to understand the relative ease with which most common liquids cavitate when subjected to at most several atmospheres of tension. Once a vapor cavity has formed its subsequent collapse can be highly dynamic and the possibility of material damage is present. The extent of material damage is known to be basically the result of both the mechanical and electrochemical properties of the solid. Although the details of the processes are very poorly understood, it has been shown that at the termination of the cavity collapse, a shock wave in the liquid can be produced. In addition, when other surfaces, or pressure gradients are present, early in the collapse an asymmetry in the initially spherical shape occurs. This leads to the involution of one part of the surface and the formation of a liquid jet that passes through the collapsing cavity. For sufficient symmetry of shape to be maintained such that a shock is produced, the cavity must be away from a solid surface. Thus significant attenuation of the shock occurs before it impacts on the surface. When the cavity is initially near or on the solid then the jet most probably represents the significant mechanism for mechanical material damage. It has been observed that the most extensive damage is apparent when the jet strikes the solid directly and does not have to pass through any intervening liquid. For cavitation in an acoustic field there is now strong evidence suggesting that most damage is due to the repetitive growth and collapse of a cavity at the same location on the solid surface. This discovery may help account for the fact that acoustically generated cavitation produces an accelerated damage rate compared with the hydrodynamically generated cavitation. It should also be mentioned, in relation to the previous comments, that there has been no observed cut-off in bubble size for the damage production.

Clearly, the actual mechanism by which a material fails, following an impact, is neither simple nor identical for all solids. However, in order to help obtain a better insight of the mechanical damage process, even simplified views have their merit - particularly if no more exact explanation is available. As a first approximation, solids can be considered to fail first either in shear (ductile material) or in tension (brittle material). For materials that nominally remain ductile it can be shown that there is some combination of material properties and impact pressure such that the solid responds as a viscous liquid, (ref. 2). In essence, when the shear stress (τ_{max}) is sufficiently high the shear modulus goes to zero and rapid plastic flow will occur. Table I gives the limiting particle velocity of the solid $(U_{ps})_{limit}$ above which this phenomena will be present, for various liquid-solid combinations. This type of deformation is commonly observed and has been used to qualitatively indicate the intensity and diameter of the impacting jet. From the tabulated data one can qualitatively see the importance of both the solid and the liquid physical properties.

When the solid typically fails in a brittle manner or when the liquid impact velocity is insufficient to produce hydrodynamic deformation, then some indication of the stress distribution in the solid is useful. This can be done quite easily with the following assumptions: (1) only elastic deformation occurs, (2) the impact pressure has a hemispherical distribution with the maximum impact pressure determined by the Rankine-Hugoniot relations, and (3) the impact pressure has a duration sufficiently long to allow a quasi-steady state to exist. The third assumption is the most critical because the impact must last sufficiently long to allow the stress wave to travel a distance such that the stress levels are quite low, (see summary in ref. 2). Recent numerical and experimental efforts have shown that to a first approximation this assumption is acceptable since the jet impact times have been estimated to be of the order of 1×10^{-6} seconds. Figures 1 and 2 show the variation of the maximum shear stress and one of the principal stresses, respectively, and the manner in which they vary within the solid. The principal results are as follows: (1) the impacted surface is under compression and thus should not fail, (2) the maximum shear stress is within the solid and below the impacted region and thus shear failure will occur beneath the surface, and (3) surface tensile stresses are present <u>outside</u> the impacted region and thus brittle failure can start at the surface. These same conclusions were reached when single impacts were experimentally studied for alumina, glass and plastic. Interesting enough, glass has also been observed to have the above forms of failure when the impact duration was only of the order of 10^{-8} seconds. In any event, much more study of the modes of material failure are necessary to understand the mechanical aspects of the damage process.

In addition to mechanical damage, many investigations have shown that electrochemistry can also have a significant role in the damage mechanism. As an example of the interrelation between cavitation and electrochemistry, it is instructive to review some particular experimental results, (reference 3). In this experiment, a stationary specimen was located in a cavitating acoustic field. The subsurface properties: mosaic block size (i.e., subgrain size), microstress, and density of dislocations, were determined by X-ray analysis for plain carbon steel with a 8-16 μ inch finish. These properties were compared for "neutral", cathodic and anodic specimens. All of these measurements were made in the so-called "incubation" period prior to any significant material removal. The results are shown in Table 2. They demonstrated that the cathodic specimen was not measurably different from the specimen having zero impressed current; both had significantly altered subsurface properties due to cavitation. However, the anodic specimen had very little subsurface property change due to cavitation but did have a shorter incubation time. After the incubation period, the anodic specimen maintained a relatively smooth surface whereas the other two specimens developed a cratered surface. The application of the impressed currents resulted in a lower surface microhardness compared to the zero current condition, with the anodic specimen having the smallest microhardness increase.

From many other tests it has been shown that materials with a low corrosion resistance experience greater cavitation erosion when the corrosivity of the liquid increases. Two of many possible explanations would be that (1) the generation of microscopic galvanic action by material microstress gradients and (2) the continuous cathodic depolarization of existing oxygen concentration cells by high cavity collapse induced velocities.

In summary, it can be seen that the physics associated with cavitation induced material damage is by no means completely understood. Our understanding of the processes is just emerging and as more definitive information becomes available, our options in the design process will become more apparent.

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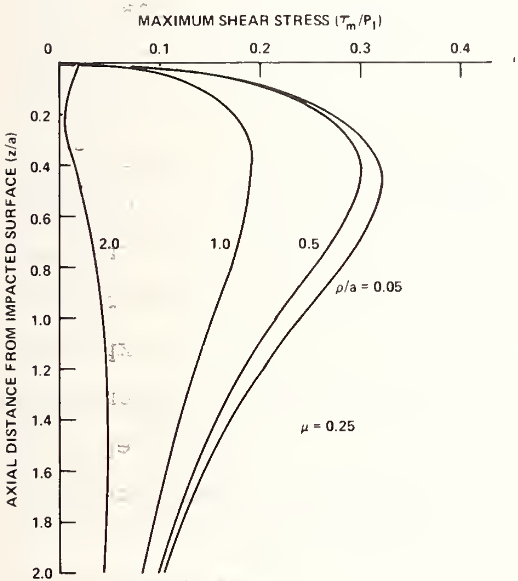

FIGURE 1. Variation of maximum Shear Stress (τ_m) with Radial and Axial Distance from Point of Impact.

SOLID	LIQUID	τ_{MAX} IN KILOBARS	$(U_{P_s})_{LIMIT}$ IN METERS/SEC	$\frac{U_{P_s}}{(U_{P_s})_{LIMIT}}$
Pb	H_2O	0.124	5.6	1.3
Pb	NA	0.124	5.6	1.6
Pb	Hg	0.124	5.6	8.0
AL 5456-H117	H_2O	1.86	44.4	0.20
AL 5456-H117	NA	1.86	44.4	0.27
AL 5456-H117	Hg	1.86	44.4	1.2

TABLE 1. Hydrodynamic Deformation for Various Liquid-Solid Combinations with Liquid Particle Velocity Equal to 100 m/s.

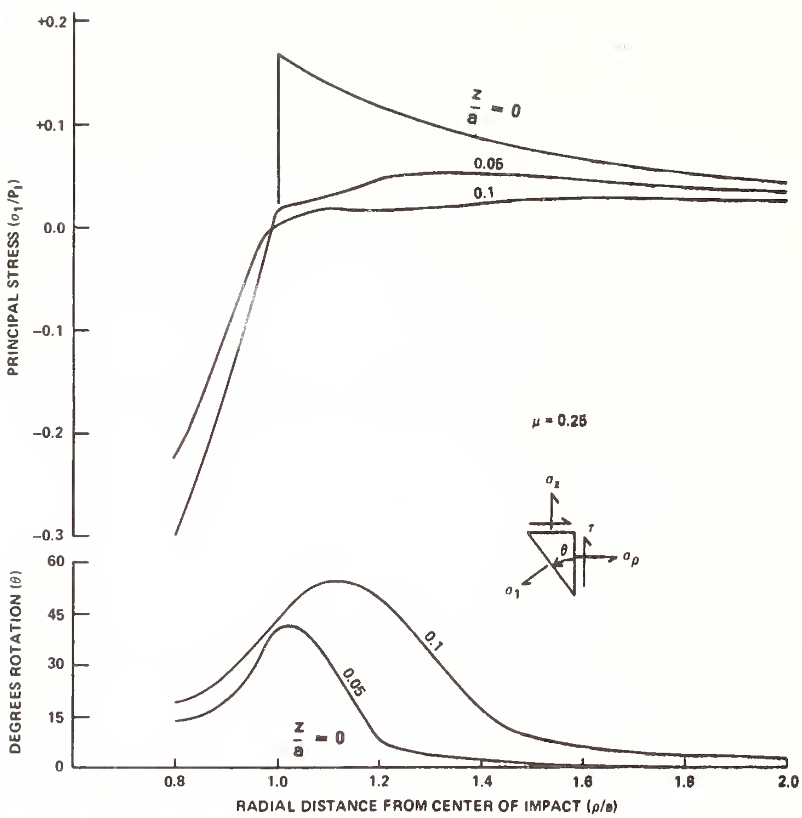

FIGURE 2. Variation of Principal Stress $(\sigma./_{P.})$ and its Direction (Θ) with Radial Distance from Center of Impact.

TABLE 2. Changes in Microscopic Substructure During Incubation Period for ST 3 Steel (USSR).

		(Specimen as Cathode)	(Specimen as Anode)
Impressed current	0	0.079 a/cm^2	0.079 a/cm^2
Mosaic block size	∿ 30% dec.	∿ 30% dec.	∿ 4% inc.
Microstress	∿ x 10 inc.	∿ x 10 inc.	no change
Density of dislocations	∿ x 10^4 inc.	∿ x 10^4 inc.	∿ x 2 inc.
Incubation time	105 min.	120 min.	75 min.

DISCUSSION

C. M. Preece, State University of New York, Stony Brook: You said that the ductile materials seem to be quasi-viscous and that there didn't seem to be any plastic deformation, that the deformation was elastic. If there is a tremendous flow on the surface, it's permanent and therefore it must be plastic. In our own studies, we have found an incredibly high dislocation density in this surface which is more indicative that the deformation is plastic, not elastic. Do you have any comments on this?

F. B. Peterson: Yes, I agree with you 100%. Apparently I gave you the wrong impression. What I was trying to say is, that the material deforms as if it's viscous. It is plastic deformation without a doubt since, as we just pointed out, the deformation is permanent. I think I said in the beginning that there were smooth pits that remained after the impact, and that was the particular situation I was describing. I was only talking about the initial deformation of the solid. Certainly it is all based upon the impact velocity, the particle velocity of the liquid, and as the impact progresses, this velocity decreases. Then it would slowly drift out of this so called hydrodynamic (my definition) deformation and go into just elastic-plastic deformation.

J. Bonnin, Électricite de France: I must mention two points. You noted that water is a unique liquid. I think that as far as the nucleation is concerned, we cannot find any experimental liquid in which we can find nuclei like in saline water. The second point concerns particle size. You have mentioned particles as small as 0.2 μm. I have found in the literature that Greenspan spoke of particles as small as 0.01 or 0.02 μm.

F. B. Peterson: I believe you were agreeing with me that water is a unique fluid. You mentioned that you've seen references pertaining to the measurement of particles which are as small as 0.01 to 0.02 μm. For particles of that size, assuming that they are solid and unwetted by water, a theoretical calculation indicates that it would take something like 100 atmospheres of tension to cavitate.

J. Bonnin: But if such particles can be removed, negative pressures up to some 200 atmospheres can be obtained.

F. B. Peterson: I agree. That was purely a theoretical calculation if the cohesive bond is broken. But you're saying that the cohesive bond doesn't have to be broken because there are solid particles in the fluid. I was saying that if there are no solid particles, there is an absolutely perfect fluid, in this case water.

G. O. Ellis, Vickers Division, Sperry Rand Corporation: I am interested in the van der Waals' equation which indicates a large tensile stress, and then a positive stress or a positive pressure. When passing through the meniscus, there is a large negative pressure that indicates that there can't be cavitation, but then there is a significant positive pressure, I believe about 750 atmospheres. I would assume that at a certain bubble size there would be a high positive pressure. There are theories that say that water has a crystalline structure for a few molecules, and so it may not be a bubble that forms, but rather a rip or a tear. I wonder what you think of that theory?

F. B. Peterson: With regard to the van der Waals' forces, the consideration that I was really talking about was the energy required to separate the fluid, which would mean moving the molecules about 3-10 angstroms apart in order to overcome this cohesive force. You are talking about a gas-liquid interface in the case of a bubble, and I haven't thought about it from that standpoint. I have thought about it more from the standpoint of surface tension, maintaining a pure surface, etc. With a surfactant, there would certainly be changes in these forces that you are talking about. I suspect it would be fairly difficult, at least in water, to sustain a pure vapor-liquid interface without having some surfactant there. The condition I was talking about of a solid coming out of the melt is an example of the breaking of the interfacial bond that existed between the liquid molecule and the solid, the low bond strength that existed there. What was happening was not microscopic, it was something that was visible. But if you want to talk about it as a tear in the fluid, than I guess that would be okay.

ROLE OF PHYSICAL PROPERTIES OF LIQUIDS IN CAVITATION EROSION

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Cavitation erosion is a serious engineering problem in hydraulic turbines, pumps, valves, control devices, hydrofoils, propellers, bearings, diesel liners, aircraft engines, torque convertors, acoustic devices and processing and cleaning equipment. Basic research on bubble growth and collapse, material erosion and environmental influences has aided the design engineer in the proper design and material selection process. Various screening tests provide the relative erosion strength of candidate materials and protection techniques. There were cases in which the erosion intensities were too severe to be protected by existing materials and protecting techniques. In such cases operational limitations and redesign become necessary. Model testing and redesign would greatly help the practical engineers. The properties of liquids play an important role in the development of scaling laws and model testing techniques. They influence fluid dynamics, bubble dynamics and environmental effects.

Experimental and theoretical research has been done on many engineering liquids including water, seawater, various lubricants, coolant additives such as glycols and alcohols and liquid metals including mercury, sodium, potassium, lithium, and cesium. Physical properties studied include density, vapor pressure, surface tension, gas content, sound speed and viscosity. Some of these properties have been experimentally varied by controlling temperature and pressure of the liquid. A summary of all the experimental results obtained by various investigators is available in reference (1). The erosion rate generally increases with increasing temperature of the test liquid, reaches a maximum and decreases as the liquid temperature approaches the boiling point. While this is true in most of the liquids tested, there are a few exceptions. Commercially pure titanium (100-A) tested in liquid sodium in the temperature range from 400°F to 1000°F shows the above trend; whereas 316 stainless steel tested in the same temperature range shows a monotonically decreasing erosion rate with increasing temperature of the sodium. Any attempt to explain the influence of ambient temperature on erosion rate must take into account the effect of temperature on the energy absorbing characteristics of the material. There are some data available on the erosion rate of 316 stainless steel in mercury up to 150°c. The erosion rates in liquid sodium and in mercury are comparable around 150°c.

Nowotny (2) compared the erosion rates in water, aniline, phenol, toluene and amyl alcohol and concluded that there existed a correlation between the surface tension of the liquids and the erosion rates. More recent experiments by Plesset (3) and Thiruvengadam (1) confirm this conclusion. However, Wilson and Graham (4) studied the effects of density, compressibility, vapor pressure, and viscosity in lubricating oils and concluded that the acoustic impedence (the product of density and speed of sound) played a major role. Thiruvengadam (1) showed that the dissolved air content was also important. More recently, Plesset (5) conducted cavitation erosion tests on aluminum in several mixtures of non-aqueous liquids and water, and found that erosion rates decreased monotonically as a function of concentrations, except in one case where a minimum was observed. Plesset concluded that pure aluminum was chemically less active in non-aqueous liquids. Wilson and Graham (4) as well as Thiruvengadam (1) showed that the viscosity of the liquid did not have much effect on erosion rate.

The above results indicated that a systematic examination of the role of physical properties on cavitation erosion was needed. The mathematical analysis for examining the effects of physical properties of liquid on cavitation erosion can be traced to the work of Rayleigh (6). He obtained infinite bubble wall velocities and collapse pressures for an empty bubble collapsing in an inviscid incompressible liquid; he then made the assumption that a permanent gas obeying Boyle's law was inside the bubble, which was compressed isothermally during collapse. Furthermore, in his conclusions, he suggested that a more realistic theory should take into account the compressibility of the liquid. Herring (7), Trilling (8), and Hickling and Plesset (9) considered the effect of compressibility while Gilmore's (10) investigation included a discussion of the effects of viscosity and surface tension. Ivany and Hammitt (11) combined the effects of viscosity and surface tension with compressibility during the collapse of empty and gas-filled bubbles. The effect of surface tension was brought to attention by Plesset (12) and Noltingk and Neppiras (13), whereas the viscosity of the liquid was investigated in detail by Poritsky (14) and Ivany and Hammitt (11). In general no more than three physical properties of the liquid was considered in their analyses.

It was evident that a systematic investigation of the role of physical properties in cavitation erosion was needed. With this objective, Tung and Thiruvengadam (15) conducted both theoretical and experimental studies. The analytical study was based on the idea that the intensity of erosion is related to the intensity of bubble collapse forces (16). Considering both spherical and non-spherical collapse, this analysis leads to a relation between the rate of erosion and the product of the collapse pressure, frequency of collapse and the radius of the bubble. The maximum collapse pressure is related to the surrounding pressure, the gas content inside the bubble, the sound speed and density of the liquid. The maximum size of the bubble is related to the growth time available, the pressure difference between the inside and outside of the bubble and density of the liquid. The frequency of growth and collapse of the bubbles are related to nuclei size distribution, surface tension, velocity, pressure and size of the system. When all these parameters have been examined, and expressed in terms of physical properties of the test liquid, a relationship governing the intensity of bubble collapse may be derived. This relationship closely agrees with many different experimental results. For example, the decrease in erosion rates in water-alcohol mixtures is related to the change in the physical properties of the water-alcohol mixtures as predicted by the analytical relationship.

The dependence of erosion rates on the ambient temperature of water can also be predicted quantitatively with this relationship. The assumption that the gas inside the bubble is compressed adiabatically during collapse gives a better agreement with experiments than the assumption that the gas is isothermally compressed as assumed by Rayleigh. Calculations for the eleven liquids tested by Wilson and Graham agree closely with experimental data. Acoustic impedence is an important liquid parameter that governs the erosion intensity in vibratory devices. This investigation reveals that the major physical properties of liquids governing the intensity of erosion include density, sound speed, surface tension, vapor pressure, gas content and nuclei distribution.

Although these results are generally useful in studying the erosion potential of various engineering liquids and in selecting scaling parameters for model studies, it is only a first step in the understanding of the complex processes involved in cavitation erosion. For example, the measurement and characterization of nuclei distribution is needed in these studies. Another important area is the measurement of the sound speed and density in bubble-water mixtures. Current estimates show that the sound speed can be as low as 100 fps in air-water mixtures. It is evident that much more remains to be accomplished for an overall understanding of the phenomenon of cavitation erosion.

ACKNOWLEDGEMENT

This research was supported by the U. S. Office of Naval Research under Contract No. N00014-67-A-0377-0008.

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DISCUSSION

F. B. Peterson, Naval Ship Research & Development Center: I wonder if you meant to imply by one of your earlier slides where you used distilled water and various solutions of sodium chloride that corrosion was not a factor? Were you saying that corrosion was not an important aspect in the material loss? For a wide variety of flows, at least those that exist in systems of the Navy, erosion is really a major problem when there are cavities which are basically fixed to the surface as if there would be a separated flow regime. An example would be cavitation that exists between the intersections of the strut and a foil in a hydrofoil system, or on blades or propellers, or in pumps. I wonder if the Rayleigh calculations are the most appropriate ones when the spherical bubbles you're talking about are generated from the break up of a large vapor cavity? Lastly, would the Rayleigh equations really be valid for collapse when there is the strong jetting mechanism?

A. Thiruvengadam: As far as the influence of corrosion is concerned, it is not just the liquid alone that produces the corrosion results of material-liquid combinations. All we are saying is that if a commercially pure aluminum (99.99%) is exposed to salt water for 15-30 minutes, the corrosion influence is small compared to the erosion influence. This is the point we were talking about in terms of non-aqueous liquids. Whereas, if steel is cavitated for about 3 hours, there can be a factor of 10 difference depending upon the amplitude. Using lower amplitudes results in lower intensities, longer times, and the corrosion influence dominates the erosion influence. Coming to the second aspect of your question, we know in Navy systems why bubbles collapse when the cavity is slightly developed. At σ_i, the so-called degree of cavitation is implied by saying there is a fixed cavity at which the erosion is a maximum. Beyond the inception stage these bubbles will fully develop, i.e., reach maximum size, and then collapse. At that time, the erosion intensity is a maximum. If it grows further down, the pressure must be reduced, or the frequency has to be changed. These are two of the parameters, all of which change, that go into making up the intensity of erosion. They are all dependent upon the σ value. Now, can we assume Rayleigh bubble growth? Here again, it's an extremely complex flow field, as you pointed out. We assume that the bubbles are formed near the inception point and then are carried away by the flow. Dr. Hammitt has conducted some experiments where he photographed some bubbles that were supposed to be carried at free stream velocity values. Plesset conducted some analytical work where he traced the bubble growth along the guiding boundary and used the Rayleigh distribution to predict the maximum size, growth time, collapse time, etc. I agree that it is a very complex area. The Rayleigh equations cannot really be used in a 100% practical sense, but that's the place to start in this kind of analysis.

J. P. Tullis, Colorado State University: Since the erosion rate in a vibratory system is orders of magnitude faster than in a flowing system, are the relationships that are derived from this vast amount of data directly applicable, or can we make the transition to flowing systems which are, of course, the practical problems?

A. Thiruvengadam: This has been one of our objectives in doing the so-called modeling techniques, counting techniques, etc. The erosion intensity in the field need not necessarily be lower than in the laboratory apparatus. We can give examples in which the erosion intensities can be 100 times more severe than in the laboratory apparatus. We have all been concerned with how to extrapolate laboratory data to the field in a practical engineering system to guide designers.

C. M. Preece, State University of New York, Stony Brook: I want to comment on Dr. Peterson's first question about the corrosion. It's about time we all stopped thinking of aluminum as not being corroded by distilled water. In a dynamic system where passivation is prevented, distilled water is the corrosive environment for aluminum, and therefore little difference would be expected between the behavior of a sodium chloride solution and pure distilled water.

F. G. Hammitt, University of Michigan: In your calculation of the effects of temperature on damage rate, how can you apply Rayleigh's model which as far as I know has no way to take into account the different temperature effects? There is no thermodynamic effect in Rayleigh's model. How did you take that into account?

A. Thiruvengadam: We got the calculations through the bubble growth times. The temperature comes in ok. When the temperature varies, the physical properties vary, density varies, sound speed varies, surface tension varies, vapor pressure varies, dissolved gas pressure varies. For each temperature, we find out what these values are. One of the reasons we used water and water-alcohol systems is that some of these values are readily available in the International Critical Tables.

THE ROLE OF MECHANICAL PROPERTIES IN CAVITATION EROSION RESISTANCE

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There has been a long standing need for a correlation between the cavitation erosion resistance of materials and some of their common mechanical properties so that a prediction of erosion resistance would be possible from readily available mechanical property data. In addition to being of great practical value a correlation of this type would infer a mechanism of cavitation erosion damage or inherent material erosion resistance that currently is lacking.

In order that correlations of erosion resistance and mechanical properties of materials be attempted the erosion resistance of materials must first be measured. There are several ways of doing this experimentally:

1) Vibratory Apparatus
    a) Piezioelectric
    b) Magnetostrictive
2) Venturi Tunnels
3) Rotating Discs (with holes)
4) Impingement Apparatus
    a) Whirling Arm
    b) Stationary Target

By far the most common method of testing cavitation erosion resistance of materials is the vibratory cavitation probe. In this device the specimen is placed on the probe tip and submerged in water (or any other liquid), is vibrated at a high frequency, 20,000 Hertz, and cavitation is induced in the liquid adjacent the specimen tip. The cavitation causes damage on the specimen and the damage is normally monitored by measuring weight loss of the specimen. The second most popular method of measuring erosion resistance is the whirling arm device. This device moves the specimen through a relatively stationary field of droplets at a high velocity and the resulting impact of droplets on the specimen-target cause erosion damage and this damage is also measured as weight loss.

Hobbs(1) has shown that the erosion resistance of materials is relatively the same regardless of which of these two techniques is used to rank materials. For the sake of this discussion it is assumed that cavitation erosion damage and liquid impingement damage are the same general phenomanon and data gathered by either technique is useable for correlation attempts. There is significant scatter among the various cavitation tests when they are compared to one another as in the ASTM Round Robin tests reported by F. G. Hammitt.(2)

The first and most common correlation of erosion resistance and mechanical properties attempted has been between hardness and erosion resistance; however, this has not been successful when a wide range of materials has been analyzed.(3) A better correlation has been established using the strain energy of the material and correlations based on various forms of this quantity have been put forth by Thiruvengadam(4), Hobbs(5), Backstrom(6), and Thomas and Brunton(7). The correlation found with erosion resistance and strain energy terms is better than that found with hardness; however, there are notable exceptions.

Metallographic investigations(3) of the earliest stages of cavitation erosion damage of metallic materials show plastic deformation occurring during the incubation period and increasing until cracks form and metal fragments are lost. This observation supports, in general, a hypothesis that takes into account the total energy for fracture as an important material variable for predicting erosion resistance.

The attempts to correlate erosion resistance with mechanical properties involved the use of parameters such as work done to cause fracture (Proof Stress - 2/3) (Tensile Strength - Proof Stress) X Elongation, Proof Resilience (1/2 (Proof Stress)^2/Elastic Modulus) and Ultimate Resilience (1/2 Tensile Strength)^2/Elastic Modulus), all of which try to take into account in some way the energy absorbing capacity of the material. Hobbs(5) has shown that the erosion resistance versus ultimate resilience correlation is the best of this lot, but again the correlation becomes poorer the greater the amount of data used.

Considering the absorption of energy the important role of a material in resisting erosion by cavitation the idea of erosion resistance depending on strain energy during deformation of a material has been advanced by Brunton,(7) among others. Again, the correlation works well with a limited set of data but as more kinds of material are added the correlation becomes poorer. In particular cobalt appears, in Brunton's work, to be far more erosion resistant than its strain energy would indicate. This observation is of more than passing interest since some of the most erosion resistant materials are the Stellite alloys which are cobalt based alloys.

Investigation of the Stellite alloys has been reported(8,9) and in these investigations a deformation induced phase transformation has been found and the transformation of FCC to HCP has been cited as the energy absorbing mechanism that accounts for the superior erosion resistance of the Stellite alloys.

Work in the field of explaining and predicting the erosion resistance of materials is continuing, and needs to continue. There is no way, now, of predicting the erosion resistance of materials from their mechanical properties.

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DISCUSSION

R. E. Maringer, Battelle, Columbus Laboratories: Has any attempt been made to associate the initial period of cavitation with residual stresses in the surface due to machining? These penetrate depths, depending upon the hardness, of 5, 10, 20 mils, which sort of correspond with the change of rate of cavitation. These are ignored in most mechanical property tests, but when dealing with something that is so surface sensitive, they have to be watched particularly.

G. C. Gould: Having just been burned very badly with that in an entirely different program, I can't agree with you more. You're absolutely right. I think, to some extent, they have been ignored. I know in my own instance I've done some electro-chemical polishing of specimens to try to get around that, and I am not certain of how well I've done it. It would appear in materials like austenitic stainless steel, as an example, and probably in stellite or in cobalt, that the incubation period might be lengthened or shortened by how much residual stress, or inherent plastic deformation, is there because of sample preparation. During the incubation period, the material is severely deformed, and then the process of chipping it away proceeds. So I would expect that it has residual stresses, or that specimen preparation has its biggest influence on the length of the incubation period, and not so much on the subsequent, what we like to call rather glibly, steady state.

F. G. Hammitt, University of Michigan: I have some confirmation of what you just said. We did some experiments where specimens were held under tension and also under compression near the yield point or beyond it. For compression, it seemed to inhibit the initial pitting and thus did, in fact, increase the nucleation period. Tension didn't seem to have much effect, at least not a reproducible effect. Neither of them seem to have very much effect in the developed damage portion, much as you summarized there. Another point I want to mention is that about 10 years ago, there was some work reported by Plesset where x-ray diffraction techniques were used to examine the surface at the very beginning of cavitation. It was found that there were some distortions in the surface long before any noticable weight loss could be found. I don't think that work has been repeated. But it's a good approach, I think.

C. M. Preece, State University of New York, Stony Brook: I am not certain that the surface effect is necessarily the important one, because our experiments indicate that it's a bulk phenomenon far more than a surface phenomenon. As Professor Hammitt said, experiments indicated that a bulk stress, not a surface stress, was being applied. We have, in fact, repeated some of the work that Plesset did on single crystals of aluminum. One of the things that surprised us was that a single crystal of aluminum which has nice, sharp diffraction patterns prior to exposure to erosion, has streaked diffraction spots from the front face of the sample after exposure, but so do the ones from the back surface. The deformation is definitely a bulk phenomenon. Furthermore, in a cobalt sample with a face-centered cubic structure, it was found that both the front and the back of a several millimeter thick sample is transformed after about a 1/2 hour exposure to cavitation without any detectable weight loss. So I think it's more the state of the bulk of the material rather than the surface which may be important.

G. C. Gould: I can't let that go uncontested. In your work you're using a specimen on an anvil, or some such thing, and a probe with a non-wearable tip. You're irradiating it, if you will, with a cavitation environment, and that's what you observe. I don't dispute that, but if I take the stellite specimens which are the tips and are not in any way able to be irradiated in the back and held reasonably rigidly in this titanium mechanical transformer, I find by means of x-ray diffraction a transformed layer on the surface. This electropolishes off with just a few milligrams of dissolution, a non-deformation kind of dissolution. It would appear under these circumstances that the effect of the cavitation is rather minimal as far as penetrating into the depth of the specimen is concerned.

C. M. Preece: Maybe you are transforming the sample into a non-equilibrium phase. I think if you are reflecting the shock pulse, or whatever it is, from the reverse side of the sample, that you may be undoing what you have already done. It has been shown in shock deformation that the transformation is reversible, in steels at any rate, and I think perhaps this is one explanation. In our situation where we're going in pure cobalt from an unstable face-centered cubic to a stable HCP phase, it may remain undone. In your case, it may just be the stability of the two phases which is determining it.

E. E. Klaus, The Pennsylvania State University: There was some suggestion earlier that there might be a chemical effect in cavitation erosion. I wonder whether you have identified any chemically reactive films on the solid surface?

G. C. Gould: I have not. I have done some work patterned directly after Plesset's in which, with time, instead of just turning on a given level of cavitation intensity, it has been pulsed. Now the specimen enjoys ten fold greater exposure to the environment during the same total amount of damaging cavitation. In the system that I have looked at doing this, namely copper in water, which is a readily oxidizable material, there seems to be no difference. There seems to be no difference whether the water is oxygenated or deoxygenated by purging nitrogen through it. That doesn't rule out the possibility that corrosion is going on, but the amount of corrosion going on is quite minimal with respect to the overall damage rate, which in copper is very high. I guess my experiment isn't a real critical one. Plesset has shown with plain carbon steel in sodium chloride solutions that there is clearly a contributing corrosion effect. I've done a lot of work with 12 chromium steels, and I have not found a lot of corrosion products. Maybe I shouldn't have expected to, and maybe that material passivates so fast that the corrosion in that case is unimportant.

J. E. Stern, NASA, Goddard Space Flight Center: In regard to the electro-polishing of your specimens before tests, what are the possibilities that you might have encountered some hydrogen embrittlement that might have had an effect on the behavior of the surface?

G. C. Gould: The thought of hydrogen embrittlement went through my mind when Frank Peterson mentioned the Russian work. All I can say is, it's a possibility. I don't know the effect on a cobalt base material when it's permeated with hydrogen. Being face-centered cubic, it would probably be much less likely to be embrittled than would a body-centered cubic material, but I really don't know the answer.

RECENT THEORIES OF CAVITATION DAMAGE INCLUDING NON-SYMMETRICAL BUBBLE COLLAPSE EFFECTS

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Recent theories of cavitation damage mechanisms will be discussed in the present paper as opposed to the classical theories on that subject, originated primarily by Rayleigh in 1917 (1), who considered the collapse of an empty spherical bubble initially at rest in a static, incompressible, inviscid, infinite liquid. It was assumed in the various studies based on this initial work that at least the mechanical portion of cavitation damage (as opposed to chemical effects) resulted from shock waves propagated through the liquid by the collapse of cavitation bubbles under the ideal fluid and spherical symmetry assumed by Rayleigh.

A more realistic approach to the problem requires primarily a consideration of the non-symmetries inherent in most actual cavitation collapse situations. Photographic evidence, dating primarily from the work of Naude and Ellis (2), shows that the actual collapse of bubbles near a symmetry-destroying feature such as a nearby wall results in a toroidal-like collapse, with final generation of a liquid microjet oriented toward the wall. However, this has since been substantiated by numerous photographic studies, and also theoretical studies of varying and increasing complexity (3, 4, e.g.). Present photographic and numerically-computed evidence indicates that the microjet velocity is only marginally sufficient to be the sole cause of the observed cavitation pitting in strong materials.

Relatively recent numerical calculations including numerous real fluid effects (5, 6, e.g.) indicate that the shock wave intensity emitted during collapse is not likely to be strong enough to be damaging to most materials, even if spherical symmetry were maintained through a very large volume ratio, and if the bubble were touching the wall at the start of collapse. Of course, spherical symmetry is impossible for the collapse of a bubble in such a position, but the shock wave intensity is in general of maximum intensity for a given volume ratio of collapse, if spherical symmetry is maintained. However, the numerical calculations go on to show that if a "rebound" occurs such that the bubble grows again after collapsing, the event is similar to a micro-explosion (rather than implosion as for collapse), and in this case the radiated shock-waves are much stronger, so that damage through their impingement on a neighboring wall is much more likely. Photographs by various investigators, including Kling of our own laboratory (7, 8, e.g.) show that non-symmetrical collapses with rebound occur almost exclusively in a real flowing system. Hence it appears to this writer that actual damage is usually a result of a combination of the impact effect of the microjet and the shock-wave pressures generated by bubble rebounds. There is much more confirmatory evidence than that which can be covered in this relatively brief paper. However, much of the general applicable material is covered in the book Cavitation (9), as well as an extensive pertinent bibliography.

A final pertinent point is the photographically demonstrated and theoretically justified fact that the bubble centroid during collapse is strongly attracted toward a solid wall, and that the microjet is then directed toward the wall, provided other influences such as velocity or pressure gradients are not sufficient to overcome the wall-attraction effect. For these reasons, a relatively strong sorting mechanism exists preventing the great majority of bubble collapses in the vicinity of a wall from reaching damaging intensity. This is confirmed experimentally. On the other hand, a collapse near a free (or very flexible) surface, affects the bubble behavior in a precisely opposite manner. The bubble is repelled from the flexible surface and the jet is directed away. This also is observed photographically (10, e.g.) and is also expected on theoretical grounds. It may explain the surprisingly good cavitation resistance of various elastomeric materials.

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DISCUSSION

J. Bonnin, Électricité de France: You noted that when the cavitation parameter is reduced, there is sonic inception followed closely by visible inception. These are very close together. This is true, I quite agree with you, but only in cold liquids. You showed a figure with curves with visible inception, first the marriage, sonic inception, etc. We can observe with liquid carbon dioxide that we could have cavitation inception, and even develop some cavitation without any noise. But it was, I must say, in carbon dioxide and very close to its critical point.

F. G. Hammitt: We have generally found that if you look carefully enough, when you can hear something you can see something, or vice versa, at least in our venturi with water. But I have no experience with carbon dioxide. We've done some work with liquid metals, but then nothing can be seen. Sonics must be relied on.

R. M. Whittier, Endevco: Have you done experiments using ultrasonic stress wave sensors and things like this?

F. G. Hammitt: No.

SESSION II

Chairman: R. S. Miller
Office of Naval Research

SOME PRACTICAL EXAMPLES OF CAVITATION EROSION AND THEIR PREVENTION

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PREFACE

The concepts and approaches to the prevention of cavitation damage which are outlined in this abstract are almost entirely those presented in the two recent review articles by A. Thiruvengadam (1, 2). As these reviews contain such a wealth of detail and references about this complex subject, and as Dr. Thiruvengadam taught this author what little he knows about cavitation, no attempt will be made here to repeat this information in any detail. The reader is strongly urged to obtain Reference 1 if a complete review of this subject is desired.

INTRODUCTION

This presentation surveys the problem of failures caused by cavitation erosion from an engineering point-of-view, i.e., with de-emphasis of on-going "state-of-the-art" research controversies, in an attempt to provide the designer and engineer with some tools which can be used to: a) assess the magnitude of his cavitation erosion problem, and b) rationally select from one or more alternative solutions.

The concepts of intensity of erosion, erosion strength and the time dependence of erosion rate are described; and the relation of these parameters to system variables such as pressure and velocity, and to the properties of materials are discussed. Using several examples of actual cavitation erosion, methods of prevention and their limitations are examined.

CAVITATION EROSION PARAMETERS

Any assessment of damage from cavitation erosion requires, at least, some quantitative knowledge of the amount of material removed and the exposure time in order to estimate the rate at which erosion has proceeded. Although the time history of erosion typically has four periods, namely: incubation, acceleration, deceleration, and steady, one may use, particularly in more severe cases, an averaged rate based on the overall elapsed time.

The severity of cavitation may be characterized by the intensity of erosion, I, which has the dimensions of power per unit area. Physically, this intensity parameter represents the rate at which energy is being absorbed by the eroding material, and it is highly dependent on the velocity, pressure, and temperature in the system, and on various fluid properties such as viscosity and surface tension. Minor design variations can greatly influence the value of I in a system, causing severe localized erosion.

Although in general the harder and stronger materials are more resistant to cavitation erosion, the search continues for a single parameter, easily measured or inferred from other material properties, to characterize this resistance. One finds, for limited classes of materials, that good correlations can be made between erosion resistance and almost any parameter such as hardness, strain energy, ultimate strength, or "ultimate resilience". However, the high frequency, repetitive nature of the cavitation erosion process, and the inherent variations in the response of materials to this type of energy input, makes one wonder if a universal correlation factor is worth seeking.

Several investigators have suggested the use of some type of relative erosion resistance scale, based on the results of a standardized test procedure. Among these are Heymann's "normalized erosion resistance", N_e (3) and Thiruvengadam's "erosion strength", S_e (4). Thus, without requiring a full understanding of the role, if any, of other material properties, one may subject a variety of materials to one of the screening tests, and acquire what is needed for design purposes.

It may be shown (4) that the rate of erosion, r , is related to the intensity of erosion, I , and the erosion strength, S_e , by: $r = I/S_e$; and this relation may be used to compute any one of these parameters after the other two have been determined.

ASSESSMENT AND FAILURE PREVENTION

Faced with a system that has experienced damage from cavitation erosion, and concerned with preventing a failure either by fracture due to weakening of the material or hydrodynamic degradation below a functional level, the designer must first assess the seriousness of the problem, and then select the most effective approach to eliminate or at least minimize the damage.

In the previous section of this abstract, the basis for assessing the magnitude of the problem, namely, the intensity of erosion, I, is outlined. The rate of erosion must be estimated, and with the erosion strength, S_e, of the material being eroded, one can then make an estimate of intensity. If the S_e is unknown, one of the screening techniques such as the vibratory test, the rotating disk test, the venturi test, or a jet impact test can be used on samples of candidate materials to provide this evaluation.

If the intensity of erosion is found to be around 10^{-1} watt/meter^2 or less, then one of the following methods of protection should be effective: substitution of a more resistant material, either for the entire component or at critical areas in the form of either inlays or overlays; use of elastomeric coatings; cathodic protection; or air injection.

In the intermediate intensity range from about 10^{-1} to 1 w/m^2, it may be possible, in addition to one or more of the above, to sufficiently reduce the rate of damage by imposing operational limitations on velocity, power, or pumping capacity. In many cases it has been found that the intensity of erosion is proportional to the velocity raised to an exponent of six or greater. Thus, a velocity reduction of 10% could halve I; and 20% less speed could reduce I by almost 75%, which would quadruple the operating lifetime.

Intensities of erosion above 1 w/m^2 will usually require major design changes. Provision for air vents, or severe limitations in operation may prolong the system lifetime, but hydrodynamic redesign or frequent periodic maintenance are probably the only practical solution in these cases.

It should be emphasized that, for non-aqueous fluids, and with other than ambient conditions the screening tests must be conducted so as to approximate the actual service conditions as closely as possible. Much research remains to be done before predictions of material erosion can be made from simple laboratory tests. Thus, for severe situations, the expected pressures, temperatures, times, and corrosive factors should be imposed during the screening tests.

CONCLUDING REMARKS

Much remains to be learned about the basic nature of the cavitation erosion phenomenon. Research is actively underway throughout the world (see Ref.5) on aspects such as fluid properties, bubble dynamics, size scaling, and the role of various material parameters in the resistance to erosion. Studies into the failure of coating-adhesive-substrate systems continue to raise more unanswered questions, and trial and error is still the main tool for the hydrodynamicist faced with a badly eroding propeller or pump. However, despite what we still need to learn, the approach outlined in this presentation allows the designer to understand the magnitude of his cavitation erosion damage in terms which will permit him to quickly isolate the most effective mode of failure prevention.

ACKNOWLEDGMENTS

The author would like to express appreciation for the support of the Fluid Dynamics Branch of the U. S. Office of Naval Research during the many years of study at HYDRONAUTICS, which have provided such major contributions to the present state of understanding of cavitation erosion, and to again acknowledge Dr. A. Thiruvengadam, who performed most of this research.

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DISCUSSION

F. J. Heymann, Westinghouse Electric Corporation: In the nomogram, along the line that defines erosion strength, you have listed materials. Is the value of erosion strength given to those materials based on comparative erosion tests, or is it based on calculated strain energy?

A. F. Conn: The history of that goes back to a time when the materials first being looked at were eroded out to steady state and there were some very good correlations between steady state erosion and strain energy. If I am correct, those are based on the steady state erosion strengths.

F. J. Heymann: There are two additional comments I wanted to make. In using this method, which is, I am quick to say, a good practical method, it should be remembered that the intensity that you are talking about when you are saying 1 watt/meter^2 is not an intrinsic, independently measureable property of the environment. In fact, erosion rates vary with the 6th power of the velocity in flow cavitation and with about the same power in liquid impingement, whereas the kinetic energy associated with the environment varies with the second power. It's clear that that sort of energy exchange is a very complicated one. We must remember that erosion intensity is a value based on the amount of material eroded. The other point I wanted to make pertains to the slide you showed of Thiru's tests where you plotted the reciprocal of erosion rate versus engineering strain energy for a number of materials and drew a first order linear correlation. If those same data are plotted on log-log paper, they will give a better fit to a second order. That is, the erosion resistance is approximately proportional to strain energy squared, and almost every correlation that I've seen shows that erosion resistance is approximately proportional to the square of some kind of a strength property. Whether you take engineering strain energy, or ultimate strength, or hardness, there always seems to be some general dependence on the square of this property. One reason that the ultimate resilience proposed by Hobbs seems to give a linear proportion is because it includes the square already. It's $\frac{S^2}{2E}$, and the E doesn't vary that much.

A. F. Conn: Thank you Frank, I agree.

F. B. Peterson, Naval Ship Research & Development Center: I have two comments and questions associated with them. First, there is a kind of classical experiment of rotating a disc at high speeds in a non-cavitating situation, where at the outer edge of the disc, material is removed due just to corrosion. Oxygen reaches various parts of the surface at different rates. With regard to Thiru's impeller on the pump of his washing machine, isn't it possible that the pot metal could have been significantly weakened by corrosion, particularly corrosion of the outer edge, and possibly cavitation wasn't even involved in the damage process until the surface was severely corroded? The other thing is that when a sample is vibrated, it's my understanding from looking at various peoples' results, that there is a certain, definite pattern of damage on the surface. Some people have shown photographically that over a period of time the number of cavities generated on vibratory apparatus changes, and after the surface is significantly damaged and is no longer a flat smooth specimen, the number of cavities is less. In extrapolating the work on the vibratory rig to a flowing situation, let's say as you showed on the propeller, or on coatings on hydrofoils, isn't there some difficulty when the hydrodynamics in the flow situation are different with time?

A. F. Conn: Thiru's washing machine was certainly corroded. The intensities that I estimated are certainly low enough to be down in the corrosive range, and corrosion had to play a role. With regard to that geometry and to the outer tips having high velocity and seeing more oxygen, the pits were distributed rather evenly over the case as well as over the impeller. I agree that it was probably a factor, but not quite the same as the disc. With regard to the key question about using screening tests and comparing them with other flow situations, it is not known for sure what effects there would be on screening due to crevices and too little or too much air, etc. and their relationships to the characteristic flow, incubation, etc. The very same thing is seen in foil tests, i.e., the very same rate curve, incubation, and well defined steady state curve. Comparisons between methods should be made in the steady state condition.

H. Weinhold, TRW: On your graph of erosion rate vs. cavitation parameter, you showed a maximum value. It seems to me that could very well be inherent in the test method. Because of the use of a disc, I suppose you ran all your tests at the same tip speed?

A. F. Conn: No, this was done for various size foils and it was run for quite a spectrum of velocities. It's the same phenomenon that was observed around a cylinder flow. It's been observed on rotating discs.

H. Weinhold: The definition of the cavitation parameter, using a pump man's terms, would be essentially net positive suction pressure divided by velocity head. Obviously, if there is a low net positive suction pressure, a large amount of bubbles will be generated, but the collapse energy would be low. At the other end of the spectrum, a point will be reached where no bubbles at all are generated. There is a potentially high energy, but there are no bubbles to collapse. Now I can't see where this is applicable to a propeller. It may not necessarily be applicable for all cases. I can imagine a pump which is forced to ingest two phase flow, maybe all condensables, maybe a mixture of condensables and noncondensables, and force the fluid into a high pressure regime. The results may not be the same.

A. F. Conn: There are arguments about the temperature effects that cause this same kind of distribution and the effects on cavitation number. I am certainly not saying that this thing is going to apply in every single case.

EXAMPLES OF OIL CAVITATION EROSION IN POSITIVE DISPLACEMENT PUMPS

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Introduction

Investigation over the past twenty years has uncovered certain trends as regards cavitation in an aqueous flowing system that are also useful in understanding cavitation in power hydraulic systems. However, care must be exercised in attempting to scale water data to hydraulic oils. In the hydraulics industry, we are dealing with dissolved and entrained air containing vapor rather than pure vapor. Any drop below saturation pressure, shown in Figure 1, can cause bubbles. Since pumps by definition create pressure differences, we can expect cavitation to be a major problem.

Examples of Erosion

Among the variety of hydraulic components, this presentation is concerned principally with one particular hydraulic device, namely, a piston type, positive displacement pump. Figure 2 is a schematic of the type of unit that is discussed. The important parts are the reciprocating pistons, which displace the fluid to produce flow under a pressure differential, the swash plate, which produces the reciprocating motion when the cylinder block is rotated, the slipper shoes that ride on the swash plate and connect the pistons to it, the cylinder block, the valve plate that separates the high pressure discharge and low pressure inlet, and the shaft that rotates the cylinder block. Interfaces that are sites of potential material erosion, such as the valve plate-cylinder block, and shoe-swash plate are identified and discussed. In addition, sites such as cylinder block-piston bore are also touched upon. Some examples of these parts damaged by oil cavitation erosion will be available for your examination.

Cavitation Mechanisms

An eight minute film showing cavitation phenomena occurring in a plexiglass modification to a 20 gpm piston pump is to be shown. Two mechanisms of cavitation phenomena that were observed with the model are discussed. The first is the bubble formation associated with pressure regions below the saturation pressure of air in the system. The second mechanism observed is the bubble formation associated with the discharge jet at the pump metering grooves located at the inlet and discharge ports. The effects of design changes as well as material substitutions are reviewed and their practicality as solutions to the oil cavitation erosion problem are discussed.

Concluding Remarks

Finally, we shall comment on one observation on oil cavitation erosion that was quite different from what we had expected. Perhaps some are aware of it already. We have a venturi to study the effects of cavitation and one test was to study the effect of contaminants. To our surprise, we found that we could go to a lower pressure before bubbles formed when we added dirt to the oil.

We are in some disagreement as to why this occurs and time does not permit a full development of one theory, but, according to van der Waal's equation, a high pressure vapor could exist inside small bubbles in a metastable state. Thus, a very small decrease in pressure is required to cause the bubble to expand. Adding the dirt destroys the metastable condition and a much lower pressure exists inside the bubble so a much lower pressure outside the bubble is required before the bubble expands.

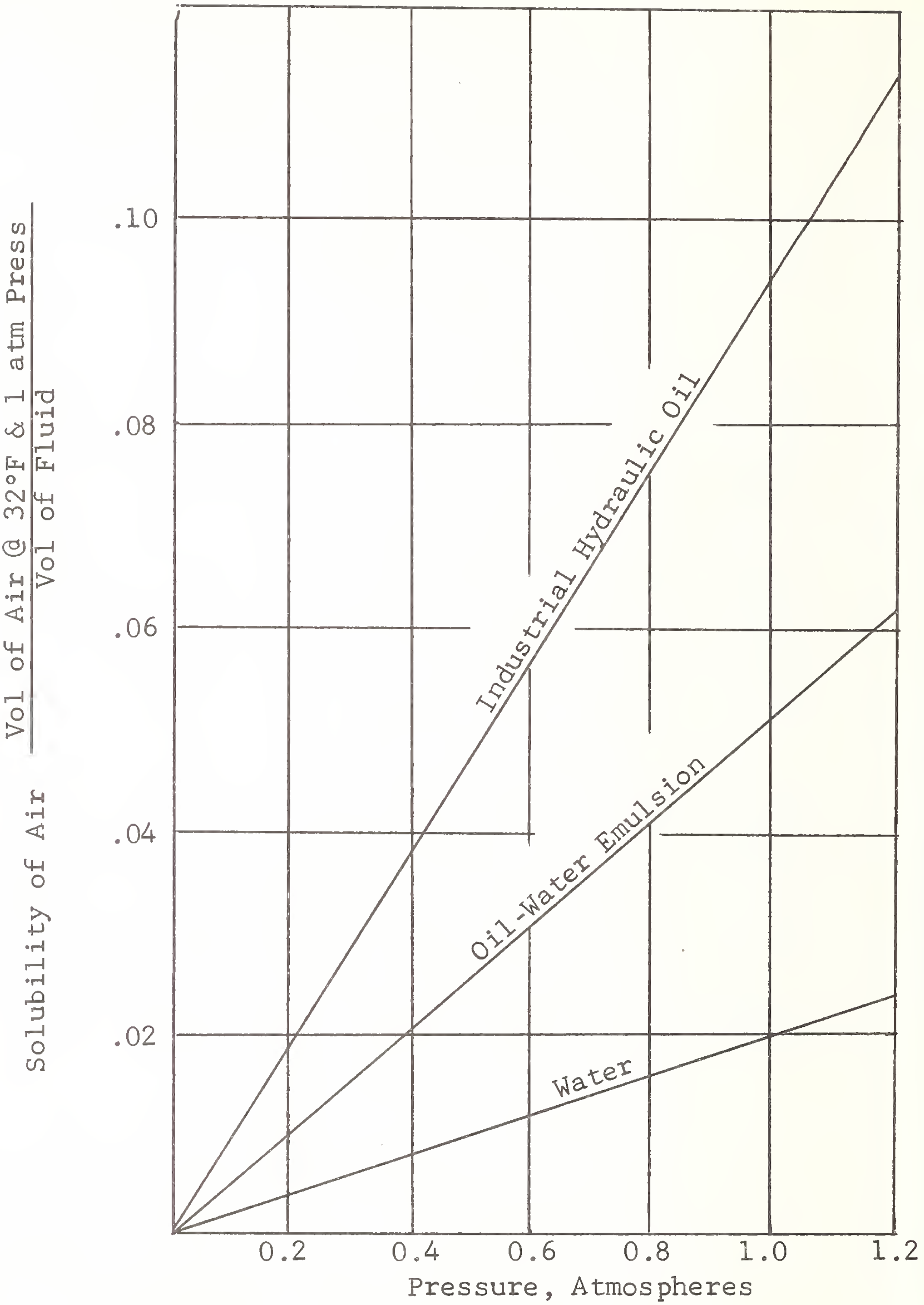

FIGURE 1 - SOLUBILITY OF AIR IN COMMON HYDRAULIC FLUIDS

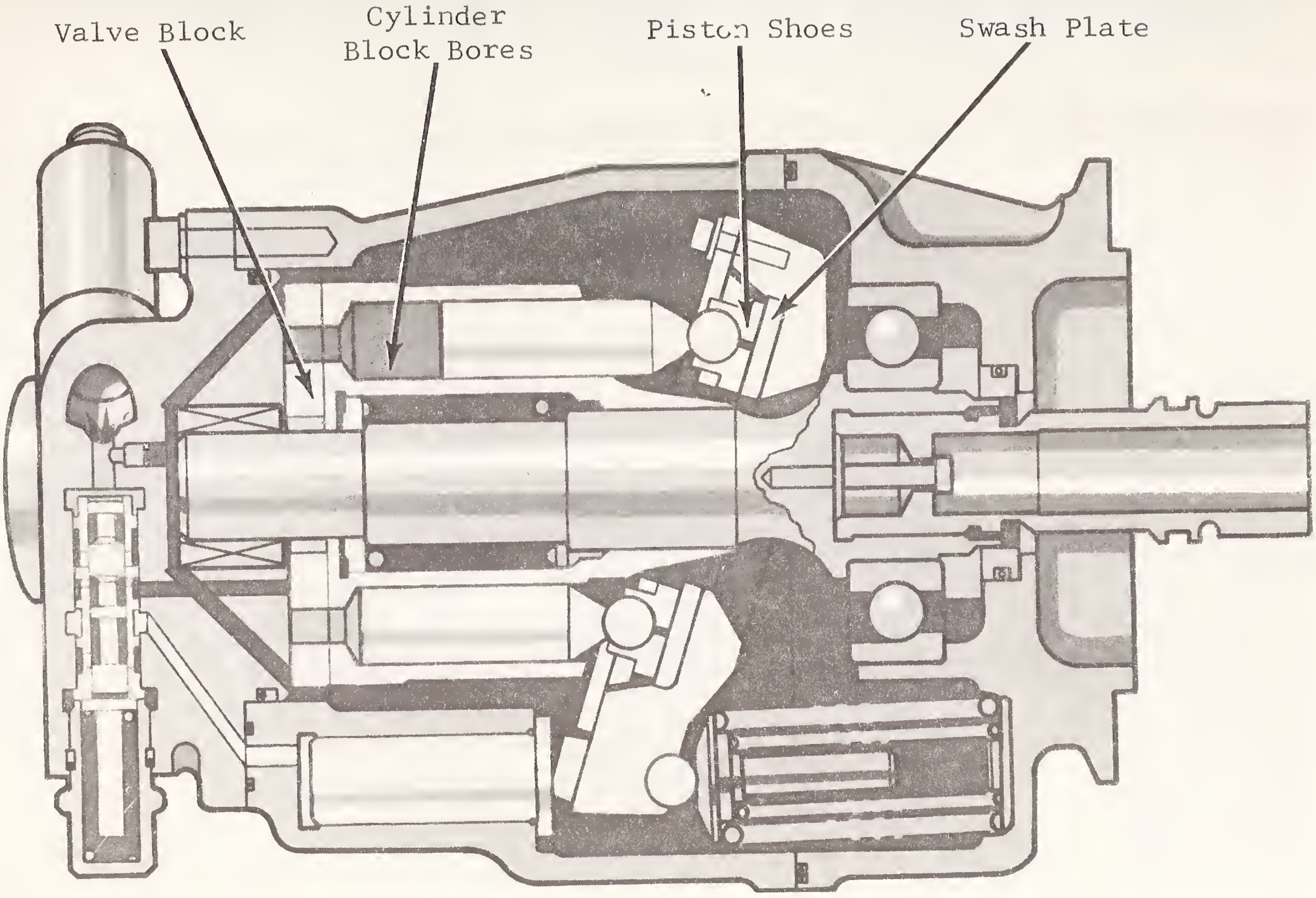

FIGURE 2 - VARIABLE DELIVERY INLINE PISTON PUMP

DISCUSSION

F. B. Peterson, Naval Ship Research & Development Center: When I think of van der Waals' forces, I think of the very short range forces between molecules. They may be dispersion forces, dipole forces, etc. These forces act over distances of about 3×10^{-8}cm. It would seem to me that in the vapor there would have to be a very high density of molecules in order to have the molecules that close. In other words, if it's a gas phase, I don't see how the molecules would be that close because that's on the order of molecular sizes.

G. O. Ellis: There must be some transition from the liquid to the vapor. I can't see that liquid instantaneously changes to vapor.

F. B. Peterson: There is an unbalance in the forces between the molecules. A molecule out in the middle of a fluid, with essentially no other types of molecules around, is going to have a kind of balanced force field. But the molecule that's at an interface is going to have an unbalanced force field, and its attraction is going to be greater in one direction than in others. I don't see the problem of having molecules extremely close. There is a constant interchange, but I don't see why it has to be a smooth transition.

H. Weinhold, TRW: Frankly, I don't think it is a problem for a physicist. It's a simple engineering problem. In one of the pictures shown, the worst erosion occurred at the bottom dead center. There was little erosion at the top dead center point, the transition from the discharge point to the inlet point. In the movie, what you term as your metering slot is very reminiscent of a diffuser. It is probably only a moderately efficient diffuser. It appeared that when bottom dead center was reached, a stream of bubbles began to be ejected. Now, if those things are put together, it's very reminiscent of a cavitating venturi-a venturi forced to work in the cavitating regime. If it was a highly efficient diffuser there could be a high inlet pressure. The pressure would decrease to the vapor pressure at the throat and maybe 90% of the velocity would be recovered, so there would be a total pressure drop of 10%. The bubbles collapse some place in the wheel. I don't know why you have a tapered diffuser shape featuring a metering slot in there at all. Maybe you need it; maybe it's just for manufacturing reasons. Tell those guys to jump in the lake and put a flat slot in there. That immediately gives a maximum opening and thus takes the diffusion capability away. That will probably reduce the problem greatly.

J. A. Halat: We agree. We've tried maybe every possible design we could think of, e.g., ramps, slots, holes. We do reduce the amount of erosion damage with certain designs. If the material loss is reduced with this type of a unit, the overall noise produced (the airborne noise) is increased. Only half the cylinders are under pressure, the other half are not. There is a pressure balance to hold. If the balance is not held, there are violent oscillations.

Anonymous: Are you talking about a sound audible to the human ear?

J. A. Halat: Right.

Anonymous: What is the frequency of it?

J. A. Halat: It's in the significant hearing range — 2,000 cycles. Although I haven't measured it, people in our lab have. It can be traced directly to modifing timing grooves to overall noise.

MICROSCOPIC INVESTIGATION OF CAVITATION EROSION DAMAGE IN METALS

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Cavitation erosion results from repetitive, localized pressure pulses applied to a material surface by the collapse of cavitation bubbles. Since cavitation erosion is a mechanical process, many investigations have been undertaken to correlate erosion rates with some mechanical property or properties of materials. The lack of success of these investigations is understandable because the pressure pulse generated by the collapse of a cavitation bubble is applied over an area that is microscopic in size (estimated to be on the order of 0.0001 to 0.010 inch in diameter depending on the source of the cavitation). Thus, the bulk mechanical properties of the material specimen would have little bearing on the material's response to localized pressures applied at the microscopic level. The microscopic properties and microstructure of the material would be expected to dictate the form of the erosion damage mechanisms and to control erosion rates.

This paper presents the results of research to identify the cavitation erosion damage mechanisms at the microscopic level for three metals (aluminum, stainless steel, and titanium) representing a range of properties and microstructure. The metals were exposed to cavitation generated in distilled water by a 20-kHz ultrasonic facility operating at a vibration amplitude of 2 mils. Representative properties of the metals and experimental details are summarized in Tables 1 and 2, respectively. Replicas of the eroded surfaces of the specimens obtained periodically during exposure were examined with a transmission electron microscope to follow progression of the erosion damage and identify dominant erosion mechanisms as a function of exposure time. Eroded surfaces of selected specimens were also examined with a scanning electron microscope to assist in the interpretation.

1100 Aluminum. – Scanning electron micrographs in Fig. 1 illustrate the acretion of bubble collapse pits on the surface of 1100 aluminum. The pits occurred at random locations in the initial stage of the erosion process (0 to 45 sec.); however, multiple impacts at previously formed pits became apparent as exposure times exceeded 45 sec. This stage of multiple impact is illustrated by the transmission electron micrographs in Fig. 2. Repeated impacts within preferential pits enlarged and deepened these initial pits. The walls between these relatively large pits became thinned and were extruded upward from the surface by 120 sec. Fracture of these thin walls between pits became apparent after exposure of 150 sec. as illustrated by the encircled region in Fig. 3. The surfaces of these fractures exhibited dimples characteristic of ductile rupture as shown by Fig. 4.

316 Stainless Steel. – Progress of cavitation erosion of 316 stainless steel in the initial stage is illustrated in Fig. 5. Pressure pulses generated by bubble collapse were generally of insufficient magnitude to form indentations on the surface as was the case with pure aluminum. The first noticeable changes in surface topography was localized delineation of grain boundaries (5a) and formation of a few scattered slip lines (5b). Removal of small chips of material became evident at grain boundaries after 12 min. exposure (5c) and at slip bands after 30 min. exposure (5d). Erosion by chipping at grain boundaries and slip bands within grains grew more extensive with time (5e and f). The fracture surfaces showed no evidence of ductility or fatigue striations. Removal of each chip appeared to occur as a single event associated with a single bubble collapse pressure pulse.

Titanium-6Al-4V. – Progress of cavitation erosion of Ti-6Al-4V is illustrated in Fig. 6. No evidence of surface impact pitting was found. The first observable erosion damage was cracking and chipping at phase boundaries and inclusions (6a). The chipping increased with exposure time (6b and 6c) and became extensive by 48 min. (6d). The nature of the erosion after 48 min. is readily apparent in the scanning electron micrograph in Fig. 7. The fracture surface features, more apparent in the transmission electron micrograph (6d), show that the small chips were removed by brittle fracture. The removal of each chip appeared to result from a single impact associated with collapse of a single bubble. Fig. 7a also contains a relatively large and deep pit of the type which first appeared at an exposure of 36 min. and became more prevalent as exposure increased to 120 min. The striations in the bottom of these pits as shown in Fig. 8 indicate fatigue fracture.

Erosion Damage Mechanisms. – Results from the microscopic analyses provide the basis for defining the primary cavitation erosion mechanisms operative in the three metals investigated. Bubble collapse pressure pulses readily deform the low-strength 1100 aluminum forming pits which became preferential sites for subsequent bubble collapse. The walls between these preferential pits grow thinner and are extruded outward forming lips as the pits enlarge and deepen during this incubation period. Shearing of the pit lips by subsequent pressure pulses appears to be the erosion mechanism for pure aluminum.

The magnitude of most of the pressure pulses is insufficient to indent the surface of the 316 stainless steel and impact pits, per se, do not contribute to the erosion of the stainless steel. However, the magnitude is sufficient to induce shearing in favorably oriented grains. The incubation period consists of the relative displacement of grains across grain boundaries and the formation of slip bands within the grains. These grain boundary steps and slip bands concentrate the stresses produced by the pressure pulses so that localized fracture of the material occurs with subsequent removal of small particles which serve as nucleation sites for the development of larger pits. The radial growth of these pits by fracture of small particles at the outer periphery appears to be the erosion mechanism for annealed 316 stainless steel.

The sources of stress concentration in the Ti-6Al-4V alloy are the preexisting interfaces between the different phases within the grains. Cracks which develop at these interfaces during incubation serve as stress concentrators for the pressure pulses to initiate material removal by localized fracture. This initial erosion mechanism appears to be similar to the mechanism for 316 stainless steel. However, a second mechanism based on fatigue fracture becomes operative as exposure time increases. The occurrence of dual erosion mechanisms in the titanium alloy illustrates the complexity of cavitation erosion.

This investigation demonstrates a rational approach for isolating the material characteristics which most significantly affect the material's response to cavitation. The results show that response of a material exposed to cavitation is not governed by mechanical properties evaluated on a gross scale, but by microstructural features which interact with the erosive environment. Definition and understanding of the erosion mechanisms and the controlling microstructural features provide the base required for the development of erosion-resistant materials.

TABLE 1. PROPERTIES OF MATERIALS INVESTIGATED

Material	Condition	Ultimate Strength (psi)	Yield Strength (psi)	Cavitation Erosion Rate* Mils/Hr
1100 Aluminum	Annealed	13,000	5,000	1.3
316 Stainless Steel	Annealed	85,000	35,000	0.5
Ti-6Al-4V	Annealed	136,000	131,000	0.2

*"Steady-state" erosion rate in distilled water in 20-kHz ultrasonic facility.

TABLE 2. EXPERIMENTAL DETAILS

Material	Specimen Location During Exposure	Maximum Exposure Time (min.)	Mean Depth of Penetration at Max. Exposure (Mils)
1100 Aluminum	Mounted 1 mm under horn tip	3	0.14
316 Stainless Steel	Mounted on horn tip	90	0.20
Ti-6Al-4V	Mounted on horn tip	120	0.13

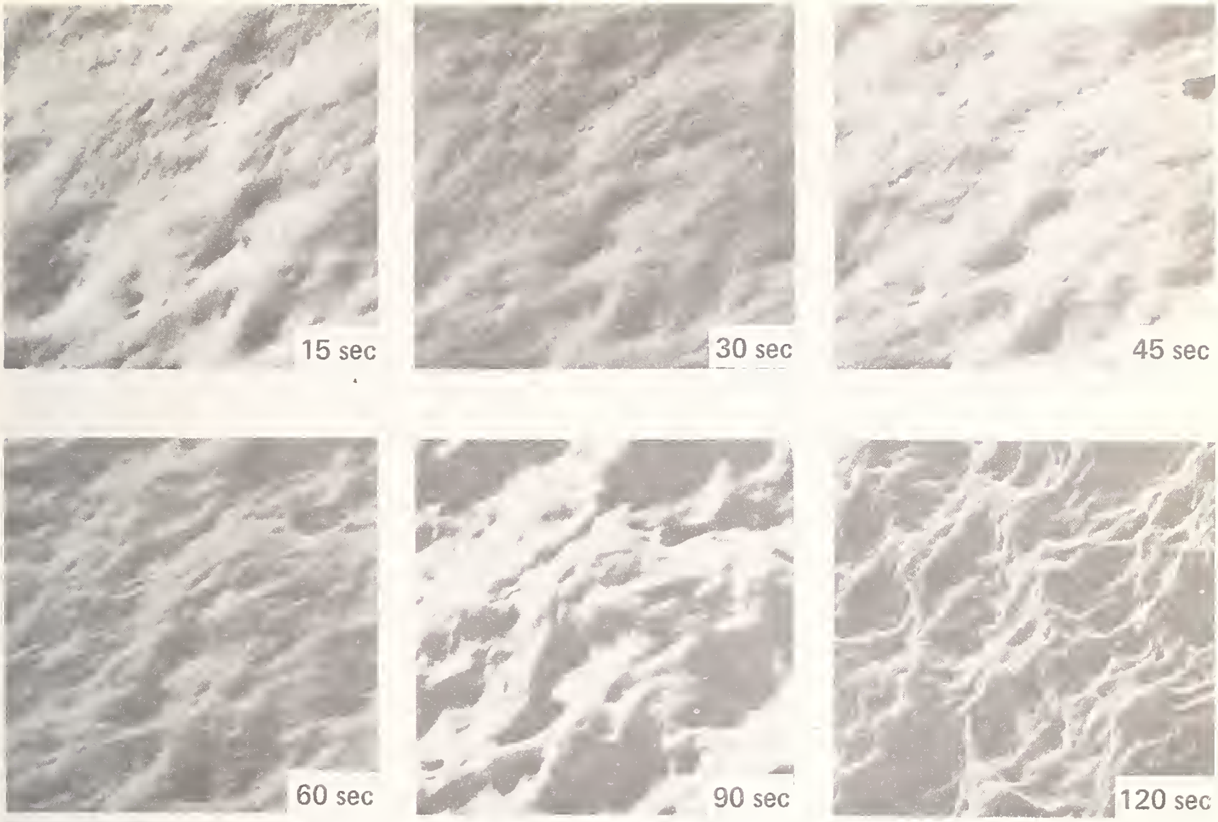


Figure 1. Incubation Stage of Cavitation Erosion of 1100 Al (650X)

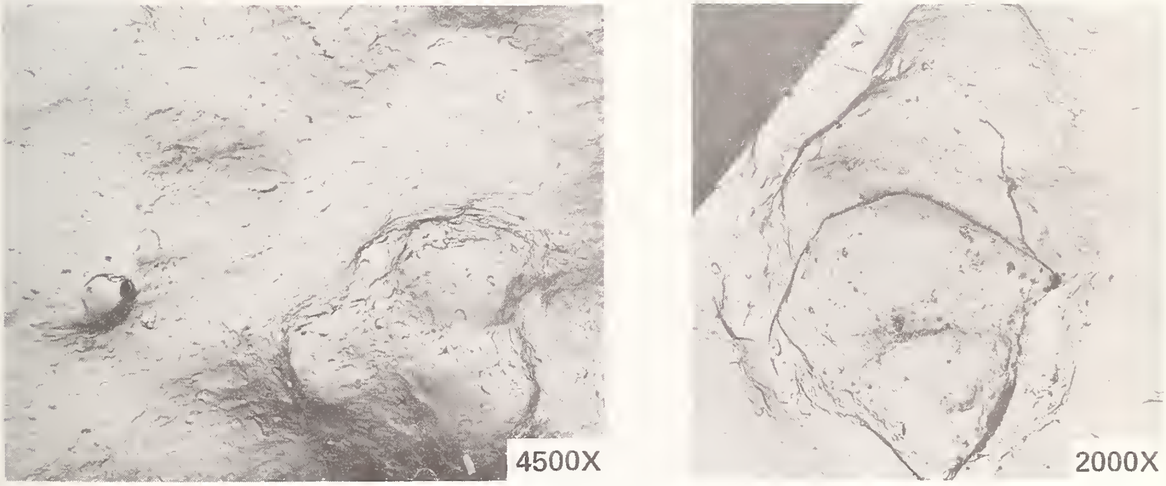


Figure 2. Multiple Impact Pits on 1100 Al after 45 sec

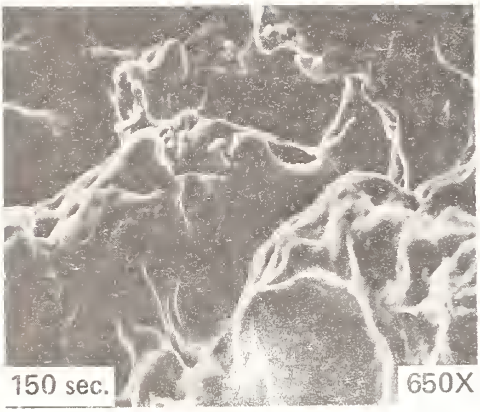


Figure 3. Fracture of Pit Lip in 1100 Al

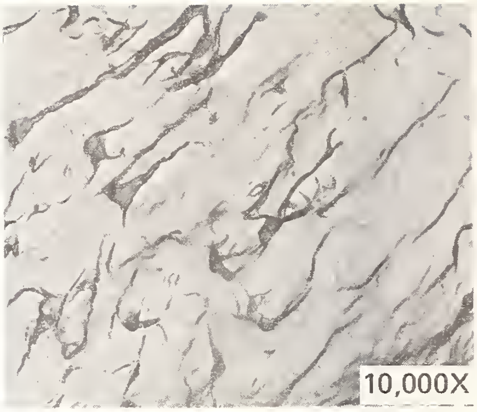
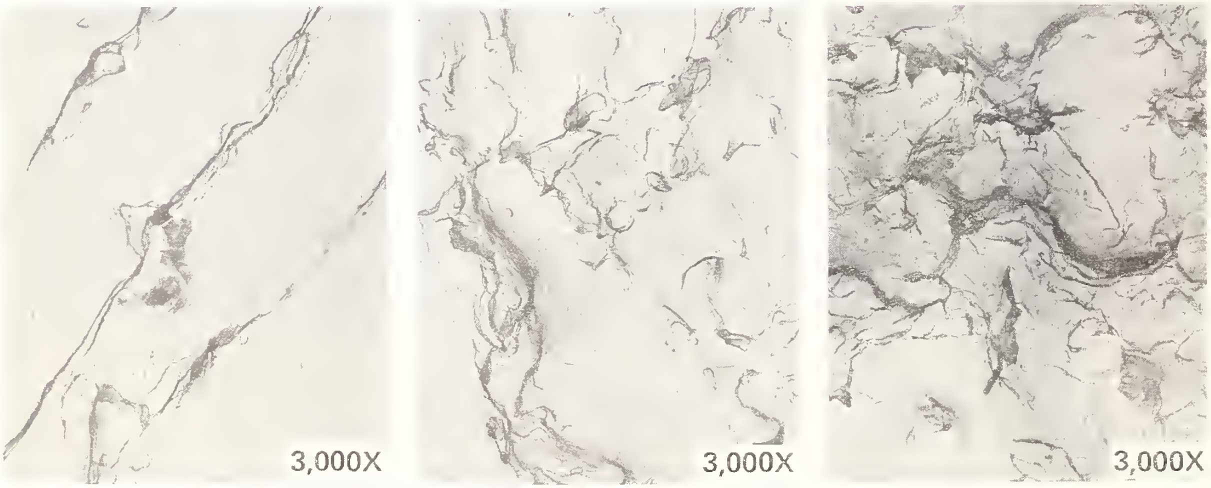


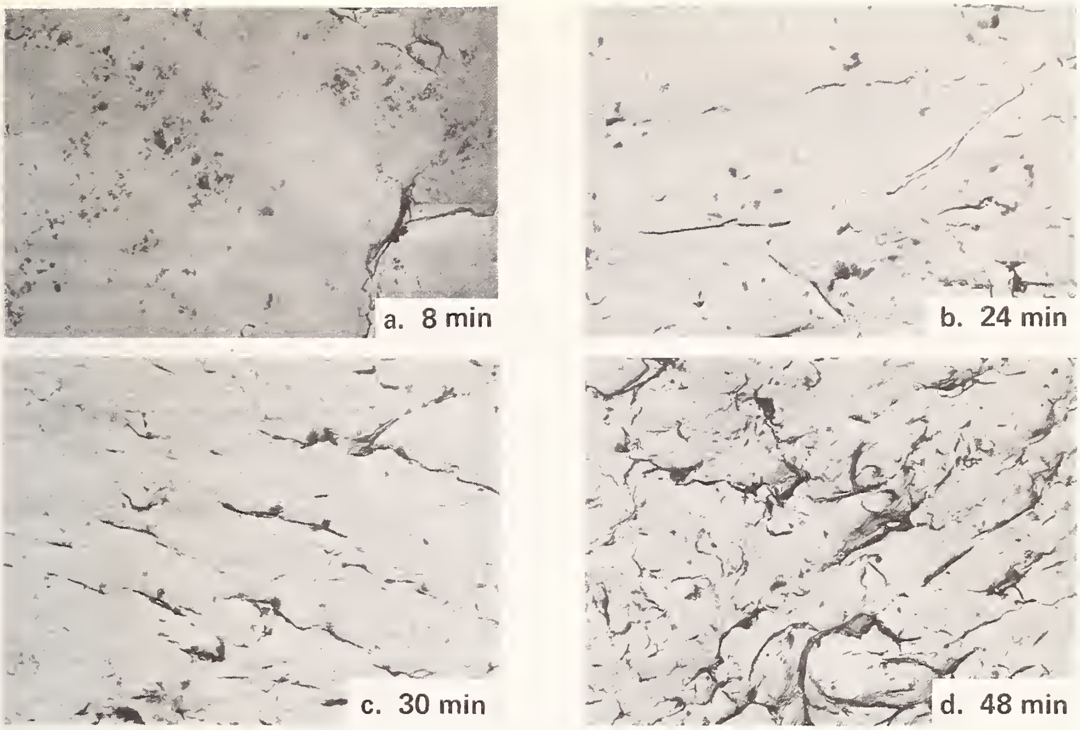
Figure 4. Pit Lip Fracture Surface

a. 4 min
b. 9 min.
c. 12 min.



d. 30 min
e. 42 min.
f. 60 min.

Figure 5. Cavitation Erosion of 316 Stainless Steel


a. 8 min

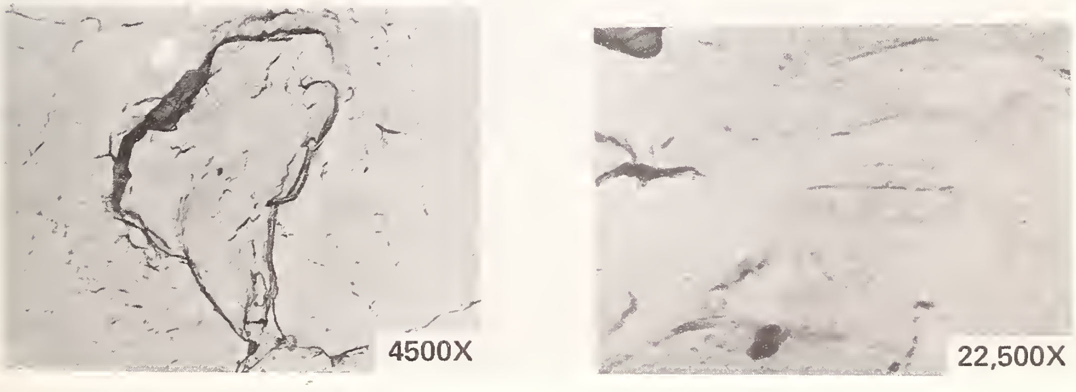
b. 24 min

c. 30 min

d. 48 min

Figure 6. Cavitation Erosion of Titanium - 6Al-4V (5000X)

Figure 7. Scanning Electron Micrograph of Ti-6Al-4V after 48 min Exposure (4400X)


4500X

22,500X

Figure 8. Fatigue Fracture Apparent after 36 min. Exposure

DISCUSSION

G. C. Gould, General Electric Company: I would first like to compliment you on doing an incredibly nice job. I saw fatigue striations one time and I believe that the alloy was again a titanium alloy. Do you know which phase, or is there a single phase, that seems to be the one that is breaking out by fatigue? Do these cusps or individual particles that break out have a constant crystallography among them? That is, are they one single grain or one single portion of the phase?

J. V. Hackworth: In answer to your first question, I really don't know. It is my impression from spending hours at the microscope that one particle is eroding preferentially in one phase, and that is the next thing we are going to look into. Based on your discussion this morning, I suspect maybe it was the α phase because the advantage of the β phase is that it has more shear planes.

G. C. Gould: That was just what I was driving at. It would be nice if you could support that.

J. V. Hackworth: The β alloy is the more fabricative. As far as the pieces coming off, I think they are about the size of the pits in the aluminum, the micro-jet type size, and we haven't tried to collect these particles and analyze them.

C. M. Preece, State University of New York, Stony Brook: The first question I have is in connection with the cracks initiating in the stainless steel. We found what appeared to be cracks initiating in aluminum, in copper, in cobalt, and in nickel, and in no case could we find any propagation of them. In other words, it appeared as though a crack was starting and we thought that with further exposure we would get a crack propagating. Never did we find this. They just stayed as a groove, effectively, and sometimes blunted out and sometimes didn't. I wonder if you found anything like that in the stainless steel?

J. V. Hackworth: I didn't really find anything in the stainless steel that I would call cracks. Before I did stainless steel I actually did the ABS type 4 bronze. There I thought I saw cracks, but as I progressed, I came to the conclusion that these were slip lines. I think that is what I found in the stainless steel. Now in titanium, between the phases, I would use quotation marks around the word cracks.

C. M. Preece: But if it's a fatigue crack, it must be a crack which is propagating.

J. V. Hackworth: Right, but I didn't find a crack like a fatigue crack. The only striations I found were when large particles had been removed.

C. M. Preece: In all of the materials we saw, we got the grain boundary effects that you observed in the stainless steel, and again, this occured earlier on and they didn't seem to develop into anything. Do you think that these striations could be stress corrosion type striations rather than fatigue type striations? These are known to occur in titanium alloys.

J. V. Hackworth: These don't look like what I have been calling corrosion fatigue. What we found for corrosion fatigue in titanium, at least in salt water, was that the striations aren't apparent. They're harder to find and they aren't straight and uniformly spaced.

C. M. Preece: Did you find any trace of the phase transformation from α to β phase, or vice versa, as Dr. Gould suggested with some of the steels and cobalt?

J. V. Hackworth: No, we didn't get into the phase transformation.

C. M. Preece: Did you look for it?

J. V. Hackworth: No. I don't think you would get a phase transformation.

LUBRICANT PRESSURE RIPPLING IN DYNAMIC HERTZIAN CONTACTS INDUCED BY SURFACE ROUGHNESS

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Because of surface roughness, the pressure distribution in a lubricated Hertzian contact will be subject to random fluctuations in time even though there may be no direct contact of the rough surfaces. The magnitude of these pressure fluctuations as measured by their RMS value for the contact of two-dimensional (long) cylinders is found to vary with 1) the location in the contact 2) the spectrum or frequency content of the surface roughness 3) the mean plateau film thickness and 4) the RMS value of the surface roughness.

Figure 1 is a sectional view of the contact zone of a rough cylinder in lubricated contact with a flat plane. (The lubricated rolling contact of two rough cylinders of general radii can always be reduced to an equivalent rough cylinder and smooth plane configuration.)

The contact width 2a is assumed to be equal to the value calculated for smooth surfaces under the same load. The surfaces move at a velocity U in the positive X direction with respect to a coordinate system fixed to the contact. The separation is a function of x and time, t, expressible as,

$$H = h(x) + r\ (x-Ut) \qquad (1)$$

where h(x) is the mean film profile i.e. the film profile that obtains when the surfaces are smooth and, r(x) for fixed x is a stationary, ergodic random process having a zero mean and variance σ^2. The roughness is considered to consist of grooves running transverse to the rolling direction.

The mean film thickness h(x) diminishes rapidly with x over the inlet region, is very nearly constant over most of the contact zone and decreases near the outlet to a value roughly 3/4 the plateau level, to form the outlet constriction. (The precise dimensions of the outlet constriction depend upon the lubricant and operating variables.)

The pressure distribution p(x) and the film shape H(x) must jointly satisfy the Reynold's equation of hydrodynamics and the displacement equations of elasticity theory.

Under the assumption that lubricant viscosity is independent of pressure, the relevant form of Reynold's equation reduces to,

$$\frac{\partial}{\partial x} \quad H^3 \frac{\partial q}{\partial x} = 12 \, \eta_0 \frac{\partial h}{\partial x} \tag{2}$$

where q(x) is the isoviscous pressure distribution. If viscosity varies exponentially with pressure, as $\eta = \eta_0 \exp(\alpha p)$, the pressure distribution p(x) may be obtained from the isoviscous solution as,

$$p(x) = \frac{1}{\alpha} \log \frac{1}{1-\alpha \, q(x)} \tag{3}$$

Eq. (2) may be integrated to give

$$H^3 \frac{\partial q}{\partial x} = 12 \, \eta_0 U(h-\bar{h}) \tag{4}$$

where $\bar{h}$ is the value of the mean film thickness at which $H^3 \frac{\partial q}{\partial x} = 0$.

Following the Grubin assumption, over most of the high pressure (plateau) region q is constant with value $1/\alpha$, and hence $\frac{\partial q}{\partial x} \cong 0$ and therefore $H^3 \frac{\partial q}{\partial x} \cong 0$ and $h \cong \bar{h}$, irrespective of H over this region. We may thus regard the right hand side of Eq. (4) as non-random and express $\frac{\partial q}{\partial x}$ as,

$$\frac{\partial q}{\partial x} = A(x) \, . \, H^{-3} \tag{5}$$

where $A(x) \equiv 12 \, \eta_0 \, U(h-\bar{h})$ is a non-random function of x.

We now find the variance of p(x) by the following series of steps:

1. Assume a spectrum for the roughness process r(x).
2. Calculate the auto-correlation function (ACF) of r(x).
3. Calculate the auto-correlation function for $H^{-3} = (h+r)^{-3}$ in terms of the ACF of r(x).
4. Calculate the spectrum $\pi(\omega)$ of H^{-3} as the Fourier transform of the auto-correlation function.
5. Calculate the spectrum of $\partial q / \partial x$ as $A^2 \pi(\omega)$.
6. Calculate the spectrum of q(x) using the relation between spectra of functions and their derivatives.
7. Calculate the variance of q(x) by integrating its spectrum over ω.
8. Calculate var $p(x) = \exp 2\alpha p.$ var $q(x)$.

In performing the calculation it is assumed that the spectrum of r(x) is bandwidth limited white noise of the form,

$$\begin{aligned} \pi_r(\omega) &= K \quad \text{for } \omega_0 - b < \omega \leq \omega_0 + b \\ &= 0 \quad \text{elsewhere} \end{aligned}$$

wherein K is selected so that the integral of the spectrum is σ^2.

The final expression for $\text{var}^{1/2}$ p is,

$$\mathrm{var}^{1/2}p = 29\exp(\alpha p)\,\eta_0 U \frac{|h-\bar{h}|}{h^3} \cdot \frac{\sigma}{h}\frac{1}{\omega_0}\left\{\left[1 + 20\,(\sigma/h)^2\right]\frac{1}{1-(b/\omega_0)^2} + 2\,(\sigma/h)^2\,\frac{1}{(b/\omega_0)^2}\log\frac{1}{(b/\omega_0)^2}\right\}^{1/2}$$

Existing numerical solutions of the EHD problem for cylinders do not give sufficient discrimination to determine maximum values of $\mathrm{var}^{1/2}p$ very precisely. This is evident in the plot shown in Figure 2 of the quantity $\frac{|h-\bar{h}|}{h^4}\exp\alpha p$ to which $\mathrm{var}^{1/2}\,p$ is proportional, constructed using data from (1).

Using the values,

$$\frac{|h-\bar{h}|}{h^4}\exp\alpha p = 2/3 \qquad \text{(inlet)}$$

$$= 2 \qquad \text{(constriction)}$$

will give under-estimates of maximum values for $\mathrm{var}^{1/2}p$ for the inlet and constriction regions.

Figure 3 shows $(3\,\mathrm{var}^{1/2}p)_{max}$ thus under-estimated for the inlet and constriction region plotted against $\bar{h}/\sigma$ for $b/\omega_0 = 0$, 0.8 and 0.95, calculated using $U = 460$ in/sec, $\alpha = 10^{-4}$ in^2/lb, $\eta_0 = 14.10^{-7}$ lbsec/in^2, $p_{max} = 4 \times 10^5$ psi, $\bar{h} = 6000$/in and $\bar{h} = 11 \times 10^{-6}$ μin.

Ripple amplitude at the constriction ranges from 7.10^4 psi to 6×10^5 psi at $\bar{h}/\sigma = 2.0$.

Ripple pressures calculated using the assumptions of this analysis are thus seen to be of an order comparable to the maximum Hertz pressure.

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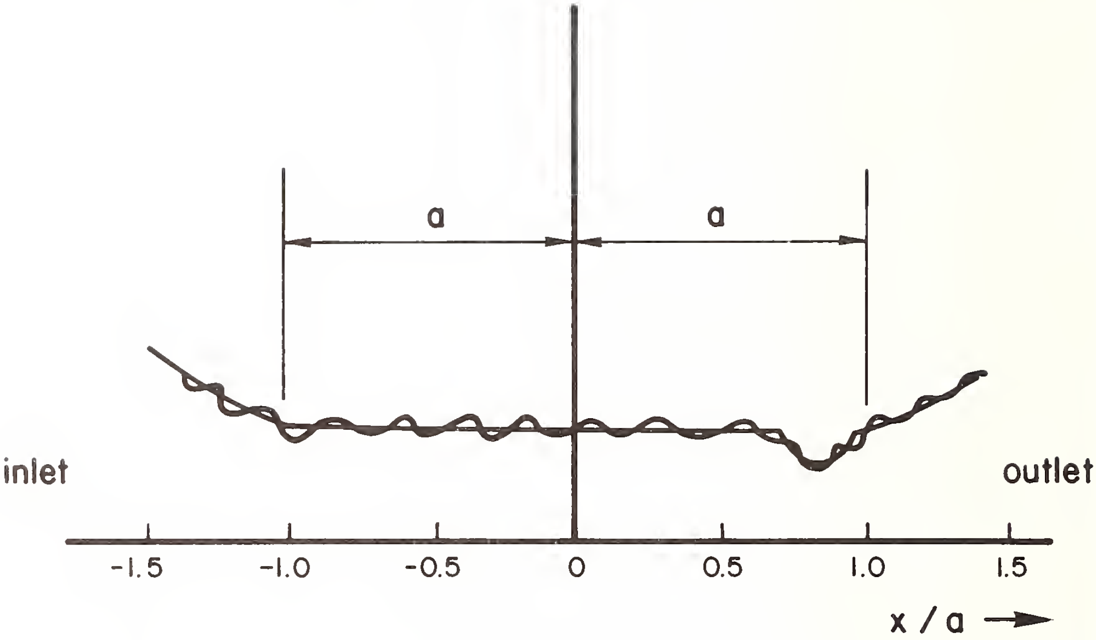

$$H = h(x) + r(x - ut)$$

Figure 1.

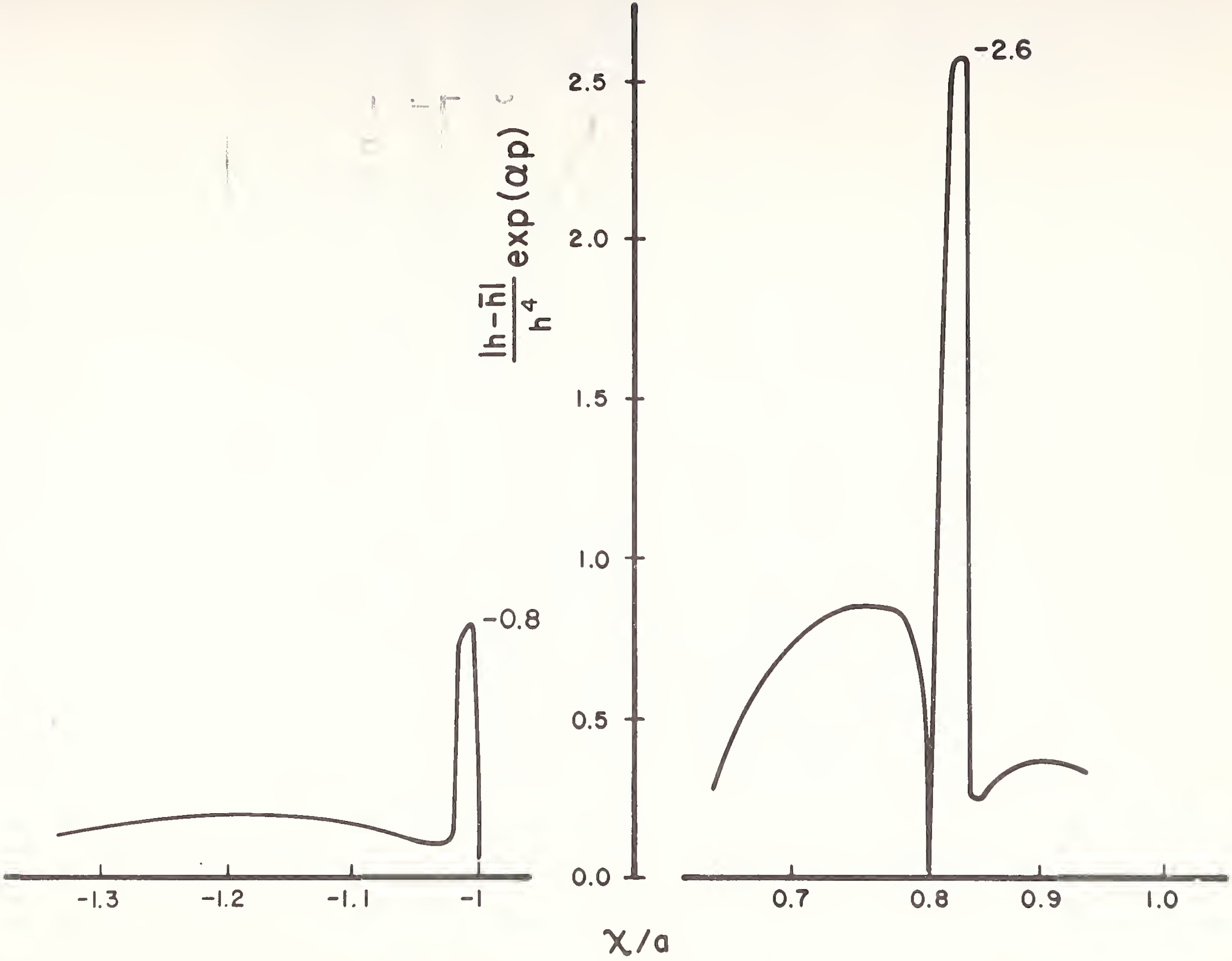
$\frac{|h-\bar{h}|}{h^4}\exp(\alpha p)$
2.5
2.0
1.5
1.0
0.5
0.0
-0.8
-2.6
-1.3
-1.2
-1.1
-1
0.7
0.8
0.9
1.0
χ/a

Figure 2.

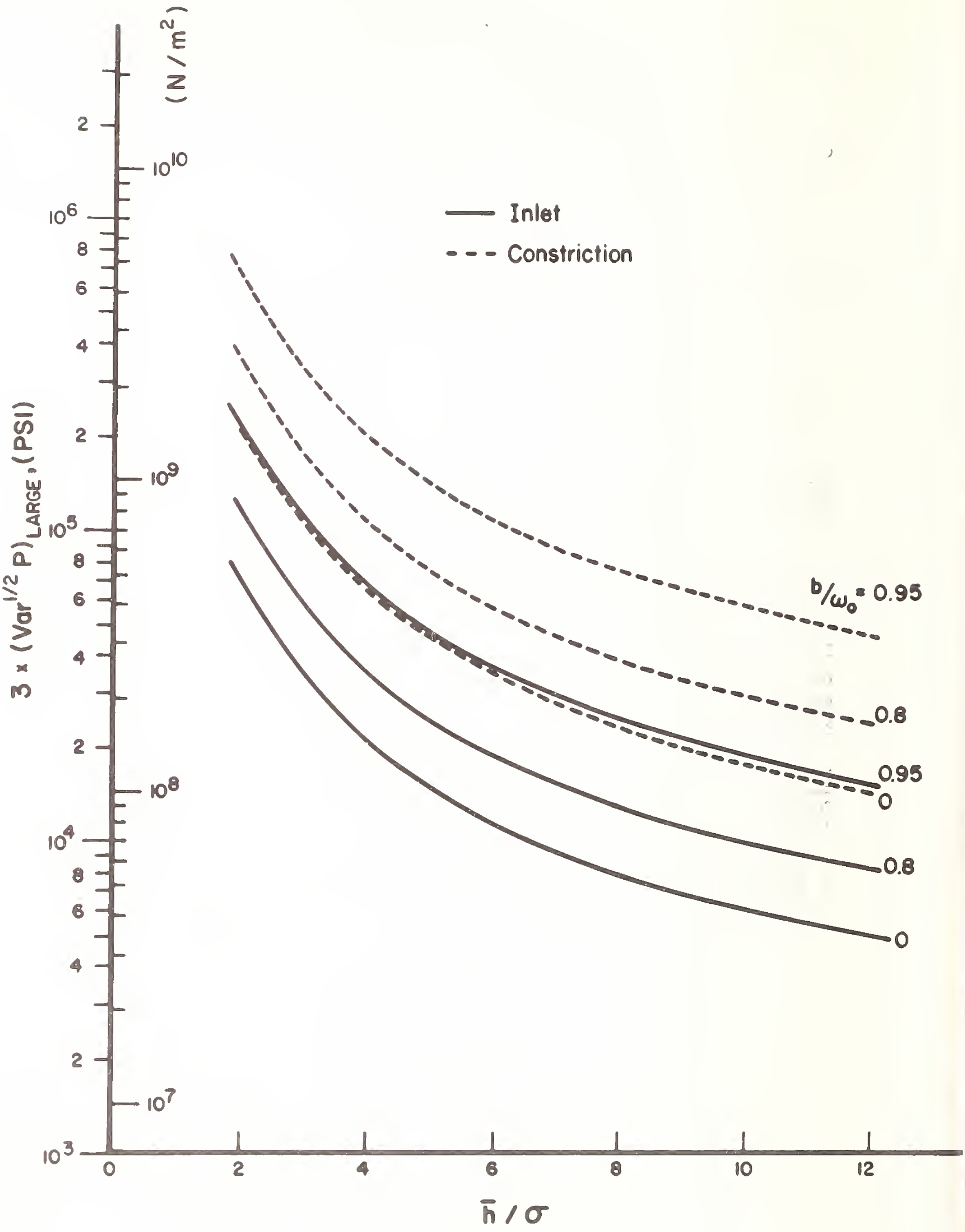
(N / m²)
$3 \times (\mathrm{Var}^{1/2}\,P)_{\mathrm{LARGE}}$, (PSI)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
2
8
6
4
Inlet
Constriction
$b/\omega_o = 0.95$
0.8
0.95
0
0.8
0
0
2
4
6
8
10
12
$\bar{h}/\sigma$

Figure 3.

DISCUSSION

J. A. Walowit, Mechanical Technology: What is going on right in the center of contact where there is 400,000 psi pressure? It looked to me like a typical asperity could have a height of the order of half the thickness of the film and a length of maybe 20% of the half-width of the contact zone. If that is the case, how would that perturb the pressure right in the contact zone? How would that affect neglecting the pressure gradient, the influence of the asperity on the pressure gradient term in the Reynolds' equation?

J. I. McCool: We did make the assumption that the roughness frequencies were large relative to the contact width. I don't know how you made that calculation.

J. A. Walowit: I was trying to take the number of waves per inch that you said were present in the example. That's about 1000, or about one mil per wave, with a half-width of 10 mils. That's 10 to 1 right there and it could easily have been 2 mils per wave which would give 5 to 1. It looked like a significant fraction just from that.

J. I. McCool: Naturally, the validity will erode down in that regime. We feel best in saying that these results will apply where frequencies are high relative to the contact width. This would get back into studying asperities as individual things, which is something that was done at Mobil a few years ago. It was found that where two individual asperities collide, there were staggering magnitudes of temperatures and pressures.

L. L. Ting, Ford Motor Company: In his original model, Christian considered three types of roughness: widths, transverse and longitudinal, and so-called isotropic uniform. It seems to me in your analysis you only solve for the transverse case. Are you going to extend your analysis to consider surface roughness independent of direction, just like the uniform isotropic case?

J. I. McCool: I certainly think it deserves attention because obviously there will be flow around these things. Maybe we've over-estimated the actual situation by neglecting this flow. In three-dimensional contacts there may be a circular contact with a horseshoe around it. By analogy, this sort of thing could be expected to occur there, but in that case, neglecting the crosswise components of flow could lead to erroneous results. Initial results indicate that the effects can be large. Now we must go further.

F. G. Hammitt, University of Michigan: With regard to the pressure coefficients on viscosity, I am running through some rough numbers from the view point of impact of droplets. In erosion or cavitation damage, one gets pressures in the range perhaps of 10^4 or 10^5 psi from straight-forward calculations. If the coefficient that you showed is applied, there would be an enormous increase of viscosity which could then affect the behavior of the fluid under those conditions rather drastically. That was for oil, I suppose. Was water at all similar in this regard?

J. I. McCool: Definitely in lubricated EHD contacts, the viscosities do rise astronomically over their ambient values. We consider the fluid to be more like a tar than a liquid as we know it.

F. G. Hammitt: That does not very much affect the calculations of pressures under droplet impact or cavitation bubble collapse.

J. I. McCool: I hadn't realized that the EHD and the cavitation people hadn't converged. Maybe this is something the two disciplines can get together on, because we have been considering pressure rises with viscosity for years.

F. G. Hammitt: Do you know if water behaves in a relatively similar way to oil?

J. A. Walowit: I think it's considerably lower than the oil. Oil can have a pressure coefficient of viscosity of 10^{-4} reciprocal psi, which means that a 10,000 psi pressure rise will up the viscosity by a factor of e. That means 100,000 is at e^{10} and 400,000 — it's ridiculous. Eventualy one of a number of things will happen as these enormous pressures are approached: 1) the viscosity curve will level off, 2) it's been conjectured that there will be solidification. Water is a somewhat different animal in that it has a much lower pressure coefficient of viscosity.

F. G. Hammitt: Do you have any idea what magnitude it is for water?

J. I. McCool: We never use water on purpose.

J. A. Walowit: You're right. Water is something you do not put in your rig. I'd say it's many orders of magnitude lower, but I don't know.

F. G. Hammitt: In the same regard, that's a steady state effect, isn't it?

J. I. McCool: Yes.

F. G. Hammitt: What about very high rates of erosion? Those also have the effect of making the viscosity apparently go up. Is that also true for oil?

J. I. McCool: Yes, there are models for that.

E. E. Klaus, The Pennsylvania State University: There are several problems in viscosity-pressure. One is the effect of temperature. The effect of 400 psi pressure on the viscosity is about equivalent to the effect of one degree temperature change. The pressure rise causes an increase and the temperature rise causes a decrease. It is true that at the very high pressures, there are very high viscosities. There are some classic data in the literature on this, and there is a lot of current activity trying to find out what happens in transients. The EHD film behaves as though the viscosity is very high once it gets in the region that Jack McCool was showing in his slides. It's the inlet zone that people are talking about as to how much fluid will get into the conjunction. Most of the treatments, until quite recently, have been isothermal, not accounting for temperatures. Recently the people at Georgia Tech have tried to measure temperatures in the kind of contact we're talking about here and have found temperatures of the order of 600°F on the surface of the bearing during this occurrence. It's a little more difficult to measure the temperature in a fluid, but if it is assumed that the fluid temperature can also be high under these conditions, the two effects fight each other. The effect of pressure causes a very sharp increase in viscosity and the effect of temperature causes a rather dramatic decrease.

SESSION III

Chairman: M. J. Devine
Naval Air Development Center

ASPERITY LUBRICATION AND CAVITATION IN FACE SEALS

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The problem of parallel-surface lubrication has been of considerable interest to people involved in rotary-shaft face-seal and thrust-bearing technology for many years. The basic aspect of parallel-surface lubrication that distinguishes it from other areas of lubrication technology is that classical lubrication theory does not predict the existence of a stable hydrodynamic film for steady-state, isothermal, incompressible flow between smooth, parallel surfaces. Hydrodynamic films between apparently parallel surfaces have been observed in practice and are often essential for the reliable performance of thrust bearings and seals. In order to account for this fortunate discrepancy between classical theory and experiment, various investigators have proposed load-support mechanisims relating to accidental features characteristic of seal performance, which relax one or more of the assumptions in the classical theory and permit the theoretical prediction of load support. Some of the features that have been analyzed are vibratory effects such as wobble and bounce, surface waviness, nonsymmetric rotation resulting from various types of misalignment, lubricant density change, non-Newtonian lubricant effects, and surface roughness. A partial bibliography of these analyses is given in References 1 and 2. Most of the mechanisms dealt with in these analyses can account for various modes of seal performance when the hypothesized mechanism is present.

In initial experiments performed in the research described in Reference 1, efforts were made to construct laboratory face seals having smooth parallel surfaces and to keep the accidental features discussed previously to a minimum. In keeping with the classical theory, the initial result was that these seals did not develop any hydrodynamic load support. After the seals were run for several minutes, however, hydrodynamic load support did occur simultaneously with the development of cavitation streamers initiating at the many scratches that were working into the surface during the initial running period. Cavitation streamers have also been observed on practical sealing surfaces such as the carbon graphite stator shown in Figure 1. The carbon graphite stator was lapped flat to within 5 microinches, rms. The dark regions are oil and the light regions are gaseous. The points at which some of the streamers appear to terminate and originate abruptly correspond to irregularities on the stator surface indicating that streamers were associated with surface roughness.

Fig. 1 Cavitation Streamers in a Face Seal Containing A Carbon Graphite Stator and a Transparent Rotor. Motion is From Left to Right

After a series of experiments performed with smooth and rough lapped copper stators (see Reference 1) it was decided to study the effects of surface roughness and cavitation on load support by photoengraving an array of large regularly shaped asperities having a controlled geometry of cylindrical asperities. A photograph showing both the asperity pattern and the cavitation pattern about a photoengraved stator is shown in Figure 2.

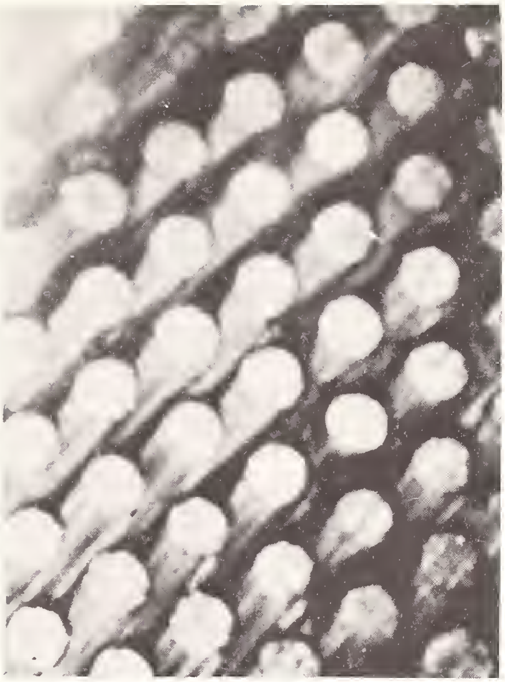

Fig. 2 Asperity Pattern Showing Cavitation Streamers on a Photoetched Copper Stator. Asperities are 12 Mils in Diameter and 130 Microinches High.

The surface finish on the tops of these asperities were apparently as smooth as the surface that did not support load in the initial experiments with smooth-lapped stators, since the etching process associated with the photoengraving process attacked the region around the asperities but not the asperity surfaces. These photoengraved stators were found to develop stable hydrodynamic films immediately; i.e., no wearing-in was needed.

Lubricant film thicknesses over the asperities were determined by measuring the capacitance reactions between the rotor and the stator and were found to range between 5 and 20 microinches which is small compared with the asperity heights.

The cavitation patterns were relatively steady and the cavities are believed to be filled primarily with gas coming out of solutions as opposed to vapor. No cavitation damage has ever been observed and the cavities did not disappear instantaneously upon shutdown.

In general, the pressure profile about an asperity would tend to be positive in regions where the film thickness decreases in the direction of motion and sub-ambient in areas where the film thickness increases in the direction motion. These high and low pressure regions should tend to cancel each other out over an entire surface resulting in little or no load support were it not for the occurrence of cavitation. Cavitation will limit the sub-ambient pressure to the cavitation pressure thereby preventing this complete cancellation.

An analysis of the load support that could be generated over and around perfectly flat-topped asperities having a geometry such as that shown in Figure 2 drastically under-predicts measured film thicknesses. Some rounding has been observed to occur near the edges of the engraved asperities however, and it is possible that convergent portions of the asperity tops could be responsible for the observed load capacity. Cavitation would be expected to occur over divergent portions.

In an attempt to correlate film thickness measurements, the asperity tops were modelled to have a small effective tilt as shown in Figure 3 where the film thickness was assumed to be small compared with the asperity height and the tilt $\delta = h_1 - h_o$ was assumed to be small compared with the mean film thickness h_o. The analysis of this model which is described in Reference 2 resulted in the following formula for load capacity:

$$\overline{p} = .75 \mu u_o R_o \delta / h^3_o$$

where μ is the lubricant viscosity, u_o is the linear speed of the rotor and $\overline{p}$ is the applied load divided by the area of the tops of the asperities. The effective tilt parameter δ was determined by a fit to the experimental data to be . 43 microinches which is small compared with the film thickness.

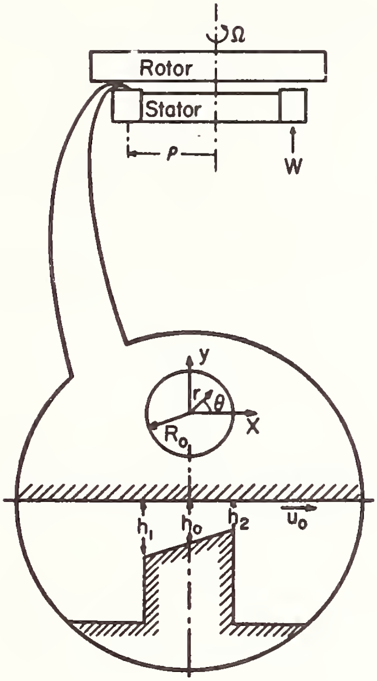

Fig. 3 Theoretical Asperity Geometry

A comparison of the semi-empirical relationship given above and the experimental data is shown in Figure 4. The data were obtained with three different test machines, two different lubricants [a mineral oil (Sohispin 100) having a viscosity of 9 centistokes at 130 F and a jet-engine fuel (JP-5) having a viscosity of 1.3 centistokes at 130 F] five different stators, and eight different rotor speeds [varying from 220 rpm (3.5 fps) to 900 rpm (14.4 fps)]. Although scatter in the data is evident, in general the correlation is good. The standard deviation of the film-thickness data from the curve being fitted is 1.25 X 10^{-6} in.

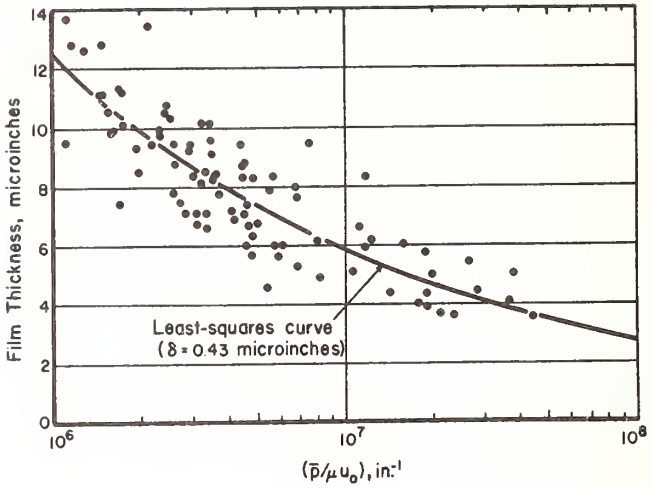

Fig. 4 Correlation of Film-Thickness Data With The Parameter ($\bar{p}/\mu u_o$), R_o = 6 Mils.

All of the research summarized here was performed at Battelle Memorial Institute and is described in detail in References 1-3. It is concluded that the theory, developed on the assumption that there exist small tilts on the tops of the asperities, correlates well the experimental data on film thickness for the microasperity patterns studied. Further, from the load support observed, it is apparent that use of planned microasperities is an effective method for lubricating the parallel surfaces of face seals and thrust-bearing surfaces.

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DISCUSSION

J. D. Cogdell, Caterpillar Tractor Company: I was intrigued with your film thickness measurements. I am curious as to how you got down to such fine measurements with capacitance probes.

J. A. Walowit: We did not use capacitance probes. We measured the gross capacitance across the film. In other words, the whole machine, the rotor and stator, was the capacitor.

M. Wildmann, Ampex Corporation: If you used the gross capacitance, how did you take account of the dielectric of the oil and the effect of the cavity which has a different dielectric from the oil itself?

J. A. Walowit: This is indeed a problem. We did make the assumption that the areas over the asperity tops were largely oil, and we did use the dielectric coefficient corresponding to the oil. The area around the asperities will not contribute much to the capacitance because we are talking about 10 μin. over the asperities, and the asperities themselves are about 100 μin. high. But even over the asperities there can be cavitation which can lead to some error.

G. O. Ellis, Vickers Division, Sperry Rand Corporation: Right now I'm involved with the cameraing on vane pumps and on the vanes themselves. We have random failures on our production tests and I am trying to find out why. I've developed a mathematical theory, much as you have, based on roughness. It was pretty hard to convince people that some roughness is needed in order to get the vanes to ride on a film. The vanes have a slanted tip, and the tip has a 0.025 in. radius which will usually generate a film. We studied surface roughness and we couldn't find much difference between just a fairly smooth surface and a smooth surface, but we found a lot of waviness. We first found it in the axial direction with a Talysurf. We obtained a trace of the contour to see if we were getting the correct contour. We had two machining procedures which gave us different contours and different waviness. The one with the larger waviness always failed. They both had about the same mean average roughness, but one had more waviness than the other. It should be realized that a CLA (center line average) roughness, doesn't indicate anything about waviness. By waviness I mean that the roughness is superimposed over a 1/4 inch wave, and it seemed the wave was the thing that was generating the film.

J. A. Walowit: I agree. Surface waviness, if present, is a very effective film generator, but other factors may have to be considered. If there is a wedge to begin with, waviness can either be advantageous or detrimental. It can detract from the wedge action. In my case, I have perfectly flat surfaces. With a small wave on them they will support a lot of load. Surface waviness will really work well, and this is one of the "accidental" features that has been studied quite a bit in the seal literature. In our particular work on asperity lubrication, the surface waviness and the asperities will fight each other. Particularly, the asperity lubrication will provide so many ambient pressure sources along the wave that the wave itself will cease to be effective. Furthermore, in our own test rig, we had looked at surface waviness quite a bit and we had gotton the amplitudes of the surface waves way, way down.

R. L. Johnson, NASA, Lewis Research Center: I am wondering if, in your asperity lubrication, you ran under conditions where, by virtue of cavitation phenomena, you were getting starvation on the asperities. This could adversely affect the load capacity, the lift obtained from the fluid at the interface. Another point I want to make is simply a comment. All of this discussion brings out the very pointed need for better ways of defining surfaces. Three-dimensional methods of measuring surfaces are needed to give both texture and roughness, and also a model for properly describing the surface so that it can be treated mathematically. This is a very urgent need that I think is pointed up by work such as this.

J. A. Walowit: In answer to your first question some of those asperities were certainly at least partially starved. For our own apparatus, though, we have these tall asperities and a radically interrupted surface. There are many ways for lubricants to get in, so in some cases there is probably more flooding than there normally would be. In other cases, because of the cavitation going right up to another asperity, there is probably partial starvation. So both are probably entering in.

H. Weinhold, TRW: In one of your schematics you solved the Reynolds' equation for a tapered wedge with a circular cross section. How did you solve the Reynolds' equation? Did you use relaxation techniques? It sounds like a formidable mathematical undertaking — it must be solved in three dimensions.

J. A. Walowit: A great deal of linearization and simplification occurs based on the assumption that the tilt itself is small compared to the mean film thickness.

H. Weinhold: So the end leakage doesn't have to be accounted for.

J. A. Walowit: There is a simple analytical formula. It turns out that the value of the tilt that we used was about 1/2 μin. The mean film thickness was on the order of 10 or 20 μin. There is a 1/2 to 20 ratio which is indeed a small tilt.

H. Weinhold: So you solved it actually as an infinitely long bearing?

J. A. Walowit: No, we made use of the circular geometry. We could use essentially a constant H except for the generating term in Reynolds' equation where we plot the slope.

H. Weinhold: Do you know of any work that is being done to define surface configurations as produced by various processes? I remember years ago at an MFPG session there was a gentleman who was doing some work where he showed mathematically that for the definition of the surface, the rms, the first derivative, and the second derivative are needed. Then by statistical analysis he could prove he knew what the surface was. Has any work been done along those lines? In addition, has any work been done to non-dimensionalize hydrodynamic effects of such surfaces? Is there a practical tool available for the designers?

J. A. Walowit: A great deal of work has been done in many of these areas in heavily loaded contacts as opposed to parallel surfaces, where again small films are dealt with and the roughness is not necessarily responsible for the lubrication. It's affecting the process, partially elastohydrodynamically, bordering between thin film lubrication and dry contact. There has been a great deal done to classify surface roughness and to take into account its interactions. There has been some work done in seal-type geometries in a continuation of the study that I have spoken about. Special types of controlled shapes of surface roughness have been looked at.

L. L. Ting, Ford Motor Company: Is it necessary to consider elastic deformation of the micro-asperities in your analysis?

J. A. Walowit: Not these particular ones. We had done that. We computed the elastic deformation to see if that was interacting with the tilt. But with a tilt of about 1/2 μin. across the asperity, to fit the data elastic deformation would give 1/10 to a couple of hundredths of that magnitude.

EFFECT OF CAVITATION ON FLUID STABILITY IN POLYMER THICKENED FLUIDS AND LUBRICANTS

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Linear type polymeric additives are widely used in modern hydraulic fluids and lubricants to improve the viscosity-temperature characteristics of the finished product. In some cases these additives have been developed to provide detergency, pour depression, dispersancy and lubricity in addition to improved viscosity-temperature properties. The effects of high energy input from high temperatures, gamma radiation, turbulent flow and ultrasonic irradiation on polymer solutions are shown as a permanent loss in viscosity of the fluid. In all cases the initial rate of viscosity loss is high and a stable viscosity above that of the base stock is approached with time. Both the type of high energy source and the energy intensity influence the asymptotic viscosity of polymer solutions. The similarity of time-energy severity relationships has resulted in a number of studies to determine the similarity or differences in the mechanisms of polymer degradation.

The polymeric additives used in functional fluids includes polybutenes, polyacrylates, polymethacrylates, polystyrenes, polyesters, etc. The comparisons used in this evaluation are based on polybutene and polymethacrylates. Several molecular weight ranges of polymethacrylate are represented.

A comparison of thermal and mechanical stability tests for these polymer solutions show distinct differences in the mechanism of the polymer degradation. The thermal degradation tests appear to cause an unzippering or depolymerization type of reaction in which there is no particular selectivity based on molecular weight. The reason for the selectivity noted by the characteristic asymptotic shape of the viscosity curve as a function of time is not clear at this point. However, the mechanical degradation of these fluids appears to be based on molecular weight. Measurements of molecular weight distributions during mechanical degradation show that for a given level of intensity only molecules above a certain minimum size are degraded. The independence of the degradation mechanisms can be shown by conducting mechanical tests on thermally degraded polymers and thermal tests on mechanically degraded polymers. In each case the second test shows a substantial change in properties after the initial test had indicated essentially no further degradation with time.

Radiation is in many ways the most severe of the degradation tests conducted. This type of stability test still shows an appreciable rate of deterioration after extended exposure time. In fact effective nuclear collisions appear to result in polymer degradation in all cases.

Ultrasonic radiation is probably the most widely used test to degrade polymer solutions (ASTM Test Method D2603-70). The mechanism of polymer degradation in this test appears to be cavitation. The sonic stability tests and the mechanical stability tests have been compared by investigators with the general conclusion that there are significant differences between the degradation produced by the two test methods. In general agreement between sonic and mechanical degradation tests are relatively good when the same polymer or polymer type is compared. Comparisons involving polymers of different chemical classes are not in good agreement. This lack of agreement suggests that the mechanisms involved in the two processes may be different. On the other hand the mechanisms may well be similar and the level of severity different. Several mechanical evaluation tests have been devised to determine the potential role of cavitation in the mechanical degradation process.

In this study, a sharp edge orifice was employed as a device for producing mechanical degradation in polymer solutions. The sharp edge orifice is a simple yet severe device for producing mechanical degradation of polymer solutions. When the pressure downstream of the orifice is of the order of less than 100 psig degradation is a function of pressure drop across the orifice and gives maximum severity levels. If, however, two orifices are used in series or if a capillary is used to produce a high pressure downstream of the orifice, the severity of the upstream orifice for mechanical breakdown is greatly reduced. These effects are shown in Table 1.

If one defines the conventional cavitation number as

$$\sigma = \frac{P-P_c}{1/2\ \rho U^2}$$

where P = absolute static pressure

P_c = vapor pressure of fluid

ρ = mass density

U = characteristic velocity

then it follows that the degree of cavitation or the tendency to cavitate increases as this parameter is decreased. An increase in pressure downstream of the orifice will decrease the cavitation number and the cavitation intensity but will not influence the shear field in the orifice. The influence of the absolute pressure on the degree of degradation clearly indicates that the degradation is a cavitation related phenomena.

Another series of experiments was conducted to demonstrate the mechanism of mechanical breakdown in an orifice. In this series of tests a single pass through an orifice is used instead of continued recirculation through the orifice. In simple one pass tests through the orifice, depending on pressure and orifice size from 3 to 7 percent of the maximum breakdown after 5000 cycles through the orifice can be achieved. By using a direct gas drive on the fluid reservoir feeding the orifice it was possible to force the fluid to pass through the orifice close to the edge of the orifice by replacing the fluid in the center of the orifice with the nitrogen gas. As shown in Table 2, the use of the direct gas drive gave as much as a two fold increase in severity of the test orifice. These results show that the critical position for the polymer degradation is the concentric layers of fluid flowing by the surface of the orifice. The fluid in the center of the orifice does not appear to be degraded.

One additional series of single pass tests through the orifice was conducted to test this mechanism. In these tests the fluid was saturated with carbon dioxide prior to passing through the orifice. The test results presented in Table 3 show a 30 to 70 percent decrease in degradation due to the presence of the dissolved carbon dioxide.

The combined data from the orifice degradation test can be taken as proof of cavitation as a major contributing factor to the polymer degradation in this test system. The overall data show that the outer edge of fluid flow through the orifice is the part of the fluid degraded on each pass. This region of fluid flow would encounter the maximum velocity and pressure change on going through the orifice. That is, this portion of the fluid would be in the cavitation zone. The application of back pressure on the downstream side of the orifice reduces cavitation tendencies and also reduces fluid degradation. The use of dissolved carbon dioxide in the system tends to make cavitation easier to achieve but affects the collapse rate of the cavities thereby reducing the cavitation damage. These data all point to cavitation as the major degrading factor in the orifice system. The level of severity may, therefore, be the major difference between the ultrasonic and orifice devices.

Some additional tests have been conducted to evaluate a more severe mechanical device than the orifice. The device in this case is two tapered roller bearings loaded against each other by a series of springs. In the orifice pressure drops up to 3000 psig were used. In the bearing the pressure in the concentrated contact at the race and the roller ranges from about 50,000 to 200,000 psig. In addition, the fluid films (elastohydrodynamic) in the conjunction are estimated to be thin enough that all of the polymer molecules in this film will be degraded. Some test results with this bearing rig are shown in Table 2. The results indicate an increased severity anticipated by the increase in pressure drop and a change in the relative stability of polybutenes and methacrylates over that predicted by the orifice data.

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Table 1

PERMANENT VISCOSITY LOSS WITH ORIFICES

(ALL DATA FOR 100°F. WITH OILS OF 14-15 C'STOKES AT 100°F.)

Polymer	Pressure Loading Device	Pressures, P.S.I. Before Orifice	After Orifice	ΔP	% Vis. Loss After 5000 Cycles
Polymethacrylate 55	Orifice	500	50	450	7
	Orifice	2150	50	2100	37
	Orifice	2700	50	2650	38
	Orifice + Low Shear Coil	2650	375	2275	32
	Orifice + Low Shear Coil	2700	425	2275	28
	Orifice + Low Shear Coil	3050	950	2100	7
Polybutene	Orifice	850	50	800	21
	Orifice	1700	50	1650	36
	Orifice	2325	50	2275	40
	Orifice + Low Shear Coil	2600	325	2275	29
	Orifice + Low Shear Coil	2650	500	2150	24
	Orifice + Low Shear Coil	2650	925	1725	21

Table 2

ONE PASS ORIFICE SYSTEM FOR MECHANICAL DEGRADATION OF POLYMER SOLUTIONS

0.016" Diameter Orifice - 2500 psig ΔP
4% *n*-octyl polymethacrylate 160 in white oil

Values given are average of 20 tests under each condition

Test Method	Viscosity in cs. at 100°F. Orig.	After 1 Pass	% Visc. Decrease Due to the Polymer
Direct Gas Drive	30.40	27.26	14.6
Pistons in Both Reservoirs	30.40	28.0	11.2

Table 3

MECHANICAL DEGRADATION OF POLYMER SOLUTIONS

One Pass Orifice System
n-Octyl polymethacrylate - 160 in white oil
0.016" Diameter Orifice - 2500 psig ΔP

Percent Polymer	Gas in Sol. Type	PPM(Wt)	Viscosity cs. at 100°F. Orig.	After 1 Pass	% Visc. Decrease Due to Polymer
2.5	air	100	19.00	18.15	8.5
2.5	CO_2	1207	19.00	18.78	2.2
5.5	air	100	43.32	38.46	14.1
5.5	CO_2	1090	43.32	39.81	10.4

DISCUSSION

R. Y. Ting, Naval Research Laboratory: I have several questions. One, how do you measure the viscosity of these materials? Two, what is the molecular weight range you are working with, and for these molecular weight ranges, is the viscosity still Newtonian or shear dependent?

E. E. Klaus: These are non-Newtonian fluids. The viscosity is shear dependent, but that's not what I am talking about. That shear dependence is a temporary viscosity loss which occurs when the fluid is under shear. I am talking about low shear measurements. I can get the same order of viscosity decrease in flowing through a capillary system at high shear; but when it comes out the other end, it has the same viscosity it had when it went in. What I am talking about is putting it through a meat chopper, so that when it comes out the other end, it has that kind of a loss, and there is no way to get it back. This is low shear viscosity. As for the question on the molecular weight range, we are relatively naive on this and I would say that the molecular weight range is a couple hundred thousand to a million by the usual methods of measuring molecular weight. We used to think it was much lower than that until we added Larry Duda to our staff who set us straight.

R. Y. Ting: The reason I asked about shear dependence is because when a fluid is sheared or degraded, presumably the molecular weight distribution changes, especially if the fluid is in the million molecular weight range. There is actually a shift to a lower mean molecular weight. When the molecular weight shifts tremendously because of degradation, then the shear dependence also changes. Therefore, even though the same thing is measured at lower shear rates, the transition behavior may be different.

E. E. Klaus: The kind of things that we are talking about are Newtonian up to shear rates way beyond the shear rate used to measure viscosity. We're not dealing in these extremely high molecular weights that I assume you are familiar with in your work. We're dealing with things that are considered relatively stable as far as shear is concerned. I would say the typical shear required to show the shear sensitivity in a simple viscosity determination is something on the order of several thousand reciprocal seconds. Below that it's Newtonian.

G. O. Ellis, Vickers Division, Sperry Rand Corporation: Some years ago, we were interested in the cavitation noise in valves. This noise degrades the oil and damages the valves. To study the valves I started looking at diffuser curves. As the diffuser angle is increased, the recovery coefficient goes down, of course, until a 90° half angle or an instant opening is reached. We had a recovery factor of 1/3. We hung a valve on springs and shifted it to different positions and in each position we varied the back pressure. We found that at 1/3 back pressure the cavitation ceased. We had an accelerometer mounted on the valve and measured the frequencies. We assumed these frequencies indicated the beginning of cavitation. A 1/3 back pressure on an orifice should avoid cavitation. So if there is a series of orifices, there will be no cavitation.

E. E. Klaus: I think the case where we had the lowest permanent or mechanical shear in the loading with a low shear capillary was at about that ratio of pressures. Incidentally, I would point out with respect to the paper on cavitation damage on the valve plate, a long time ago, more like 25 years ago, we used these polymer fluids as sort of an integrated device to tell how mechanically efficient your pumps were. The amount of degradation in the fluid from Vickers pumps agreed quite well with the efficiency of the pump, or the level of noise of the pump. The lower the noise, the lower the breakdown and the higher the efficiency, which is another thing that can be done with these fluids, if you believe it's cavitation.

R. S. Miller, Office of Naval Research: How long do the polymers in our motor oils last?

E. E. Klaus: That depends on what motor oil you buy and how much you are willing to pay for it. Polymers can be made that will last from one oil change to another or they can be made to last until you drive 100 miles, and the difference between the two is the price. The higher the molecular weight, the less polymer is used and therefore the cheaper it is. I don't know what the automotive companies are doing, but in the hydraulic business, the automatic transmission business, and other areas, the polymer molecular weights are closely monitored. It is possible to control the molecular weight of the polymer so that, in aircraft hydraulics, a 15% viscosity decrease maximum is obtained from the shearing effect. The polymer molecular weight is tailored to the severity of the device so that it is always between 85-100% of the polymer effectiveness. This is not as well controlled in the commercial market.

EFFECTS OF VISCOELASTICITY ON CAVITATION IN DRAG REDUCING FLUIDS

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INTRODUCTION

The flow properties of very dilute solutions of high molecular weight polymers have attracted considerable attention in recent years. A large part of this interest involved the drag reducing characteristics of these dilute solutions in turbulent flows. A reduction of 70% in the pure water friction in turbulent pipe flow can easily be obtained by the addition of a few parts per million of a high molecular weight linear polymer such as polyethylene oxide. Such a large effect on the frictional drag is a clear manifestation of the influence of these materials on the overall flow regime. The details of the mechanisms involved in turbulent drag reduction are not yet clear, but it is generally believed that the viscoelasticity of the polymer solution plays an important role (1). In view of the demonstrated effect, a study was undertaken to determine whether these same solutions would influence cavitation and thus reduce the material damage accompanying cavitation. Specifically, this report presents the results of an experimental study of the viscoelastic effect of polymers on cavitation inception. The implication of polymer viscoelasticity on the asymmetric collapse of cavitation bubbles in the proximity of the wall is also discussed.

EXPERIMENTAL

To study cavitation inception in polymer solutions, a blow-down water tunnel with short running times was used. Tests were made using 1/4 and 1/2 inch diameter models of hemispherical-nose cylinders. To accurately detect the inception of cavitation, a reliable technique was developed using a continuously operating He-Ne gas laser. The laser beam was adjusted to grazing incidence with the model at the minimum pressure point where cavitation inception was to be expected. A sensitive photocell was placed at ninety degrees to detect the beam. As incipient cavitation occurred, the bubbles caused scattering of the laser beam which was picked up by the photocell. Static pressure near the model in the working section of the tunnel was measured using a solid-state pressure pick-up. The signals from the photocell and the pressure pick-up were recorded on an oscillograph. Velocity field visualization was achieved using one microsecond duration light pulses scattered by small polystyrene latex spheres in the flow. Dark field multiexposure photographs taken at ninety degrees to the direction of the light beam provided reliable data on the flow velocity. Data are presented in terms of the "incipient cavitation parameter", σ_i. This parameter designates the state of liquid flow in which cavitation appears, and is defined as the difference between the local static pressure and the liquid vapor pressure, $P_s - P_v$, normalized by $1/2\ \rho u^2$ with u being the free-system velocity. The drag reducing polymers tested included Polyox-WSR-301 and guar gum (J2FP).

RESULTS: CAVITATION INCEPTION

Fig. 1 shows the variation of σ_i with respect to Reynolds number. Data for tap water indicate that the incipient cavitation parameter first decreases with increasing Reynolds number until a critical value of about 1.5×10^5 is reached. Beyond this point σ_i increases with increasing Reynolds number. The present data for water generally agree very well with the previous studies (2,3), and thus lend confidence in the measurement technique developed here. It is also clear from Fig. 1 that σ_i is much lower in polymer solutions. This reduction in the value of σ_i, by as much as 60%, shows a definite inhibition of the cavitation inception of a submerged body in flows of dilute polymer solutions. According to the present data, it is believed that this incipient flow-cavitation suppression by polymers is a real effect of considerable magnitude, effective over a large range of flow velocities and object sizes.

Fig. 2 shows the variation of σ_i for different concentrations of Polyox-WSR-301 at Reynolds number 85,000. It indicates a steady increase of cavitation inhibition with increasing polymer concentration until about 50 PPMW (parts per million by weight). Also included in Fig. 2 are data obtained by Hoyt (4). In this case, a similar, definite inhibition of the inception of jet cavitation was demonstrated in turbulent jets.

If the percent reduction of incipient cavitation parameter is defined as

$$R_I = \frac{\sigma_i^w - \sigma_i^p}{\sigma_i^w} \times 100\% \qquad (1)$$

where $(\ )^w$ are values in water and $(\ )^p$ in polymer solutions, then the data of Fig. 2 may be presented as shown in Fig. 3. It is clear that initially the effect of cavitation suppression increases rapidly with increasing concentration. Then the effect becomes saturated as R_I approaches a certain limiting value at higher concentrations.

The concentration dependence of R_I can be well-described by an equation of the form

$$\frac{R_I}{R_{I-m}} = \frac{c}{[c]_I + c} \qquad (2)$$

where c is concentration, $[c]_I$ the intrinsic concentration for incipient cavitation suppression, and R_{I-m} the maximum value of R_I. If the limit of R_I/c at zero concentration is examined, it can be seen that the parameters R_{I-m} and $[c]_I$ are useful measures of the "effectiveness" of the polymer additive on a unit concentration basis at infinite dilution. The validity of Eq. (2) may be tested easily, since a linear relation should exist between c/R_I and c if this relation is applicable. The data of jet cavitation shown in Fig. 4 serve a good example of this linearity.

ELONGATIONAL VISCOSITY AND ASYMMETRIC BUBBLE COLLAPSE

One distinct feature of polymer viscoelasticity is the behavior of polymer solutions in flows with longitudinal gradients. Consider the case of a column of viscoelastic liquid stretched with its axis oriented in the direction of stretching. Since the velocity field in this case is irrotational, additional normal stresses, existing as tension in the axial direction and compression in the transverse direction, could be very high. These stress components represent a high resistance to the flow. To indicate these high stress-levels, an "elongational viscosity", $\bar{\eta}$, is usually used (5), defined as the sum of these stress components normalized by $\eta_o \Gamma$, where η_o is the zero-shear viscosity of polymer solutions, and Γ is a constant stretching rate. Fig. 5 shows $\bar{\eta}$ as a function of the dimensionless stretching rate $\lambda_1 \Gamma$, where λ_1 is the terminal relaxation time of polymer solutions. It can be seen that as flow time increases, a very high resistance may build up to retard this stretching even at fairly low stretching rates.

This phenomenon, characteristic of high molecular weight polymer solutions, may have strong implications on material damage effects caused by the presence of small, transient cavitation bubbles near solid surfaces. Benjamin and Ellis (6) asserted that cavitation damage is mechanical in nature and that study of individual collapsing bubbles is the key to understanding the damage process. One important mechanism involved in cavitation damage is the action of liquid jets formed on bubbles near the solid surface. The formation and damaging potential of these jets have been experimentally shown in both a static (7) and flowing fluid system (8). Recent analysis of asymmetric bubble collapse near a solid surface (9) showed that the jet formed near the end of the collapse process impinges against the solid surface, and generates pressure pulses with pressures of the order of 1,000 atm. These pressure pulses are generally believed to be the source of cavitation damage.

In a liquid jet, fluid elements deform along the axis of the jet and the flow is of a stretching nature. In Ref. 9 it was shown that during the later stage of asymmetric bubble collapse the jet velocity may be as high as 100 m/sec. Furthermore, an increment of 35 m/sec in jet velocity may take place in 0.02 second. For a bubble with an initial radius of 0.1 cm, the stretching rate may be estimated as $\lambda_1 \Gamma \sim 35{,}000 \text{ sec}^{-1}$ during this period of t = 0.02 sec. For polymers such as polyethylene oxide with molecular weight higher than one million, the typical terminal relaxation time, λ_1, is of the order of milliseconds. Therefore, the jet formation process in cavitation collapse near a solid surface represents a case where $\lambda_1\Gamma \sim 30$ and $t/\lambda_1 \sim 10$. In view of the result shown in Fig. 5, an astronomical increase in elongational viscosity may be anticipated and the formation of liquid jets could be greatly retarded or inhibited. While experimental confirmation is needed, this analysis suggests that cavitation damage could be greatly reduced by using polymer additives with appropriate viscoelastic properties.

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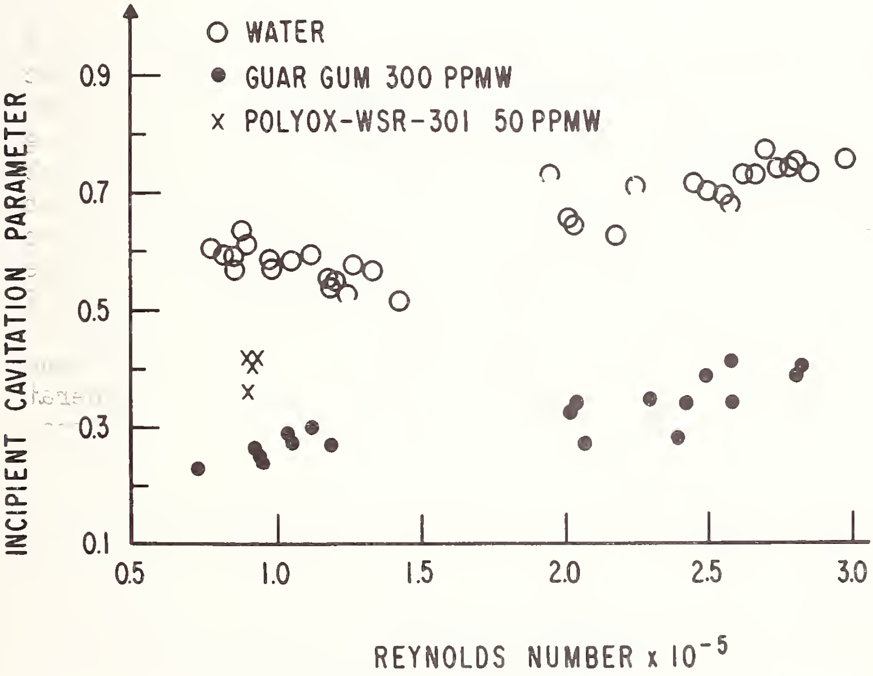

Figure 1: Incipient cavitation parameter vs. Reynolds number.

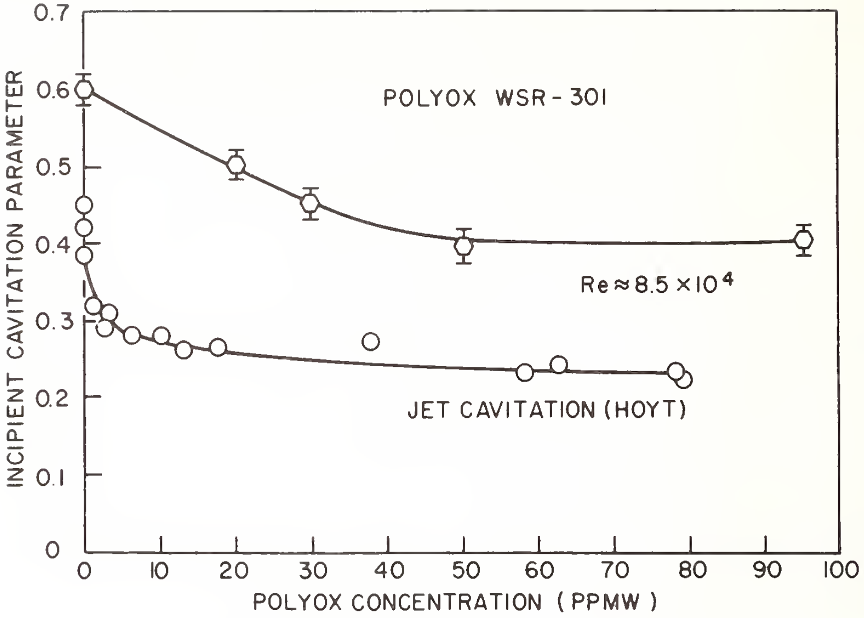

Figure 2: Incipient Cavitation Parameter vs. Polymer Concentration

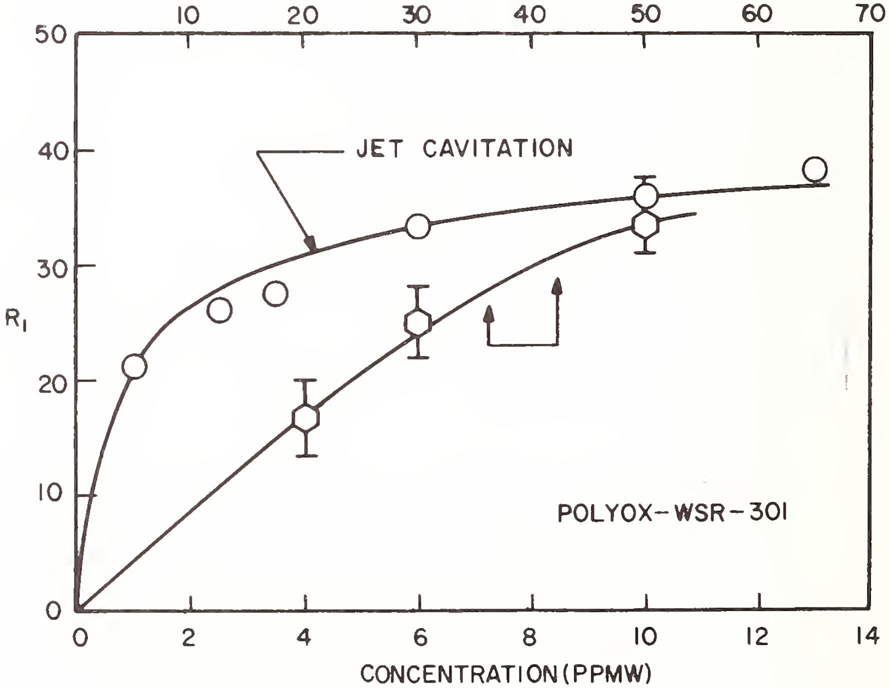

Figure 3: Percent Reduction of Incipient Cavitation Parameter vs. Polymer Concentration

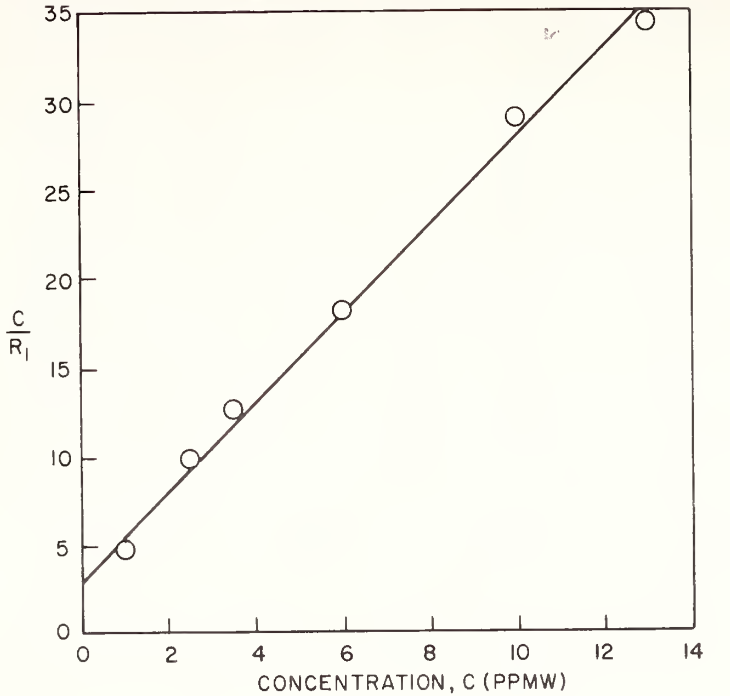

Figure 4: c/R_I vs. Polymer Concentration

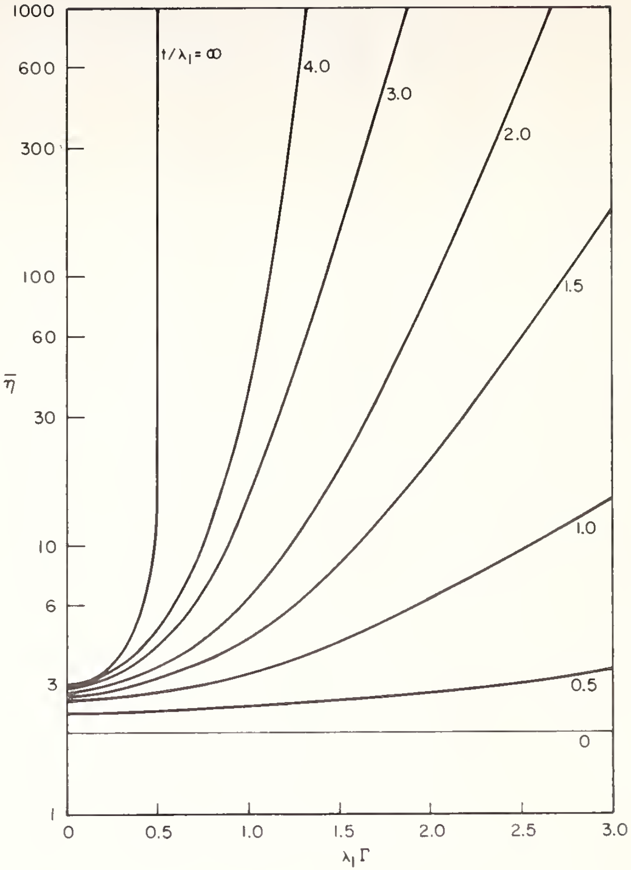

Figure 5: Elongational Viscosity vs. Stretching Rate

DISCUSSION

F. G. Hammitt, University of Michigan: In the plot where you showed time and velocity of the microjet, time was plotted in seconds. Could this be true? You had a full second required for that bubble to collapse which doesn't seem reasonable to me.

R. Y. Ting: This is Plesset's data from an article which appeared in the Journal of Fluid Mechanics. I just took the data and plotted it.

F. G. Hammitt: Usually a few milliseconds is sufficient and the end of the thing is a matter of a microsecond or so. I thought maybe there was a mistake in the scale, like a factor of 10^3.

R. Y. Ting: In Plesset's calculations, he ignored viscosity effects, compressibility, etc. That could be the reason why the calculation appears as it does.

PROGRESS AND PROBLEMS IN EROSION PREDICTION

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In order to predict the adequacy of a component to resist the loads put upon it, one must be able to express quantitatively

1) the character and severity of the loading,
2) relevant material properties measured in standardized tests, and
3) failure theories which relate the behavior measured in simple tests to the behavior expected under different or more complex loading conditions.

This paper discusses the problem of erosion prediction from the above-mentioned viewpoint. Its objective is to evaluate the present status in each of these three areas (although they cannot be completely separated), and to point out some of the unresolved questions and needs for further research. It concludes with an estimate of the accuracy which can reasonably be expected for erosion rate predictions. The emphasis is on liquid impingement as well as cavitation erosion.

Characteristics of Environment

The preponderant opinion today is that erosion results from repeated localized impulsive loadings, due to impacts of droplets, or, in cavitation, due to impacts of microjets or of shock waves caused by bubble collapse. The most fundamental way of characterizing this environment would be to describe the actual stress regime to which the component is subjected.

The repetitive nature of loading leads to obvious analogies with fatigue, although one should not assume that the removal of material always occurs by fatigue failures. Experiments have suggested that the mechanism can range all the way from true fatigue, through repeated plastic deformation and eventual brittle fracture, to ductile necking and tearing.

The stresses and deformations in the material depend on the time-varying surface pressures and shear flows associated with each impact. For cavitation, only the roughest estimates are available. Even for impacts of liquid drops on a plane surface, the magnitude and distribution of impact pressures is still a subject of controversy. But even that is not the whole story, because the deformation and erosion of the surface will itself modify the fluid forces it experiences. On a deeply pitted surface the impact pressures, flow patterns, and stresses for any given impact will depend on where it happens to occur.

Thus, characterization of the environment in terms of the actual microscopic stress loadings is a very difficult prospect. Even so, there have been some recent efforts to predict erosion on the basis of simplified models of these fundamental processes (1, 2), with instructive results.

Lacking exact information on the fundamental fluid-solid interactions, a more common approach has been to characterize the severity of the environment in terms of directly measurable fluid-dynamic characteristics. For liquid impingement it is possible, at least in principle, to measure or predict the number, size, velocity and impact angle of impacting droplets. Characterization of such an environment then depends on developing empirical relationships between erosion rates and these various parameters. To a first approximation, the severity of impingement can be represented by the volume flux of impinging water times the fifth power of the normal component of impact velocity (3).

For cavitation this approach is more difficult. The number, size and collapse velocities of cavitation bubbles is not generally determinable. In the vibratory cavitation test, frequency and amplitude are measured, but correlations based on them are not transferable to field problems involving flow cavitation. Flow cavitation environments can be characterized by fluid velocity, cavitation number, etc., but the severity of erosion will also depend strongly on the gross geometry and flow patterns.

The difficulty of independently determining the severity of a cavitation environment has led Thiruvengadam to characterize it in terms of the erosion it produces (4, 5). This approach is of practical value when correcting a field problem or when model tests of a projected system can be carried out. Thiruvengadam's method is based on an energy-transfer concept and yields a cavitation intensity (analogous to acoustic intensity) having units of power/unit area. While valid within the context of his method, at present this parameter is not susceptible to independent measurement.

Characteristics of the Material

Because of the relative inconvenience of conducting erosion tests--especially of long duration--investigators have long sought to correlate erosion resistance with tensile test data, hardness, or other independent material properties which the designer can more easily determine. But all such correlations, when tested against a wide spectrum of materials, show scatter ratios of 10:1 or more (3, 6). We must accept that erosion resistance is an independent property and must be measured in erosion tests. There is now an ASTM Standard Vibratory Cavitation Erosion Test (ASTM G32-72), and a current round-robin test program of liquid impingement facilities is expected to lead to recommended practices and reporting procedures, if not a standardized apparatus.

The raw result of an erosion test is a curve of material loss versus time. Its typical shape is now familiar (7): It begins with an "incubation period" with no material loss but increasing plastic deformation of the surface. This is followed by a rise of the erosion rate to a maximum, during which erosion pits proliferate. From the maximum the erosion rate gradually falls off (possibly leading to a terminal steady-state value), during which the number of pits remains fairly constant but they enlarge (8), thereby attenuating the severity of the interactions.

In order to merely rank materials, many investigators have characterized the result by one number--most often the maximum erosion rate. It is obvious, however, that if we want to predict erosion-time histories in the field, we need a mathematical representation for the complete curve which, of course, must involve several parameters. Depending on the completeness and on the approach, from 3 to 5 parameters have been required to formulate long-term erosion-time curves (3, 9, 5, 10).

In all cases, some of these parameters pertain to the shape of the curve and some to the actual magnitudes. Now, the crucial question is this: Are the fundamental proportions of the curve invariant, so that the whole curve can be predicted by one material property and one environment intensity property? Or are different parameters influenced by different material characteristics and different environmental characteristics?

At present, there is good reason to believe that the material must be described by at least two properties. For instance, the results of the recent ASTM Liquid Impingement Round Robin suggest that the incubation time is affected by both a different material property and different environmental properties, than the maximum erosion rate.

All three of the above-mentioned models include as one parameter the mean depth of erosion at or near which the attenuation of erosion rate begins. An important practical question is how this depth can be estimated. From some test results, its value appeared to be roughly independent of the material, but possibly dependent on drop size in liquid impingement (3, 5). However, comprehensive or conclusive data are still lacking.

Another important question is whether there exists a threshold erosion property, much like an endurance limit in fatigue. Field experience as well as some experimental investigations have suggested that there is threshold velocity for liquid impingement erosion, but several related questions remain: 1) How is this velocity to be reliably determined? 2) Does it depend only on the material or also on impingement conditions? And 3) can the material parameter involved be related to those measured in a standard erosion test? Impact stresses, in a first approximation, should be independent of the size of impacting droplets. Yet experimental data indicate that threshold velocities (as well as erosion rates) are dependent on drop size. A good deal of additional experimental work is needed to settle the threshold question.

Erosion Rate Models

In the erosion context, the role of a "failure theory" is taken by a mathematical model which relates the parameters of the erosion-time history to the characteristics of the environment. Some aspects of this question have already been discussed under the previous headings.

It must suffice here to say that for impingement erosion, there are vast amounts of data of the dependence of maximum erosion rates and incubation times on impact velocity and angle; less so on drop size effects; and still less on the physical properties of the liquid. More of the latter is needed before we can use test data obtained with water at atmospheric conditions to predict erosion at elevated pressures and temperatures, or with different fluids.

For cavitation, on the contrary, generalized laws based on hydrodynamic parameters are more difficult to obtain, but the convenience of the vibratory cavitation test has led to much research on the effects of pressure, temperature, and corrosive interactions, with various fluids including lubricants and liquid metals.

Accuracy of Prediction

In dealing with erosion test results and predictions, we must learn to accept uncertainties greater than we are normally accustomed to. One reason for this is that the range of erosion resistance is much greater than that of conventional strength properties. Ref. (9) shows "normalized erosion resistance" values, relative to 18-8 stainless steel, from many test data in the literature. The overall range covers a ratio of about 2000 to 1, and the scatter band for any one material covers a ratio of typically 3 or 4 to 1. This scatter derives from differences among test materials, differences among reference materials, and differences among test conditions.

Among the most closely-controlled tests so far have been the two ASTM "round robins" of vibratory cavitation devices and liquid impingement devices, where samples from the same bars, for each of several materials, were tested under relatively similar conditions. The normalized erosion resistance values from these tests exhibited "scatter ratios" of 1.5 to 3. It can be shown that, on a logarithmic scale, this scatter band is about the same proportion of the overall range of values as is found, for example, for tensile strengths or for finite fatigue life-times.

Consider, furthermore, that erosion rates typically vary with the 5th power of velocity in liquid impingement as well as flow cavitation. If erosion rates are so sensitive to velocity, it is to be expected that they are equally sensitive to many other factors which affect the fluid-solid interactions or the material's response to them. In the ASTM impingement round robin, erosion rates for the same material, at the same impact velocity when normalized to equal quantities of impinging water, still exhibited scatter ratios of about 5:1 among different facilities.

All of these considerations, taken together, suggest that the best accuracy which we can expect at a high confidence level, even from much improved prediction schemes, is within a factor of 2 or 3.

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DISCUSSION

F. B. Peterson, Naval Ship Research & Development Center: I would like to ask a question related to designers choices. If I was responsible for the design selection of a propeller going on a brand new large container ship, I would be faced with the problem of deciding whether I should invest in a propeller that has a different material than is typically used now from the standpoint of erosion resistance. I'd have the trade-offs of how often the propeller might have to be changed and the cost of dockside time and all the economics associated with the life of the propeller from the erosion point of view. On the other side of the coin I know that the cavitation performance of the propeller can be changed strictly by hydrodynamic design, and that also has its financial trade-offs. Now, as a designer, if I came to you and told you what I can do hydrodynamically, and I can lay out all the costs for you, such as that of changing a propeller, etc., and give you the flow condition around the propeller, could you tell me what material I should use and what it would cost or how long the material would last for a certain extent of erosion?

F. J. Heymann: A quick answer to that is no, I could not. The whole point of my talk is that there are still an awful lot of uncertainties that need more work before they can be tied down. I would imagine the best approach might be doing model tests such as Thiru has suggested and using scaling approaches and measuring erosion on a model propeller to predict the prototype performance.

F. B. Peterson: It's really impossible model-wise to scale cavitation correctly from model to full scale. Model users either lose the dynamics of the collapse and get the correct pattern of cavitation, or they get the correct dynamics of the collapse in terms of energy but have nowhere near the correct cavitation pattern. Therefore, a full scale prediction based on model work can't be made.

J. F. Corso, Naval Ship Engineering Center: It appears that there must be some correlation between corrosion resistance and erosion resistance. We found that alloy 20, while it's not a hard material, is superior from a corrosion and erosion standpoint to many harder materials. Could you comment on this and also, is your erosion prediction analysis valid if you don't take into account debris that might be in the effluent?

F. J. Heymann: Again I would like to say I have not presented an erosion prediction method. I have looked at what is required for a successful erosion prediction method. I have tried to show that we are still pretty far away from any such thing. I'm sure that it is very true that in many instances the corrosive influence is very significant. It's not always the harder material that is best. A plot of corrosion test results vs erosion test results taken from a Russian paper shows a bit of a correlation, but not a very significant one. I'm sure it depends on the particular environment. If it's one where corrosive influences are important, and the material is susceptible to corrosion, then that becomes a major factor to be considered.

A. Thiruvengadam, The Catholic University of America: My comment is in connection with Dr. Peterson's remark. In this day and age when we have seen people landing on the moon, it's rather discouraging to say it's impossible to model erosion in a propeller, etc. This is one area we have been looking at. We cannot really say we have simulated all the conditions a prototype propeller would see by using a model. Given the time and encouragement in terms of research effort, I believe it could be accomplished.

J. I. McCool, SKF Industries: Why do you classify materials resistance to erosion as a derivative, a time rate of change, rather than the time until it achieves a given depth of erosion, the integral of the curve rather than the slope? It seems that would decrease the scatter and some of the hardships you pointed out with respect to the different shapes of curves that you got. It also seems that that would be the thing that a designer would care about -- time until depth d.

F. J. Heymann: You've got a good point in the desirability. One thing that I tried to do in one paper was to base correlation not on instantaneous erosion rates but on average erosion rates and plot them vs. the depth of erosion. Take the slope, which is the average erosion rate necessary to reach a certain depth, and plot that vs depth. A time can then be predicted for any number on the curve. But it turns out that there is a good deal of scatter. We approximate the curve by an incubation time and a maximum erosion rate. It's been my experience that using this value as a parameter for the erosion resistance of material gives fairly consistant results between different test apparatus. There is much more scatter in the incubation period than there is in this. Our ASTM tests showed that. So any sort of combined thing that gives an integrated value which includes the incubation period will give more scatter. That is one of the difficulties in predicting long term erosion. I don't know yet what all the sources of that scatter are.

SESSION IV

Chairman: M. L. Picklesimer
National Bureau of Standards
(substituting for W. A. Glaeser)

POTENTIAL OF THIN, SPUTTERED FILMS AS EROSION RESISTANT PROTECTIVE COATINGS

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Part one: Sputter-coating and film characteristics. K. Gentner

A quarter century ago, thin, pyrolytically deposited films of refractory characteristics demonstrated their potential of protecting 10 atom layer thick carbon films from oxidation and abrasion. It was very tempting, to utilize this technique for the protection of mechanical components and structures operating in severe environments. However, there were several factors involved which could have adversely affected the basic structure of a metallic component. One major factor was the relatively high temperature, and another one, the presence of reactive atomic species.

The deposition of erosion resistant films on metals in a "clean" processing environment at temperatures which are harmless to the structure of the base metal can now be performed by several vacuum deposition methods. Of these, sputtering techniques offer the largest versatility of processing parameters to achieve extraordinary film characteristics and selective local and sequential variations of the material composition and film thickness at a minimum of intricate processing fixtures or operational effort. In addition, there is evidence, that the structural charactersitics of a mechanical component can be substantially improved while the protective film is being deposited.

Basically, a sputtering system consists of a vacuum chamber, which houses a sputtering electrode and the mechanical component, a high-voltage power supply, and a tank of inert gas, usually argon. The sputtering electrode, or sputtering target, can be made from one or several units of different material composition, and can have any size, shape or spatial orientation. Once installed, a sputtering target requires no further attention throughout its usually long life. Process control is simply a matter of setting a certain gas pressure in the low micron range, and a negative potential of several kilovolts on the sputtering target. While the vacuum chamber is usually on ground potential, representing the anode, the work load can be held on floating or any desired potential. This optional potential of the work load can be utilized to direct a selected flux of material to and from the mechanical component. First, by applying a high negative potential to the component prior to the coating operation, any undesirable surface layers - such as oxides - can be effectively removed. This way, a finely textured, sputter-etched surface structure can be prepared, (Figure 1) which is highly desirable to achieve a good bond between base material and film. Then, during the coating operation a proper negative bias potential at the component can function as a very powerful process parameter to create a film composition and structure of extraordinary properties. With the same ease and effectiveness as the electrical control, reactive gases or vapors can be added to the sputtering gas for further variations of the film material composition. All these variations of the sputtering operation can be easily and precisely programmed, and once the vacuum chamber has been loaded and pumped down, no special operator attention will be required until the coating process is completed.

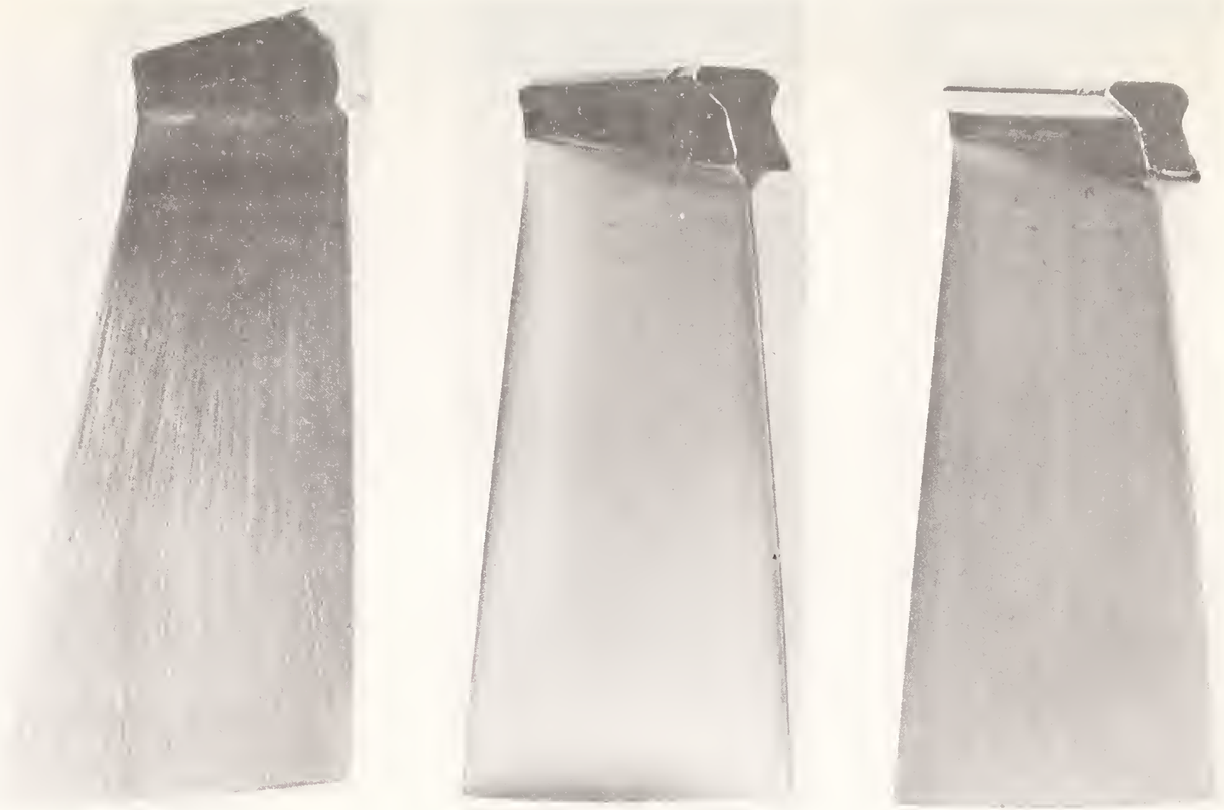
We have investigated the performance of thin, sputtered coatings in an accelerated dynamic erosion test. First stage compressor blades of the T-58 engine were first sputter-etched, and then coated inside a hollow sputtering target, fabricated at NAVAIRDEVCEN. Films of silicon carbide and tungsten carbide, both blended with stainless steel, type 304, were deposited at various field configurations. The film thickness was varied from approximately one to ten microns, with the majority of the films at the five micron range. Sixteen differently coated blades were prepared for the erosion test.

The test results were quite encouraging, considering the fact, that this was an exploratory experiment to observe such factors as minimum protective film thickness, different film composition, various deposition techniques and area distribution of erosive forces, and, furthermore, that no previous efforts were made to optimize the most favorable coating conditions or material combinations through trial coatings or screening tests.

Visual inspection and weight loss rates of the sixteen different coatings revealed that the erosive attack on the leading edge and concave surface of the blades was at least ten times more severe than that on the convex surface, which was facing the engine intake. Increasing stainless steel content of the coatings reduced the erosion resistance (Figure 2), whereas an increasing negative bias potential at the blades substantially reinforced the erosion resistance of both, the coating and the underlying blade material. The films on the convex surface of the blades retained for the most part their originally smooth appearance (Figures 2 and 3), and the concave surface, having the coating abraded, exhibited a very fine and even texture, expecially on those blades which were sputtered at a relatively high negative bias potential (Figure 4).

In comparison to uncoated blades, or blades with much thicker vapor-deposited coatings (Figures 5 through 7), the sputter-coated blades exhibited throughout the test an extremely smooth surface, which is highly desirable from an aerodynamic standpoint. Our next goal is, to develop new material compositions, and to advance sputtering techniques focusing on special protection of critical areas and on obtaining overall higher deposition rates.

While our main efforts are directed towards protection of new aircraft parts, the potential of sputtering techniques for repair of worn mechanical components is being explored. An example is shown in Figure 8.



BEFORE SPUTTER-ETCH

AFTER SPUTTER-ETCH

AFTER SPUTTER COATING

Figure 1. T-58 compressor blade NADC A-1 (concave side).

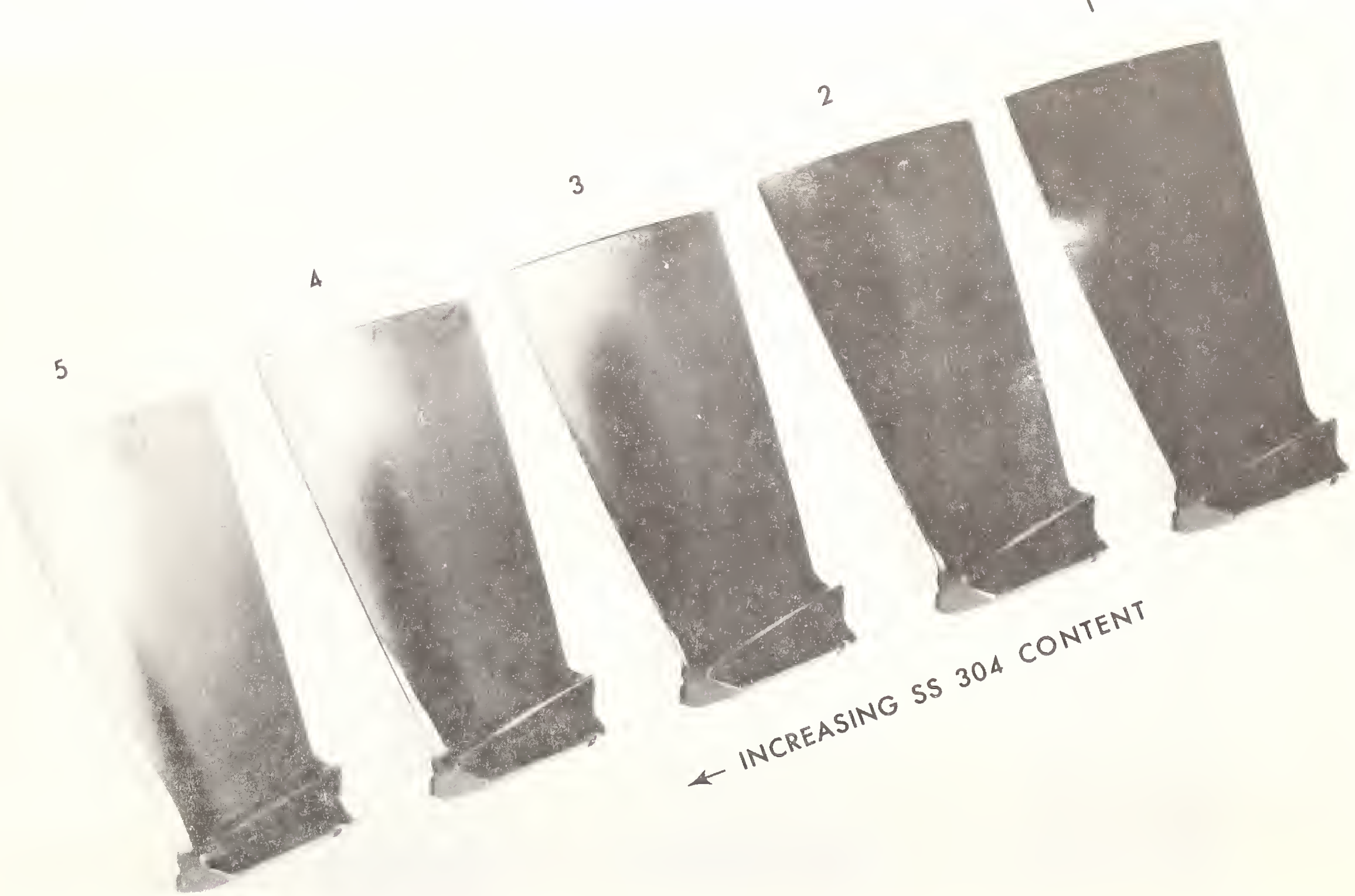


Figure 2. SiC sputter-coated T-58 compressor blades after 16½ hours erosion test (convex surface).

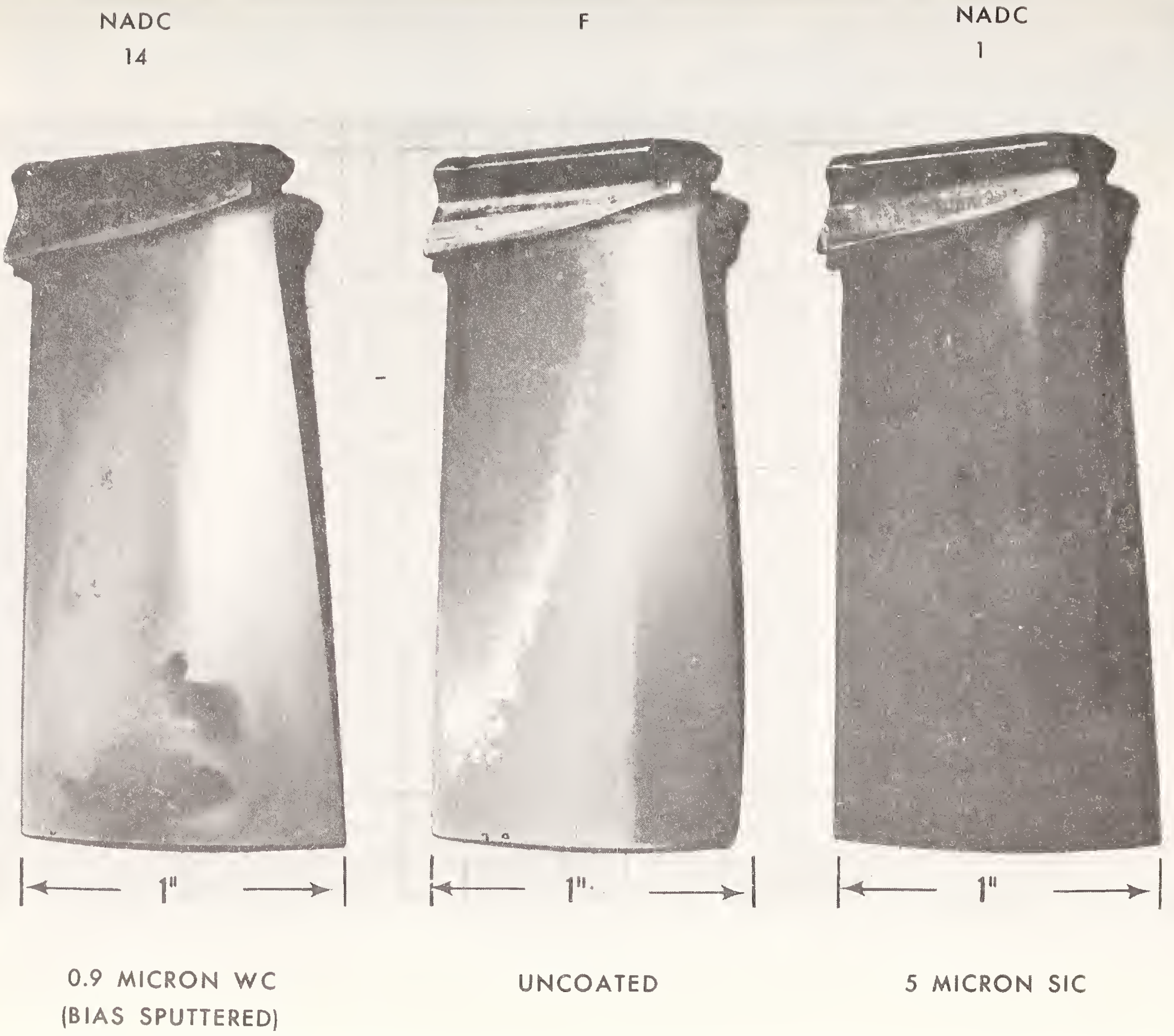
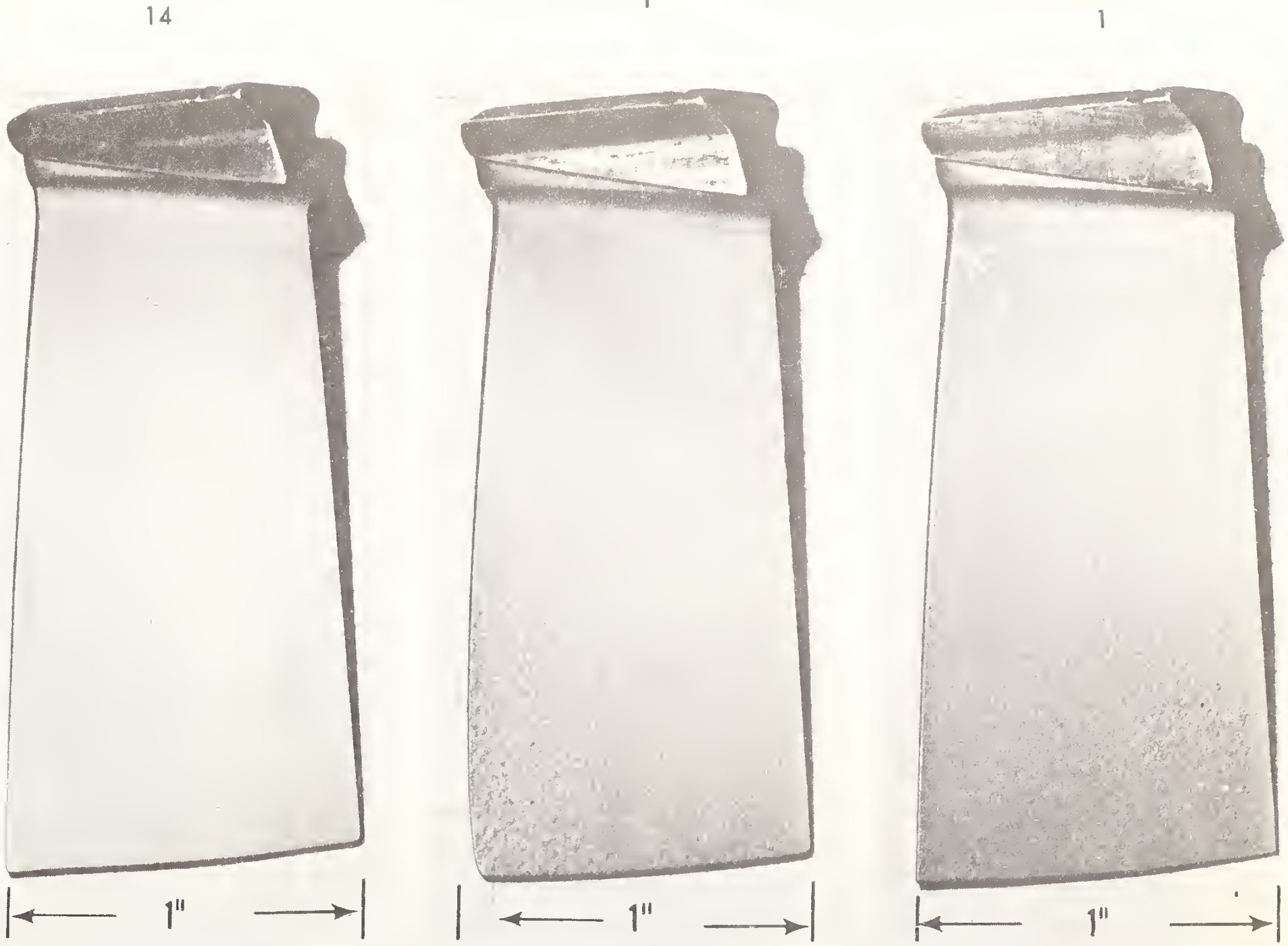


Figure 3. T-58 compressor blades after 16½ hours erosion test (convex surface).



0.9 MICRON WC
(BIAS SPUTTERED)

UNCOATED

5 MICRON SIC

Figure 4. T-58 compressor blades after 16½ hours erosion test (concave surface).

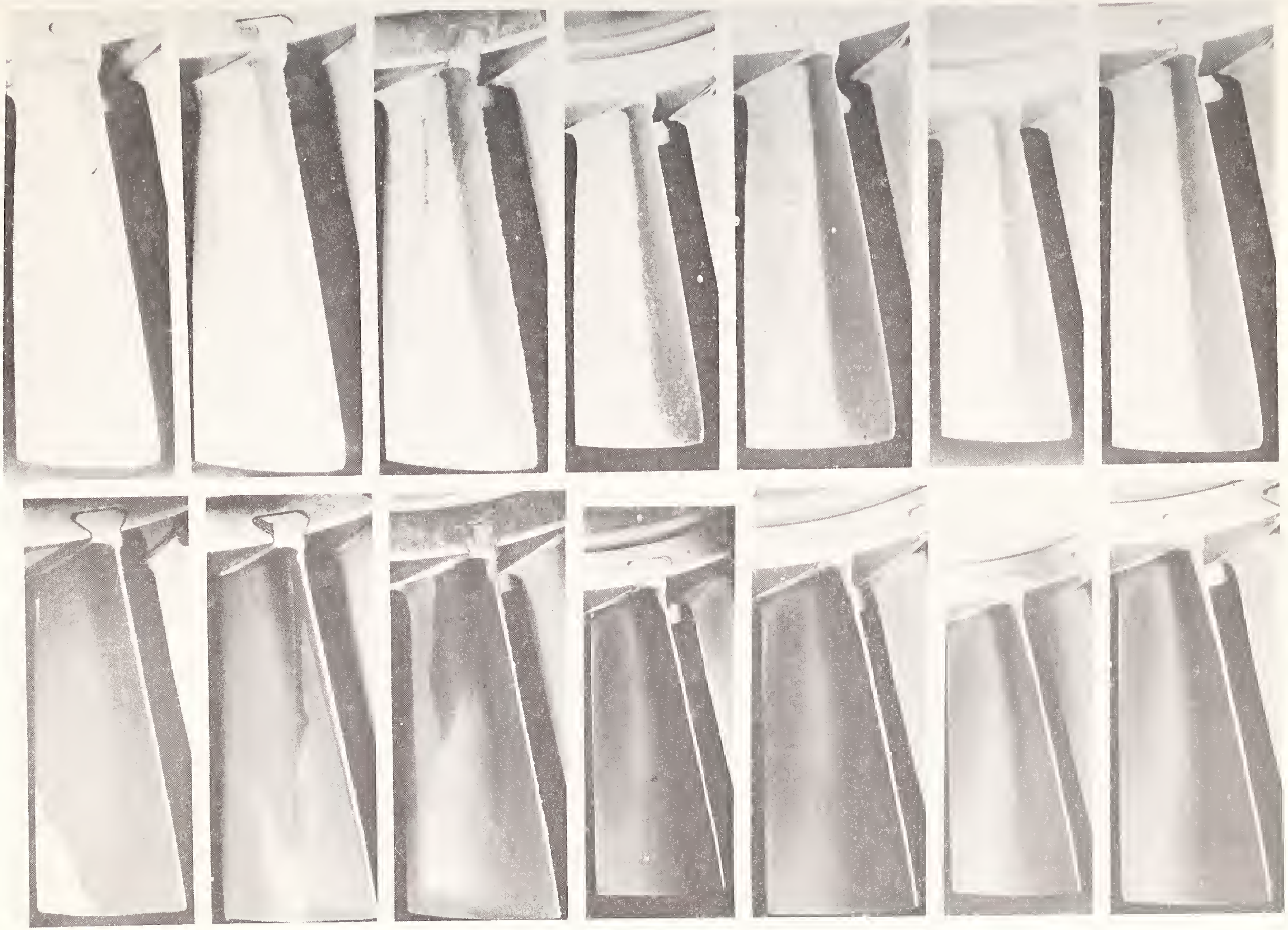
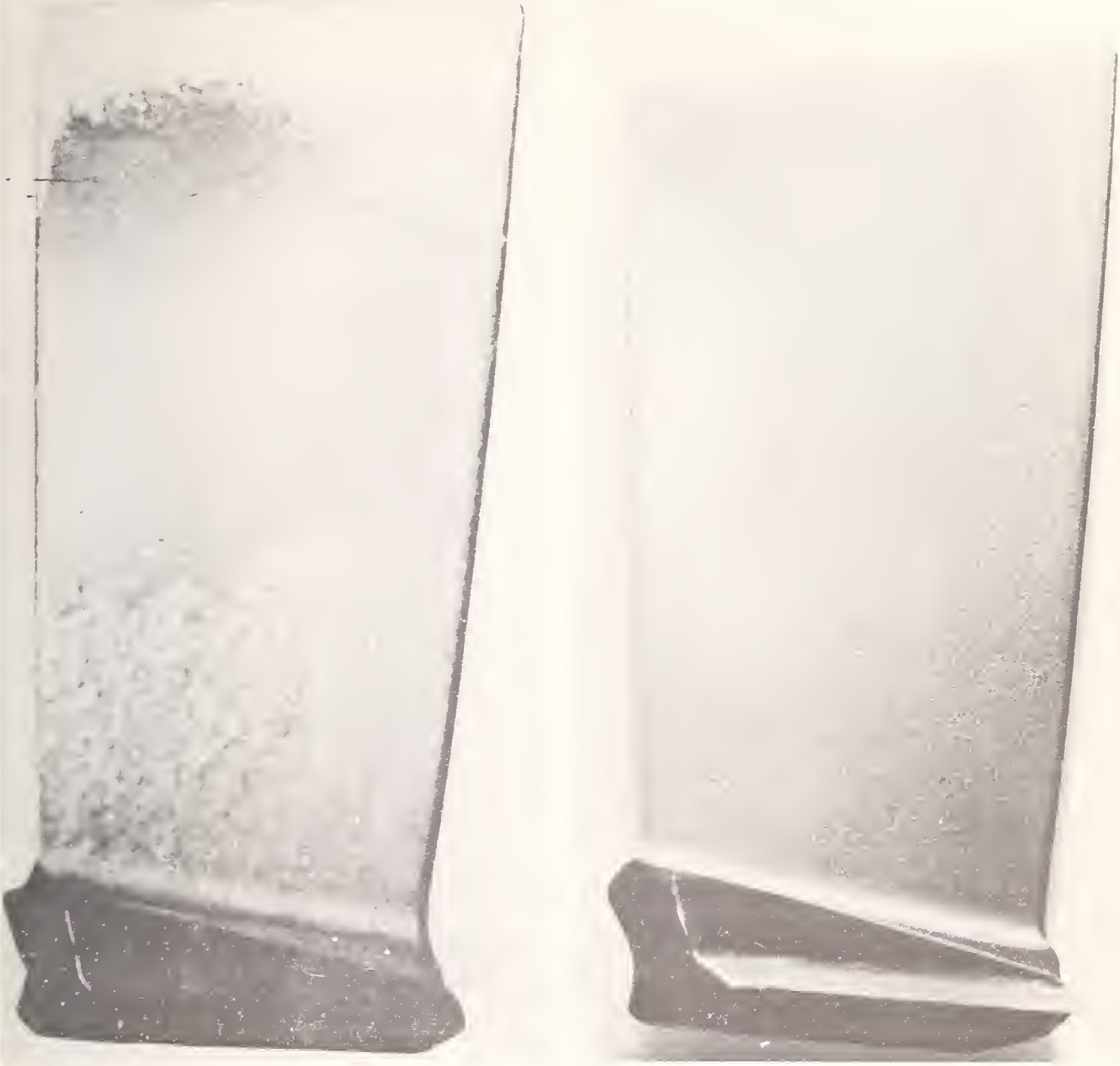


Figure 5. Erosion test of T-58 compressor blades. Top row: uncoated. Bottom row: SiC coated.

AMI
C-1

AMI
C-2

Figure 6. T-58 compressor blades with vapor deposited coating after 16½ hours erosion test (concave surface).



VAPOR DEPOSITED BIAS SPUTTERED

Figure 7. T-58 compressor blades after 16½ hours erosion test (concave surface).

BEFORE

AFTER

Figure 8. Used T-58 compressor blades, before and after sputter-coating (concave surface).

PART TWO: EROSION AND THE GAS TURBINE ENGINE

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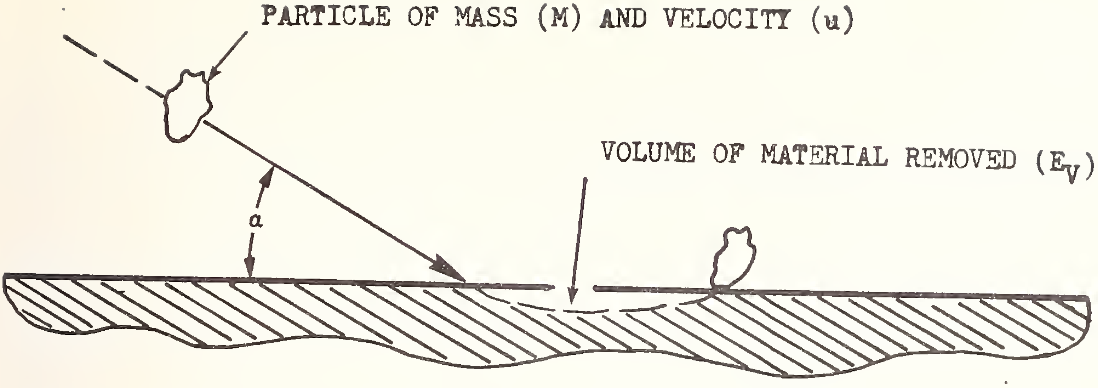
INTRODUCTION

High velocity impact of solid particles such as sand or dust, can cause significant erosion damage to aircraft propulsion components in helicopters, hovercraft, and V/STOL aircraft. The propulsion systems are normally highly optimized to obtain the power to weight ratio or thrust to weight ratio required for V/STOL aircraft and thus more susceptible to performance degradation from erosion. Operation of small gas turbine powered helicopters, e.g., over dusty unimproved land areas routinely ingest up to 25 pounds of sand and dust for every hour of low altitude operation. Consequently, many billions of high-velocity, abrasive dust particles impact the critical airfoil surfaces of compressor blades and vanes eroding away the thin metal tips and trailing edges. The inevitable result is progressive and rapid degradation of engine performance, often to the extent of premature engine failure within 10-20 percent of the normal overhaul time. The accelerated replacement of erosion damaged helicopter turbines in Southeast Asia was estimated to cost the U.S. Government about $150 million a year.

Two approaches can be used to combat this problem. One is to develop a filtration system that will remove most of the solid particles from the air stream. The other is to design blading materials and/or blading protection that are not appreciably affected by solid particle erosion. Dust filters and separators invariably decrease engine efficiency, increase critical weight tolerances, and require constant maintenance. Therefore, the optimum solution would appear to be new materials protection concepts with significantly improved innate erosion resistance.

CONCEPTS OF EROSION

Previous investigators have postulated equations of motion for angular dust particles striking a solid target (Ref. 1). For ductile metals and alloys, the majority of investigators have assumed that a micromachining process is responsible for erosion - a sharp corner of the impacting particle acting as a single-point machine tool. For hard, strongly elastic alloys, borides, carbides, other ceramics and intermetallics, (materials with negligible or limited plasticity), it has been assumed that erosion occurs by random surface cracking, joining of crack networks, and subsequent spalling. These equations (Fig. 1) predict that average erosion loss per particle should be proportional to the particles kinetic energy (Mu^2) and inversely proportional to the minimum flow or yield strength for ductile targets. The usefulness of the empirically derived equation for elastic materials is more limited because the particle velocity exponent varies from ~3.3 to 6.5 (not a simple particle energy relation) depending upon the material class. However, for a given elastic material, erosion is predicted to be inversely proportional to the material's ultimate strength. For the best empirical curve fitting, the erosion losses are also made a function of impingement angle, a, inasmuch as maximum erosion normally occurs at some intermediate angle between 9 and 90 degrees (typically 20-30 deg.) for ductile materials; and at ~90 degrees for elastic materials (Fig. 2).



$E_V = Kf(\alpha)\frac{Mu^2}{\sigma}$ FOR DUCTILE MATERIALS

$E_V = Kf(\alpha)\frac{Mu^{3.3 \text{ to } 6.5}}{\sigma}$ FOR INELASTIC MATERIALS

where σ = minimum flow or ultimate strength of the target material
K = a constant for the specific erosion system
$f(\alpha)$ = function of incidence angle
M = dust particle mass
u = dust particle velocity

FIGURE 1 EQUATIONS OF MOTION FOR DUST EROSION

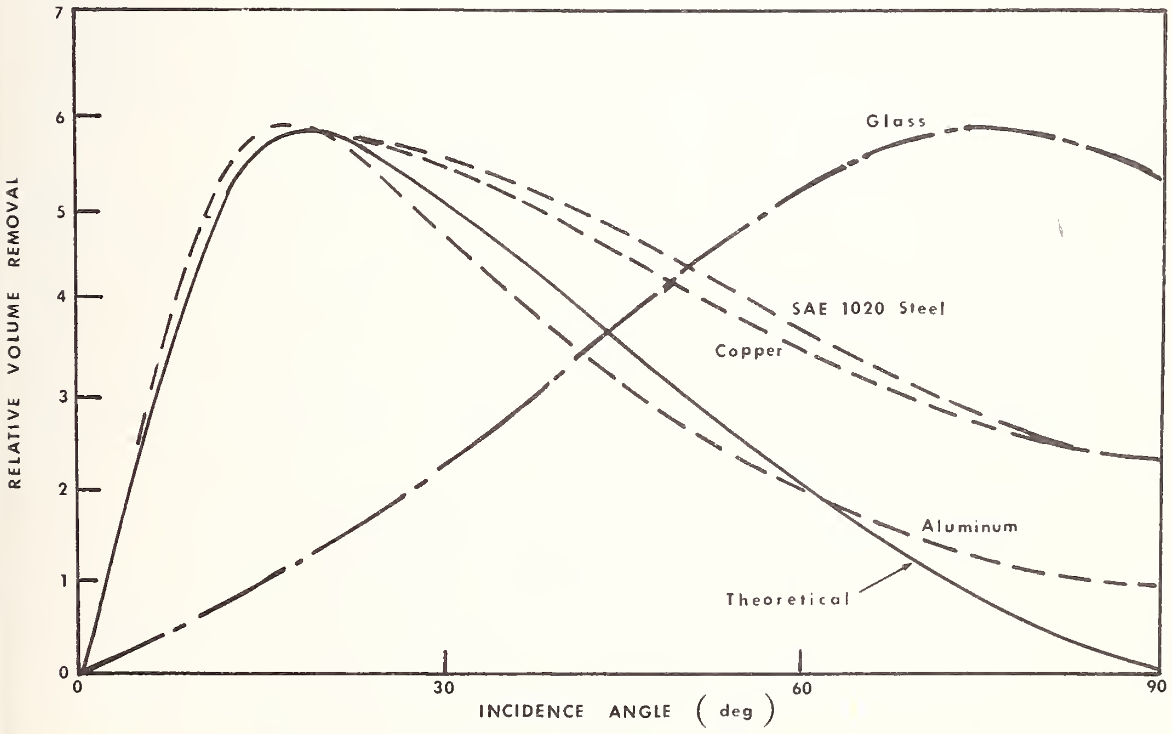


FIGURE 2 EFFECT OF IMPINGEMENT ANGLE ON DUCTILE AND ELASTIC MODES OF EROSION

TURBINES VS. DUSTY ENVIRONMENTS

Measurements of dust concentrations in clouds formed by an H-21 helicopter in stationary hovering (1- to 10-foot heights) at Yuma, Arizona, and Ft. Benning, Georgia, have yielded average concentrations ranging from 2 to 4 mg/ft^3 (average) near the rotor hub to 12 to 19 mg/ft^3 (average) near the area of rotor blade overlap (Ref. 2). Dust concentrations increased by a factor of 3 during takeoff and landing maneuvers, and by a factor of 5 with another helicopter operating nearby. It should be noted also that the ingested dust is further concentrated within the compressor by centrifugal action, which "throws a majority of the sand to the outer portion of the annulus, resulting in extremely high concentrations" near the blade tips (Ref. 3). Sand from these sites is normally high in silica, with an average specific gravity of 2.4 to 2.6. Typical particle size distribution of airborne dusts were: 98 to 100 percent $<$200u; 40 to 60 percent $<$100u; 15 to 40 percent $<$50u; and 5 to 10 percent $<$15u. Particles larger than 500u were not airborne (Ref. 2).

Of the quantitative erosion studies upon actual turbines, some of the most relevant field work was conducted by Montgomery and Clark (Ref. 4), who determined erosion rates as a function of dust particle size and concentration for a Solar Mars gas turbine. This study showed that within limits of repeatability, the erosion factor

$$E = \frac{\text{grams weight loss}}{\text{grams dust ingested}}$$

appears constant for any realistic dust concentration up to 13 mg/ft^3.

From this information they were able to predict the turbine life as being proportional to a constant, which is representative of the engine type, and inversely proportional to the product of the particle size according to the relation

$$L = \frac{A}{C \times d_m} = \frac{1.38}{C \times d_m}$$

where L = engine life in hours

A = constant (1.38 for the Mars engine)

C = dust concentration in mg/ft^3

d_m = maximum particle size in microns

It was reasoned from this relation that all particles above 2 to 3 microns should be filtered from the air stream to ensure an acceptable turbine life expectancy for high dust concentration areas. Bianchini and Koschman of Allison also carried out field studies of dust erosion in the T63 turbine using 0 to 200-micron (Arizona Road (AR) Dust, coarse) dust particles, initially at 15 mg/ft^3 (Ref. 5). They found that engine power decreased almost linearly with the total dust ingested, and that this function was apparently independent of the dust concentration (Figure 3). Also, they noted that particles up to 10 microns in size had only a small effect on engine power. On the other hand, the erosion effects of 0-80 micron dust (AR fine) and 0-200 micron dust (AR coarse) were severe, but not discernibly different.

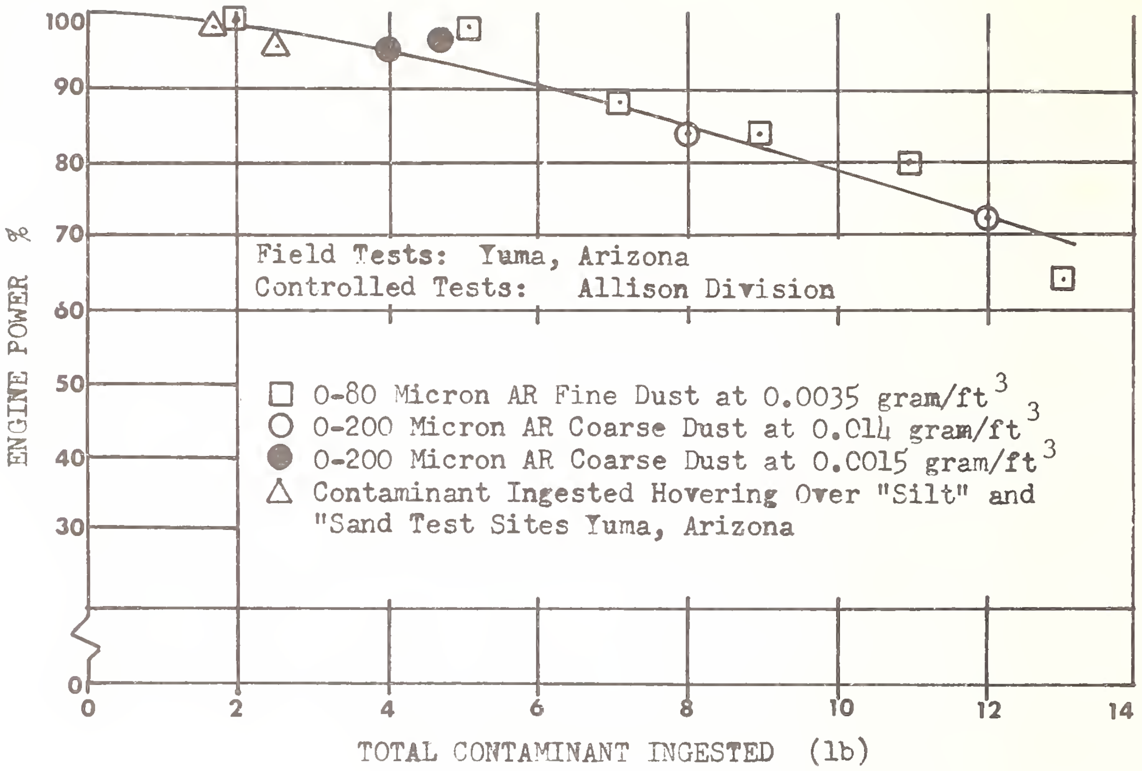


FIGURE 3

T63-A-5A Engine Sand and Dust Ingestion Tests; Comparison of Erosion Effects From Field Tests and Controlled Ingestion Tests.

Rapp and Rosenthal of General Electric (Ref. 3) also found that power degradation and the number of safe landings could be directly related to the pounds of dust ingested. Compressor blade and vane erosion was severe on engines without inertial filters (Southeast Asian operations). As a general rule, large particles caused substantial damage to the first stage blades, all along the leading edges. Large particles were apparently shattered by impact with the first stage blades and accelerated to high velocities through the latter stages, so that erosion past the first stage proved similar regardless of initial particle size ingested. Because of centrifugal effects, the site of blade damage was progressively transferred to the blade tips and trailing edges, the higher the stage. To counteract erosion, General Electric experimented with hard blade coatings, the most successful of which were an electro-deposited hard Cr plate and a beryllium diffusion coating. Embrittling side effects prevented their general application to AM-355 and similar stainless steel alloys blades, however (Ref. 3).

A difference of opinion exists over the effectiveness of small dust particles ($\leq$15 microns) in eroding turbine components. Mr. J. M. Clark, Jr., of the Southwest Research Institute cites data which shows that, in 660 hours of ingesting 0-5 micron dust at a concentration of only 0.33 mg/ft^3, a gas turbine was destroyed as an operational unit. He discounted arguments that very fine dust particles were decelerated or deflected significantly by the boundary layer on airfoil surfaces. G. Thomas, also of Southwest Research Institute, has published data showing that a Solar turbine (Model T-221N-1) was erosion damaged sufficiently to become inoperable after running 132 hours with an inertial separator on the air inlet. Ninety percent of the dust ingested into the turbine was determined to be $\leq$14 microns. Based upon other data, engine manufacturers such as General Electric and Allison feel that engine erosion is a minor problem with particles smaller than 10-15 microns. Hence, they stress that properly maintained inertial separators and mechanical filters should be adequate to effectively nullify the erosion problem. (The inertial filter has a marked cutoff in efficiency somewhere between 10-15 microns.)

The conclusions to be drawn from the published data regarding the effect of ingested dust on gas turbine performance are summarized as follows:

- Serious erosion of gas turbine components will be caused by ingestion of airborne dust generated by average military operations in unimproved areas. Efficient air filters will be required on all gas turbines to remove dust particles above 2 to 3 microns in diameter if improved erosion-resistant materials are not available.
- Anticipated gas turbine life varies inversely as the product of the maximum particle size and the dust concentration, and the erosion factor is independent of the rate of ingestion (i.e., dust concentration).
- The total erosion is independent of dust concentration within realistic limits, and is a direct function of the total weight of ingested dust of any given particle size for a given gas turbine. In the particle size range of airborne particles, there is negligible erosion of the inducer section of the compressor impeller or other areas where the absolute velocity of the entrained dust is low.
- A simple cycle gas turbine demonstrates little or no external evidence (by observation or readout) of complete destruction by dust erosion prior to the point of complete failure. Vibration of gas turbines does not appear to increase until

almost total destruction of the rotating components by dust erosion has occurred.

Field studies give only a generalized or end view of the erosion phenomena, with limited potential for insight into the basic mechanisms of erosion. This is because erosion in a turbine occurs over a wide and changing range of conditions that are difficult to control directly as variables.

EROSION TESTING

Recognizing the fact that erosion in a turbine is a product of many variables, then the development of a meaningful "bench" type test becomes monumental. Table 1 lists most of the variables that must be considered, incorporated, and controlled. It appears as if a full scale turbine engine is the only answer as a test vehicle; however, the cost consideration precludes this use as a routine test. Two of the more widely used erosion testing devices are the Roberts Jetabrader and the S.S. White erosion test. These are small, self-contained, primarily research oriented testing equipment. The Solar Division of International Harvester has developed a new erosion test facility which can apply and evaluate most of the variables in Table 1 (Ref. 6). The primary drawback of all these test techniques is the inability to evaluate more than one specimen (material and/or coating) per test.

EROSION TEST VARIABLES

Test Dusts	Arizona Road Dust (natural desert sand 68% SiO_2) Laterite (35% SiO_2) Pure Silica Sand (100% SiO_2) Pure Alumina (100% Al_2O_3)
Particle Size	Up to 200 microns diameter
Particle Velocity	100 to 1500 fps
Impingement Angle	20 to 90 degrees
Dust Concentration	5 to 200 mg/ft^3
Carrier Gas	Air, pure or mixed gases
Carrier Gas Pressure	1 to 16 atmospheres
Carrier Gas Temp.	Ambient to 800°F
Target Materials	AM 355, 410 stainless, Ti-6Al-4V, 17-4PH, 17-7PH
(Table 1)	various coatings

The Naval Air Propulsion Test Center (NAPTC) has designed and operates a dynamic erosion facility. The test rig consists of a standard T58-GE-10 engine first stage rotor, front frame, bullet nose, and bellmouth (Fig. 4). The rotor contains 30 blades of cast AM-355, the standard alloy used in current model engines. An inlet cloud chamber, close-coupled to the bellmouth (Fig. 5), allows a uniform, dispersed flow of measured abradant to enter the bellmouth. A calibrated feeder supplied the abradant through a funnel ejector to the inlet cloud chamber (Fig. 6).

The abradant used for all testing to date is prepared Arizona Coarse Grade Road Dust, 0 to 200 microns, from the AC Spark Plug Division, GMC.

Dust concentration was delivered at 0.01 gm/ft^3. The air flow was maintained at 13 lb/sec (T58 requirement) and the average rotor speed was measured at 11,000 rpm. The length of a test has been established at 15 hours for AM-355 blades, which results in a 1 gram erosion loss of material from unprotected blades. In addition to weight loss determinations, measurements are recorded for losses in chord width (tip, midspan, root).

Although this coordinated program of "sputtered" coating research and dynamic erosion test development is still in its infancy, the composite results are gratifying. As described by the author of Part 1 of this paper, distinct trends are shown for various concepts in the sputtered coating depositions. These trends are integrally related to the reproducibility of the test. For example, the weight loss rate, mg/hr, for standard uncoated blades during test shows an average deviation of less than 3 mg/hr.

A summary of the erosion protection development program at this stage shows the following:

1. Sputtered coatings -

a. Can be applied relatively "cold" with minimum effect to substrates.

b. Improve aerodynamic properties of airfoils and do not degrade these properties with erosion loss.

c. With controlled bias potentials, reinforcement to erosion resistance is obtained for both the coating and substrate.

2. Dynamic erosion testing

a. Evaluates actual hardware indicative of service experience.

b. Abradant injection technique produces random impingement angles of random particle sizes.

c. Produces a true picture of erosion prior to channeling and fracture of the abradant.

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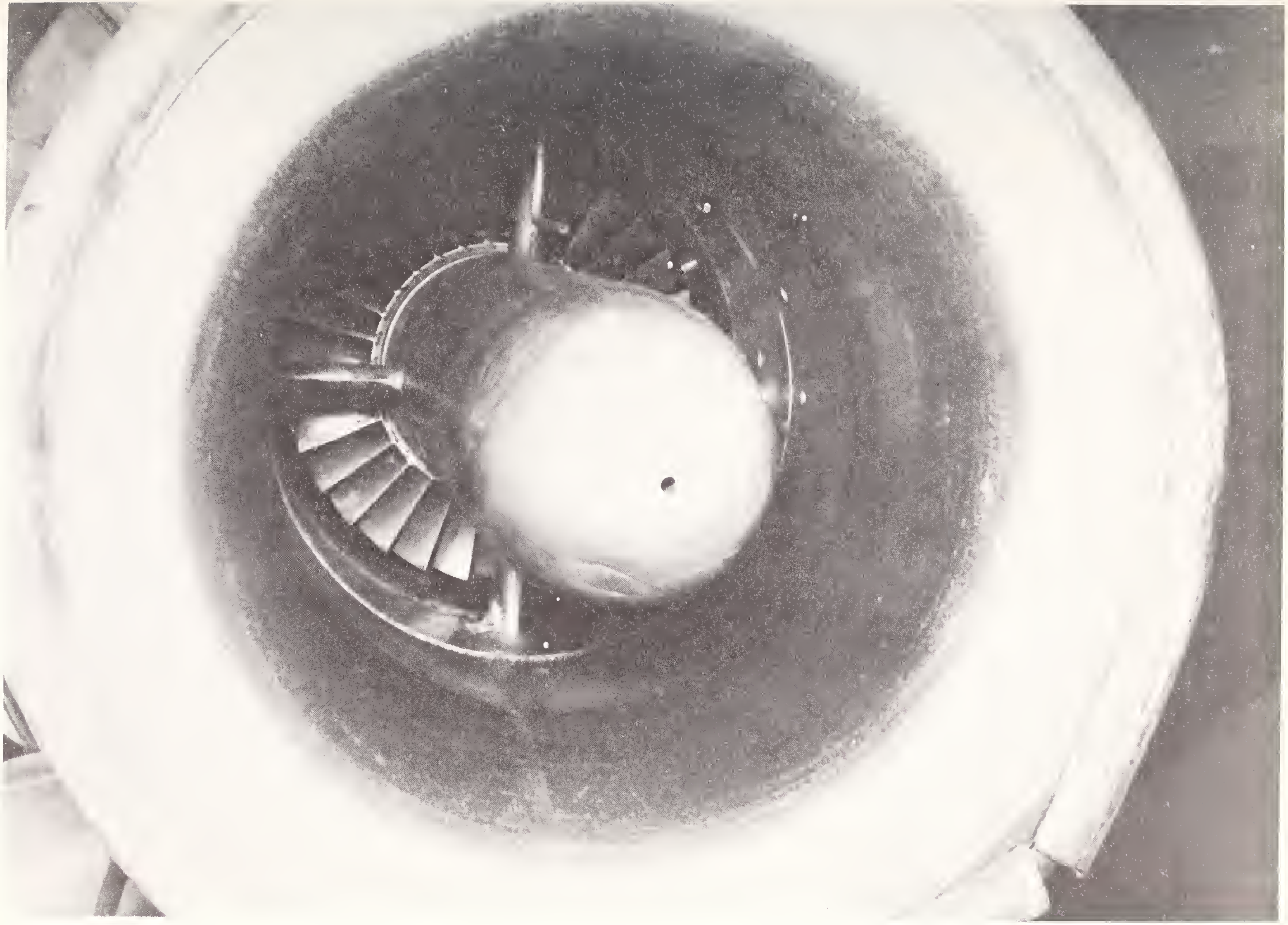

Figure 4. T58 First-Stage Rotor, Front Frame Bulletnose and Bellmouth.

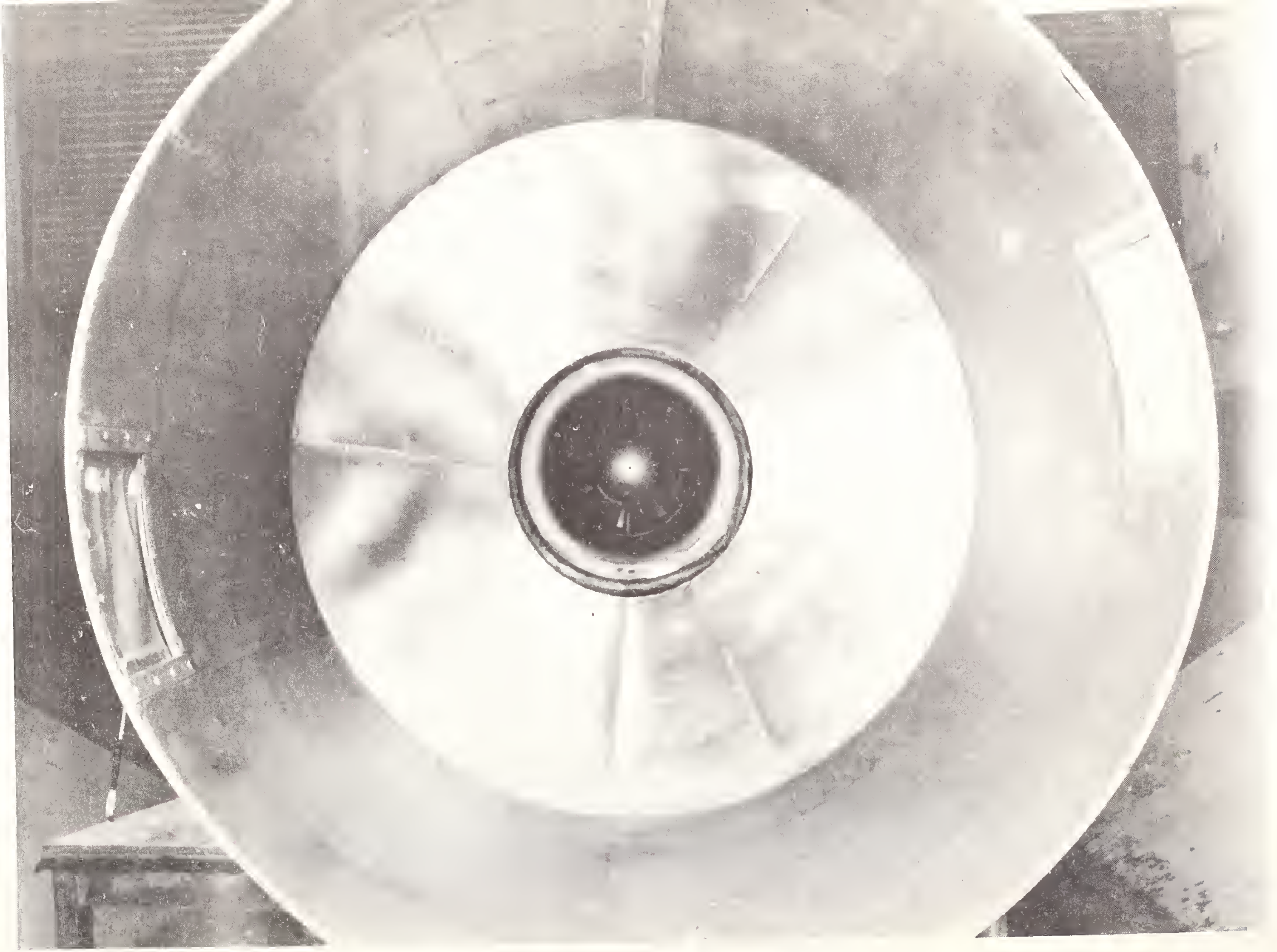

Figure 5. T58 Bellmouth Coupled to Inlet Cloud Chamber.

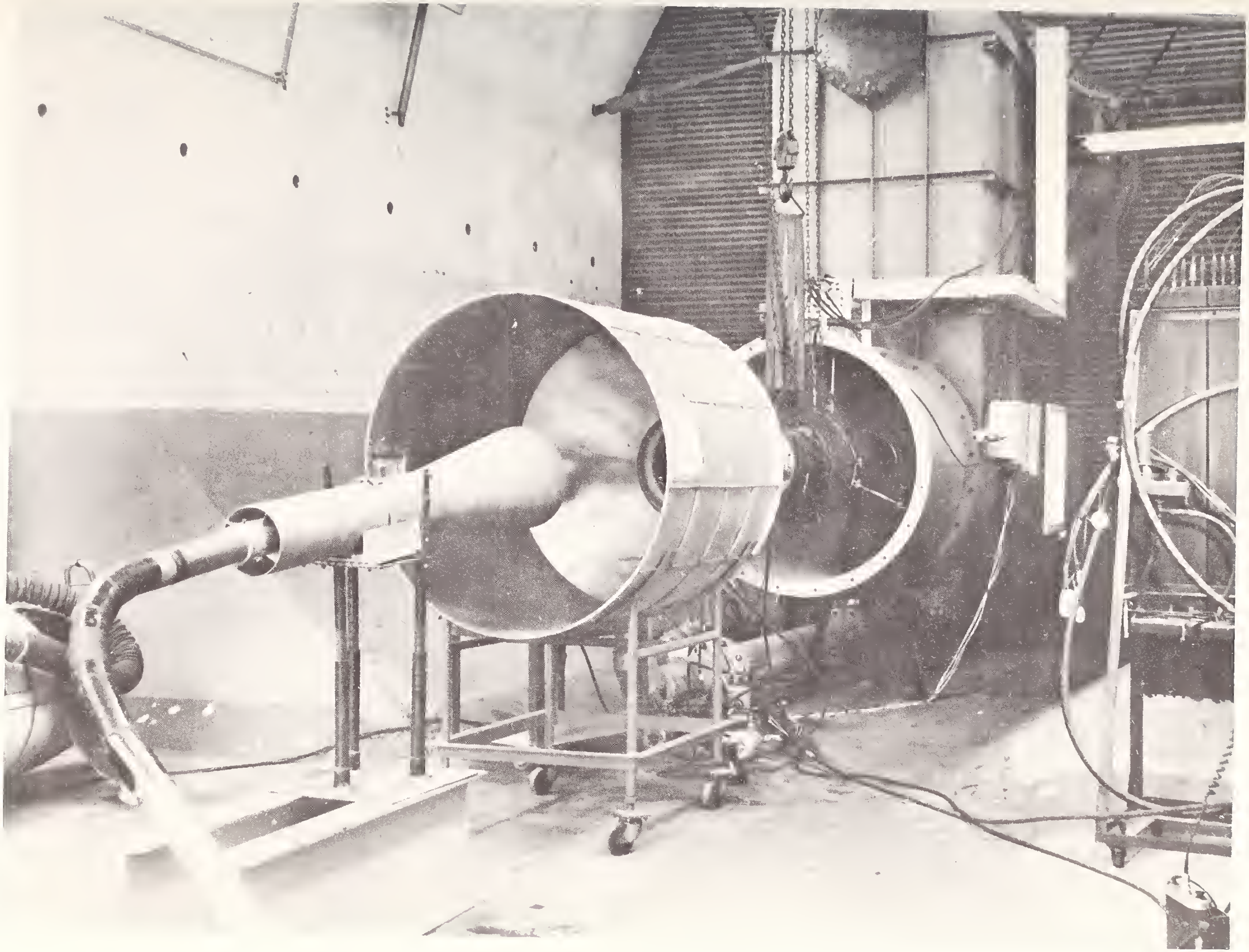

Figure 6. Abradant Accelerated Tube with Funnel Ejector Installeddfor Testing.

DISCUSSION

G. F. Schmitt, Jr., Wright-Patterson Air Force Base: Was there some particular reason for settling for a coating thickness of 10 microns or less? Admittedly you have pretty close tolerances on the thicknesses of coatings that can be put on these blades because of aerodynamics, etc. The coating thickness is certainly not limited to anything as small as that. Is there not some reason to believe that even better protection might be obtained with a somewhat thicker coating?

K. Gentner: The reason I used only up to 10 microns was that I wanted to see definitely any erosion damage on the films so I could learn something. It showed that on the back sides of the blades, the film was eroded away before we came to the end. By using a sputtering process I can coat selective coatings over the area. That means I can give the front side, which needs very little protection, a very light coating, and give the back side a real heavy coating. It has been shown that the back side erodes at least 10 times more severely than the front. Engine people are interested in a minimum added weight from a coating. With sputtering, a light coating can be put on the front side and a heavy coating on the back side which keeps the added weight to a minimum.

J. E. Newhart: The thicker the coating, the greater are the fatigue losses in the substrate. At about a 0.0015 in. thickness and with certain types of high temperature coatings, a 40% loss in the fatigue strength of the substrate can be expected. In some turbine engines there isn't much of a pad to play with.

G. F. Schmitt, Jr.: You just answered my next question which was about the effect on the fatigue life. I recognize that sputtering is a pretty low temperature process as opposed to vapor deposition.

K. Gentner: Actually, to have a high sputtering rate, the sputtering electrode is chilled. The hotter the electrode, the lower is the sputtering rate. If a film is deposited, it should be annealed on the plate. In any other process a high temperature is used which is not good for the base plate, but in sputtering the energy comes from the high speed of the incoming particles. That means the blade can be kept relatively cold and all the energy to anneal the film comes from the incoming particles.

G. F. Schmitt, Jr.: What about using it on titanium? You said you sputtered titanium carbide on titanium. What about anything else and what sort of adhesion or lack thereof would you expect?

K. Gentner: High adhesion is obtained if all the oxides are removed first. How much material should be removed? I have in many cases not removed more than 1 micron. I went as high as 4 microns in one case but it was not necessary.

R. L. Johnson, NASA, Lewis Research Center: We've used the processes of sputtering and ion plating primarily for lubricating coatings for sometime. A year and a half ago there was a conference at Lewis that dealt with both sputtering and ion plating and if anyone is interested in it I can provide copies of this. I think there is a point here that needs to be raised, though. The question was brought out in the discussion of the effects on fatigue. The usual concepts of the adverse influence of coatings on fatigue don't apply with these types of coatings. We have been doing bending fatigue studies with metal specimens with coated surfaces, and we find in some of the surface analyses that sputtered or ion plated materials put on with reasonable processes will, in fact, immobilize surface defects, rather than create them which occurs with some other kinds of coatings. We've shown an increase of 10-50% in endurance life in bending fatigue studies on thin flat sheets. This is with only about 2000 angstrom units thickness of metal coated on another metal. I think this matter of fatigue effects can be advantageous. I mentioned earlier that these coatings will, in effect, tie down surface defects. Ion plated metals will penetrate grain boundaries, and although we haven't experimented with them, in fluid erosion studies, I think that they can mitigate against some of the mechanisms that have been discussed here earlier where slip is occuring at grain boundaries, etc. We had some erosion problems with a fluid in a hydraulic system pump with a bronze surface. The problem was associated with the fluid itself, but we tried to salvage some parts using sputtering of monel. There was erosion damage on the operating parts of a pump similar to the hydraulic pump, the piston pump that we saw here earlier, in a matter of a 1/2 hour with the bronze. With the monel coating, which was a few thousandths of an inch thick, much thicker than we usually use, it took at least 10 hours before we saw any sign of damage. So the coatings can be used in this area without going to the extremely hard coatings that are being talked about. The process is a very flexible one.

RAIN DROPLET EROSION MECHANISMS IN TRANSPARENT PLASTIC MATERIALS

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The damaging effects of rain erosion on optically transparent materials such as are used for windshields and infrared, television and laser guided missiles have become an increasingly severe problem as the number of systems using this type of guidance have increased. The rain erosion of these materials is a twofold problem; first of all, subsonic erosion and runway debris damage during captive carry beneath the wings on the aircraft, and secondly supersonic erosion during free flight after being launched.

On glass materials the subsonic erosion damage takes the form of isolated pits which eventually join together with subsequent chunking of larger pieces. At supersonic speeds catastrophic fracture occurs with large scale cracking and material loss. All materials suffer a significant deterioration (up to 80% loss in transmission) after rain erosion exposure even when no measurable weight loss has occurred.

The front end covers for optically guided missiles called "domes" are typically constructed in hemispherical shapes to enable optimum transmission through them. However, this shape with its large normal (90°) or near normal incidence angles is the worst geometry possible from an erosion standpoint. Reduction in impingement angle is always desirable to reduce erosion effects but this is not compatible with the tracking requirements.

A potential important use of transparent plastic materials which possess some degree of subsonic rain erosion resistance and a moderate degree of thermal capability for withstanding aerodynamic heating during captive carry on supersonic aircraft and after launch is for guided missile optical covers. Polycarbonate and polysulfone plastics have improved thermal stability over acrylics, lower cost than glass, excellent strength properties, and good visual transmission characteristics. The purpose of this investigation was to determine the effects of subsonic rain erosion exposure on the transmission of radiation at a single wavelength (1.06μ) through these plastics.

EXPERIMENTAL APPARATUS

The erosion investigations of these transparent plastic materials were conducted by the Air Force Materials Laboratory on a rotating arm apparatus (see Figure 1). This equipment includes an 8-foot diameter propeller blade made of 4340 steel mounted horizontally and powered by a 400-horsepower electric motor. It is capable of attaining variable speeds up to 900 mph at the blade tip where the specimens are inserted. A detailed description may be found in Reference 1.

The speed of the equipment is regulated by a thyristor power supply from which rigid control is possible. A revolution counter is utilized for monitoring velocity; vibration pickups are used for gauging specimen balance and smoothness of operation. The rotating specimens are observed using a closed circuit television camera and a stroboscopic unit synchronized with the blade revolution.

Mounted above the blade is the water system used to simulate the rain environment. The 8-foot diameter, 1 inch aluminum pipe ring is equipped with 96 equally spaced hypodermic needles to yield a rainfall simulation of 1 inch per hour. The hypodermic needles are No. 27 gauge which produces rain droplets of 1.5 to 2.0 mm diameter as determined photographically. The water system operated with low pressure in the spray ring enables a stream of undistorted water drops to impinge on the material specimens.

The rotating arm simulation apparatus is used extensively in erosion investigations because of the correlation between it and actual flight test results. Various materials were evaluated under actual flight conditions in rain utilizing an F-100F aircraft. These tests verified that the rankings and modes of failure obtained on the rotating arm are borne out in actual flight experience.

Flat panel specimens were run with rain impingement at discrete angles of 90°, 60°, 45° and 30° with respect to the specimen surface.

Materials

The materials for these experiments were Lexan 9034, UV stabilized polycarbonate from General Electric Company and Bakelite P-1700 polysulfone from Union Carbide Corporation. Typical vendor-supplied physical properties are shown in Table I.

Polycarbonate and polysulfone are candidate materials because their spectra shows transmission of 90.4% and 88.2% respectively at 10,000 cm^{-1}; i.e., the wavelength, 1.06 microns, of interest.

Impingement and Transmission Experiments

For laser transmission, the DK-2 recording spectrophotometer was used with a beam size 1/4 by 1/4 inch at 1.06 microns. With the sample removed, the chart pen is adjusted to 100 percent. The shutters are closed and the chart pen is set on zero. The shutters are again opened, the sample is positioned in the appropriate spot normal to the beam direction, and the total luminous transmittance is given by the chart pen.

Nominal velocities of 400, 500 and 600 MPH and rainfall conditions of 1 inch/hour simulated rainfall (1.8 mm dia drops) were used.

Weight loss measurements were attempted but in all but nine of 110 samples a weight gain occurred. The weight gain represented approximately 0.1% to 0.2% of the total sample weight. It was approximately the same for both materials and did not vary significantly as a function of velocity, impingement angle, or exposure time. These results indicate that significant material does not have to be removed from the surface to obtain a decrease in optical transmission. As suggested by Figures 2, 3 and 4, the polycarbonate or polysulfone surface layers tend to pit under the impact of the rain drops. This pitting causes hazing or frosting of the surface.

The difference in the detailed character of the eroded polycarbonate surface compared to the polysulfone is shown in Figures 2 and 3. In Figure 2, a polycarbonate specimen which was exposed at 400 MPH for 30 minutes exhibits individual pits which are somewhat isolated from each other. The polysulfone in Figure 3 after similar exposure shows uniform light surface frosting (pits on a much smaller scale). It is this difference in the form of damage which explains the polycarbonate's better retention of transmittance after rain exposure (i.e., through the relatively undamaged areas) whereas the polysulfone's surface would diffract a larger percentage of the energy and result in lower transmission.

The progression of damage in polycarbonate is shown in Figure 4 for specimens after 90 minutes at 400 MPH. With this long term exposure, the pits have grown and intersected to obscure the surface.

The tests were terminated during the incubation period of the erosion process. This is the time during which significant cumulative damage is occurring on the materials but no measurable material loss has yet occurred. The decrease in transmission with no weight loss is a highly significant point because the short exposures on the rotating arm in these tests would correspond to very limited exposure on the missile dome during captive carry and yet up to 50 percent decrease in transmission has been measured.

An incubation period associated with weight loss for transparent materials does not appear to be an appropriate measure of the onset of significant damage. A more appropriate criterion for ranking of these materials would be the point (exposure time or number of impacts) at which a particular percentage of the original transmittance has been lost. This could be varied depending upon the sensitivity of the optical system to this degradation.

Total transmission measurements at 1.06 microns wavelength are given in Table II. Where two samples were run at each condition, the results are averaged. The data in Table II is summarized in Figure 5 for polycarbonate and Figure 6 for polysulfone where transmission as a percentage of the initial (prior to exposure) is plotted versus time of exposure in one inch per hour simulated rainfall. The parameters in this plot are the normal components of the velocity (v sin θ) corresponding to 300, 400, 500 and 600 MPH. As can be seen, only at a normal component of velocity of 500 MPH does significant decrease in transmission through the polycarbonate occur. By contrast, even a combination as low as normal velocity equal to 400 MPH exposure results in up to 20% decrease in transmittance through the polysulfone material.

DISCUSSION

The importance of the effects of erosion on reduction in transmission during the incubation period cannot be overemphasized. Traditionally, the portion of the erosion process which has been of most concern has been the accumulation period when mass loss occurs as a function of continued exposure to the environment. The loss of material with its consequent reduction in performance of the system was the major problem (see several papers each in References 2 and 3).

However, in the case of optical materials the effects occur before any measurable mass loss begins. Furthermore the appearance of the surface of the transparent materials after this limited exposure would normally be considered slight erosion or little effect. Yet it has seriously degraded the most important property of the materials; namely their ability to transmit the radiation. The obvious effect this has on knowing when a degraded dome is no longer operative and must be replaced from a maintenance standpoint is potentially serious.

The influence of physical properties on the erosion behavior is not easily discernible. As can be seen in Table I the physical strength properties of the polycarbonate and polysulfone plastics are so similar that little difference in erosion performance might be anticipated. The major difference in strength between these two materials is their impact properties as measured in a notched Izod test. The erosion resistance of most materials cannot always be directly correlated with impact strength but is usually quite good (Reference 4). The order of magnitude difference between the polycarbonate (16 ft-lb/in) and the polysulfone (1.3 ft-lb/in) would provide a difference in response to the droplet impact.

An extensive discussion of the correlation between rain erosion resistance of partially crystalline plastic materials and their notch impact strength has been presented by Oberst (Reference 4). He shows a general correlation of increasing erosion resistance with increasing impact strength for polymethylmethacrylate, polycarbonate, polyacetal and polyethylene materials. Polysulfone is not included, however. Furthermore, this correlation is not supported by specific experimentation to test it but is based on single experimental erosion values of Hoff and Langbein of Dornier Systems.

Adler, Morris and Wahl (Reference 5) specifically investigated a number of bulk plastics of varying degrees of crystallinity, including polyurethane, polyethylene, polycarbonate, acrylic polyvinyl-chloride, polyphenylene oxide, acetal and nylon and determined that no correlation could be drawn between notch impact strength and rain erosion resistance.

As shown in Table I, the polycarbonate and polysulfone are so close in hardness (even though this is a macromeasurement) that no correlation can be drawn.

Previous investigation of thermosetting and thermoplastic resins has shown that the ductility of the plastic has a significant influence on its erosion behavior (Reference 6). The erosion resistance and resulting optical transmittance appears to be a function of the ductility of the plastic also. As indicated in Table I, the elongation of the polycarbonate is 110% compared to 50% for the polysulfone. The morphology of the polycarbonate surface after erosion for 30 minutes at 400 MPH (see Figure 3), exhibits no undamaged area with incipient fine scale pitting (or frosting) over the entire surface. This behavior is certainly in keeping with the better retention of transmission by the polycarbonate compared to the polysulfone.

Ductility is a function of temperature in the plastic of course, and the higher heat deflection temperature of the polysulfone (345°F) compared to polycarbonate (270°F) may be detrimental in that it does not become more ductile during the impact process when heat is generated by energy deposition.

Although not specifically investigated in this program, polymethylmethacrylate (Plexiglas) has exhibited similar frosting type obscuration of the surface very rapidly under identical erosive conditions. With its very low elongation ($<10\%$), it exhibited extremely brittle chunking behavior at 400, 500 or 600 MPH. This would further confirm the importance of ductility for transparent plastics retention of transmittance. Obviously only a moderate amount of ductility is really desirable since too soft a material would be sufficiently deformed by the impacting drop to distort the transmittance.

A recent theoretical development by Springer and Baxi (Reference 7) shows promise for correlating the fatigue properties of homogeneous metals and plastics to their incubation period and subsequent mass loss behavior in subsonic rain erosive environment. Properties of the materials required are the ultimate tensile strength, endurance limit, Poisson's ratio, and the fatigue life. This correlation formula has shown excellent agreement with all existing experimental erosion data (mostly metals with some bulk polymers).

An adaptation of the above theory to account for the change in surface morphology during the incubation period has not been accomplished. The theory also does not treat the case where each individual drop impact does damage although this was considered in the analysis. Concepts which utilize this approach may provide insight into the governing materials properties for the erosion of transparent materials.

CONCLUSIONS

1. Significant decreases of up to 80% reduction in laser transmittance at 1.06 microns wavelength through polycarbonate and polysulfone transparent plastics are measured after short term subsonic rain erosion exposure.
2. The major changes in transmittance of these plastics occur during the incubation period of erosion; that is, before mass loss begins.
3. Although both are lacking in long term subsonic rain erosion resistance, polycarbonate is superior to polysulfone in retention of transmittance after exposure.
4. Greater notch impact strength and ductility of the bulk plastic improves its erosion resistance and reduces subsequent loss in transmittance properties.
5. The change in transmittance through the polycarbonate and polysulfone materials can be approximately correlated with the morphology of the eroded surface after exposure.
6. Transparent plastic materials for optical, infrared or laser applications, are lacking in rain erosion resistance.
7. Polycarbonate and polysulfone transparent plastics have limited application for missile dome covers where rain erosion exposure at velocities of 500 MPH or greater are involved. However, these plastics can be used with the proper design such as low impingement angle and a favorable environment such as short time exposure, low subsonic velocities, or low density rainfields.

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ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance of Dr. Richard C. Hall of the Martin Marietta Corporation, Orlando, Florida who provided the materials specimens and transmission tests.

TABLE I

PHYSICAL PROPERTIES OF TRANSPARENT PLASTICS

	Lexan 9034 Polycarbonate	Bakelite P1700 Polysulfone
Specific Gravity	1.20	1.24
Tensile Strength, psi	9000	10,200
Tensile Modulus, psi	345,000	360,000
Elongation, %	110	50 - 100
Flexural Strength, psi	13,500	15,400
Flexural Modulus, psi	340,000	390,000
Shear Strength, psi	10,000	-
Compressive Strength, psi	12,500	-
Compressive Modulus, psi	345,000	-
Rockwell Hardness	M70 (R118)	M69 (R120)
Izod Impact Strength at 72° F, ft lb/inch-notch	16	1.3
Heat Deflection Temperature, °F at 264 psi (0.010" deflection)	270	345

All values obtained by standard ASTM tests.

TABLE II

TOTAL TRANSMISSION CHANGES AS A FUNCTION OF EXPOSURE IN RAIN

Normal Velocity Component (MPH)	Impact Angle (degree)	Nominal Velocity (MPH)	Exposure Time (min)	Percent Transmittance* as a Function of Original	
				Polycarbonate	Polysulfone
400	90	400	5	98.4	94.7
			10	98.2	89.4
			20	99.1	87.4
433	60	500	2	98.9	94.7
			5	97.8	89.3
			10	97.1	75.2
			20	93.0	53.1
424	45	600	2	96.9	95.1
			5	97.3	88.7
			10	93.4	82.6
			20	88.1	72.7
500	90	500	1	99.8	94.1
			2	98.4	86.2
			5	96.6	77.7
			10	90.7	53.9
			20	74.0	18.3
519	60	600	1	95.7	84.0
			2	94.8	84.0
			5	90.0	64.4
			10	78.7	46.6
			20	65.8	25.4
600	90	600	1	89.2	81.7
			2	82.3	58.3
			5	56.6	52.6
300	30	600	5	97.3	95.3
			10	97.0	95.5
			20	95.8	91.5
354	45	500	5	96.5	93.7
			10	97.1	94.6
			20	97.2	84.3
346	60	400	20	97.4	91.7
250	30	500	10	97.3	95.6
			20	97.9	95.5

* Measurements at 1.06μ after exposure to 1 inch/hour simulated rainfall. Average of two specimens except for 90° specimens which are only one measurement.

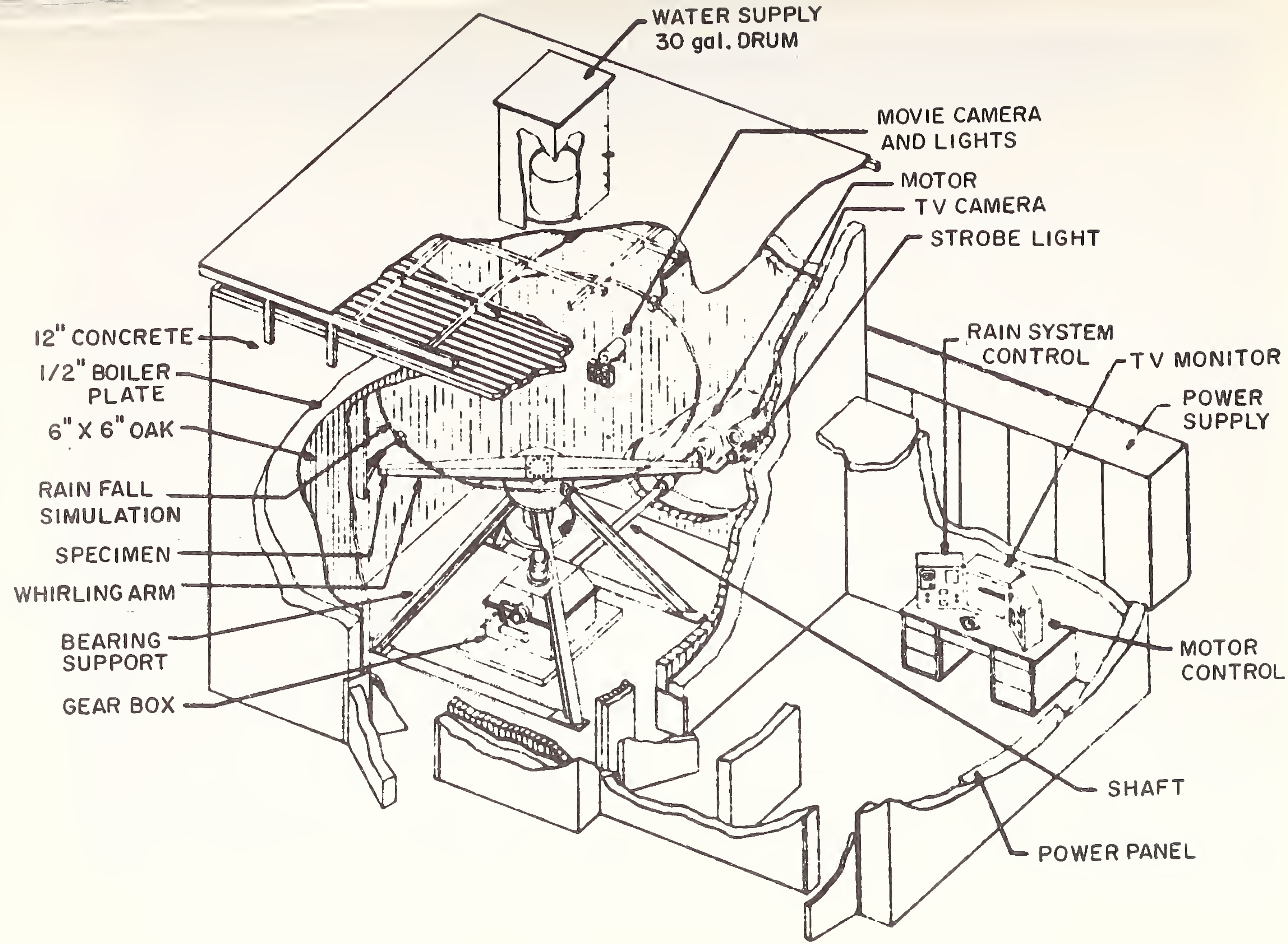

Figure 1. AFML Rotating Arm Apparatus.

Figure 2. Pitted Surface of Polycarbonate 30 minutes at 400 MPH

Figure 3. Frosted Surface of Polysulfone after 30 minutes at 400 MPH

Figure 4. Severe Pitting on Surface of Polycarbonate after 90 minutes at 400 MPH

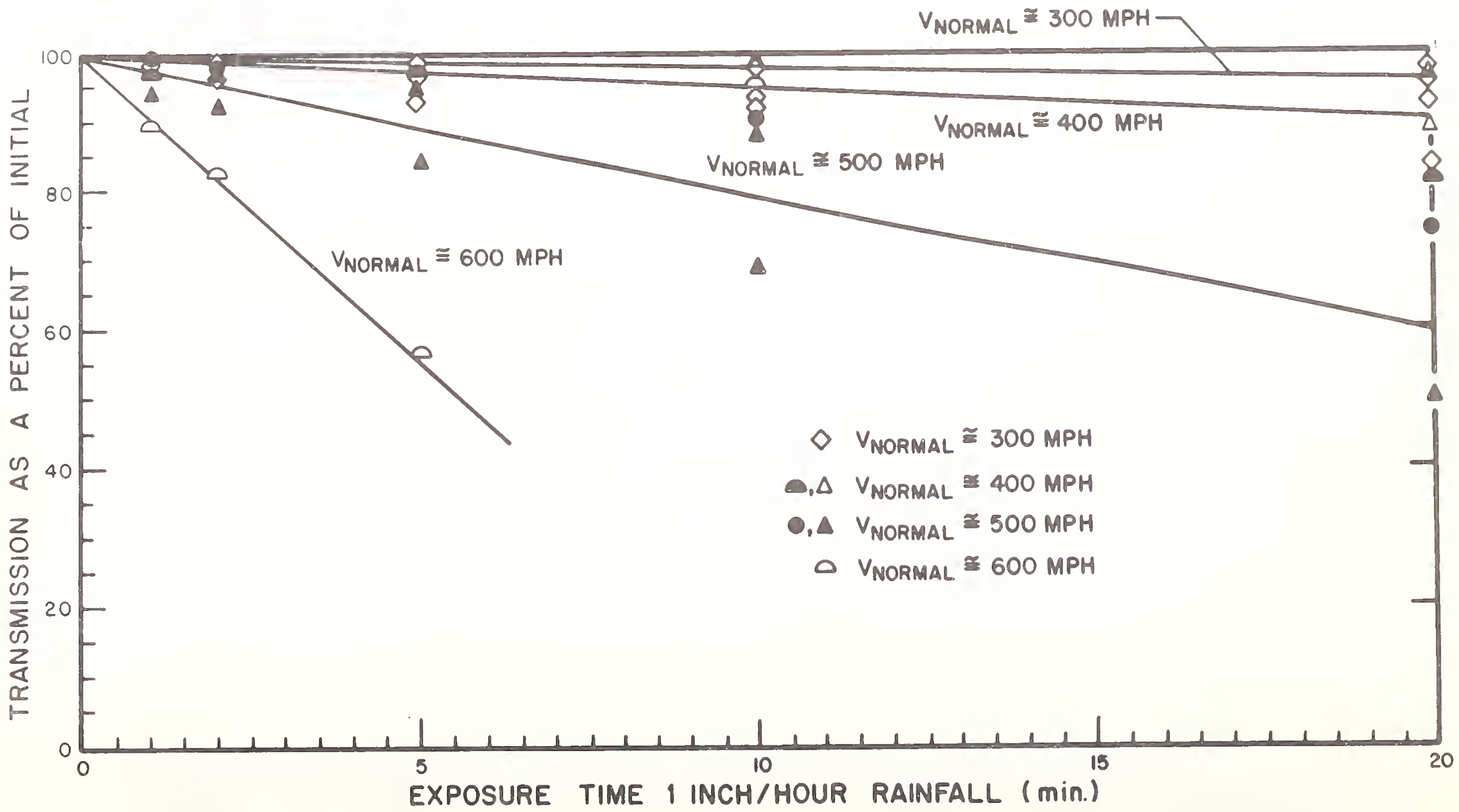

Figure 5. Normal Velocity Component Effects on Polycarbonate Transmission.

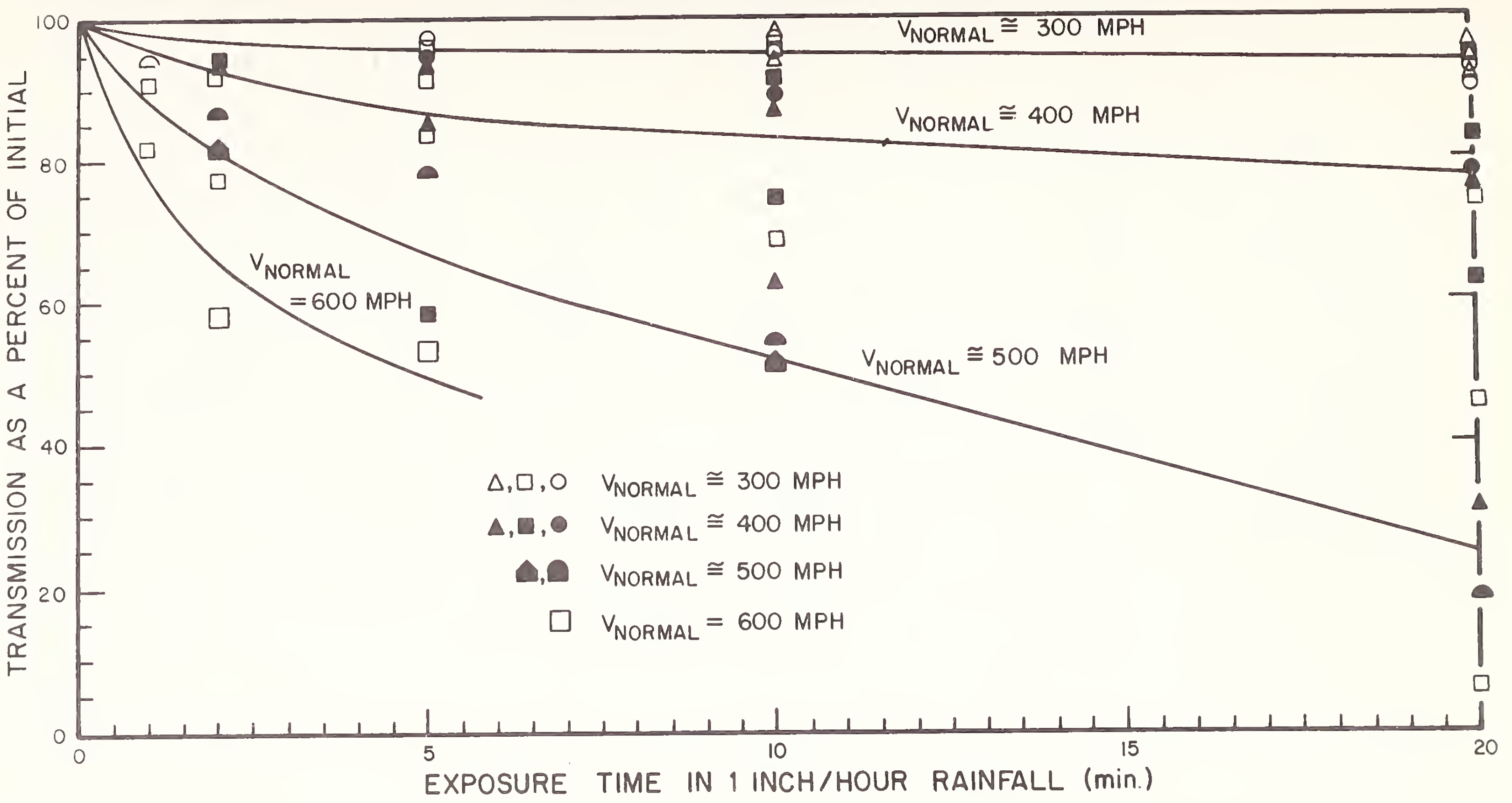

Figure 6. Normal Velocity Component Effects on Polysulfone Transmission.

ANALYSIS OF NAVY RADOME FAILURE PROBLEMS

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The analysis or diagnosis of Navy radome failure problems was done at the request of the Commander, Naval Air Force, U.S. Pacific Fleet. It was performed under the direction of the Materials Readiness Officer, Carrier Division Five, Attack Carrier Striking Force, Seventh Fleet. The survey of environmental damage and repairs included observation of all fighter and attack aircraft then operating within the Tonkin Gulf from the Subic Bay Naval Base. In addition it included the observation of all aircraft assigned to the Naval Air Station, Cubi Point and those aircraft undergoing intermediate level maintenance at the Fleet Air Wing Repair Activity, Cubi Point.

The aircraft observed aboard three attack carriers and ashore exceeded two hundred. The aircraft models observed included all first line Navy fighter and attack aircraft. Aircraft time since overhaul (PAR) varied widely although the majority of aircraft were well within the second half of their PAR cycle.

These aircraft had in general been operating within an extremely hostile environment. Combat missions into Viet Nam were continuing daily in spite of the monsoon season. A large percentage of the flight hours each day were through moderate to heavy rainfall. In addition, most of the preventative maintenance procedures for radomes were being omitted because of bad weather and tight aircraft scheduling.

The task was to carefully observe all these aircraft model by model and radome by radome and to organize the damage findings into some reasonable order. From this survey the critical problem areas were defined and a plan was developed for failure prevention.

As more and more aircraft were observed it became increasingly obvious that the erosion damage was a serious problem, that many electronic systems had been degraded through poor and improper repairs, and that certain airframe manufacturers had done a better job of providing realistic environmentally resistant radomes than had other manufacturers. It was further obvious that the military guideline specification, MIL-R-7705, "Radomes; General Specification for" was ineffective in providing adequate hardware for high performance all-weather aircraft. There was a serious lack of materials and skills to effect satisfactory repairs or to provide for a reasonable degree of preventative maintenance at the squadron level. The technicians were lacking information and help which would assist them in doing their job more satisfactorily.

At the conclusion of the survey or diagnosis of the problems the surveyor could not help feeling dedicated to the solution of as many of these problems as possible. An internal Navy report, "Task Force Seventy Seven, Aircraft Antenna Cover Rain Erosion Damage Survey" was prepared aboard the USS ENTERPRISE, approved by the Materials Readiness staff, signed by the Commander, Carrier Division Five and forwarded to the Commander, Naval Air Force, U.S. Pacific Fleet and to the Naval Air Systems Command Headquarters. This report defined the causes of the problems, listed many specific recommendations for individual product improvements and made several general recommendations. The recommendations included both short term improvements and long term improvements.

From the CTF-77 report came a series of quick reaction type projects and a subsequent series of longer term projects. All projects were in direct response to the needs of the fleet in accordance with the findings of the survey.

A major quick reaction effort was directed toward the development of an interim "Radome/Antenna Cover O-Level Repair Kit". Within 4 months some 160 of these kits were distributed among the Navy's attack carriers world-wide for immediate radome repairs.

The repair kits were developed for use by personnel having no prior experience with plastic repairs. The resin systems and curing processes required no facilities or special equipment. The reinforcement materials included a low dielectric cloth which permits the increase of wall thickness and therefore improved impact resistance on certain antenna covers. Polyurethane tape was provided for quick and easy replacement of worn coatings to prevent further damage to the substrate materials. The Repair Kit Instruction Sheet outlined specific repair instructions for the seven most chronic problems found in the survey. All of these repairs were modeled and validated for conformance with the system and antenna specifications.

Immediate assistance was provided for one small antenna cover by in-house manufacture and shipment of 125 parts within 30 days. These replacement parts were installed by squadron personnel whereas the entire antenna assembly was previously being replaced when replacements were available.

Materials, tools, equipment and repair drawings were shipped to the Fleet Air Wing Repair Activity at Cubi Point to elevate their local intermediate level radome repair capability. Development of this capability made the depot less dependent upon spares replacement, transferred some of the repair work to the shore station and permitted more complex repairs to be made within the Seventh Fleet area.

Six of the seven Naval Air Repair Facilities (NARFS) were surveyed to inspect their radome repair capabilities. Aircraft of all types were inspected as received, in-process and ready-for-delivery. The condition of radomes on completed aircraft varied from excellent to poor.

Whereas it had been previously assumed at the time of the fleet survey that all PAR aircraft were returned to the squadrons with radomes completely restored, many were being returned with their radomes in a partially damaged condition. This has since been rectified to decrease the amount of repair work at the squadron level and to effect more professional repairs.

Having completed most of the short term assist projects our efforts were turned toward the longer range objectives. At this time the NARF's overall had improved their radome re-work capability and comment sheets were being returned by the users of interim Radome/Antenna Cover Repair Kits. The frequency of receiving UR's (Unsatisfactory Reports) was diminishing very rapidly.

The repair kit users comment sheets were used to improve the Radome/ Antenna Cover O-Level Repair Kit before release to the Aviation Supply for their assignment of Federal Stock Numbers, MIL-Spec packaging and procurement. Both the basic kit and the polyester supplement are currently available from Navy stock.

A project was created for the revision of MIL-R-7705. This specification, originally prepared in 1944, had minor revisions in 1950 and 1955. It did not provide the proper guidelines for the preparation of detail specifications for aircraft or electronic systems in the 1970's. Many of the problems found in the survey could be directly related to design deficiencies which could in turn be related to the deficient MIL-Spec. MIL-R-7705 was therefore completely re-written with the objective of preventing similar problems on new aircraft. In addition to updating the electrical parameters the changes impose environmental requirements for rain impact resistance, rain erosion resistance, hail impact and high temperatures. It also establishes requirements for reliability, maintainability and certain unacceptable constructions. The new specification has been approved by the Navy and is currently awaiting acceptance or comment from the Air Force and Army.

A separate project was created under CAMSI (Carrier Aircraft Maintenance Suitability Improvement) funds to develop a service repair manual. This manual, NAVAIR-01-1A-XXX is an Organizational and Depot Maintenance Instructional Manual, titled "Aircraft Radomes and Antenna Covers". It is intended to provide the needed guidelines for quality repairs and preventative maintenance at all maintenance levels. It may also be used as a training document or as a simplified technician level reference on radomes. It contains general design and performance information; detailed materials, construction and repair information; repair techniques; and electrical test methods of repaired parts. It collects all the needed repair information into one reference, directly relates to the Radome/Antenna Cover O-Level Repair Kit and assures a satisfactory repair when performed in accordance with the instructions.

The manual has been designed for frequent revisions when systems are added to or deleted from an aircraft or when a new aircraft is added to the fleet inventory. It currently includes all radomes for all fighter and attack aircraft. The manual has been released to NATSIF for editing, illustration and publication. Preliminary copies are being reviewed by all NARFS and by select AIRPAC and AIRLANT organizations before publication.

Other long term improvements involved the complete re-design of several small radomes which had no chance of survival without major changes in their material or configuration. Some effort was also devoted to the development of a low cost throw-away or disposable radome concept. Through the use of low loss impact resistant moldable thermoplastic materials it appears cost effective to replace rather than to repair certain small radomes. Two new Navy aircraft antenna installations have already adopted this approach.

The rain erosion damage survey established a strong justification for the need of qualification testing of materials and designs which may have questionable life expectancy on the aircraft. Such MTBF and damage rate testing should be required in future specifications. This can be accomplished only if suitable test facilities and test methods are available. Such a capability is currently being developed.

To date the total effort has proven most rewarding when measured by the number of urgent messages, UR's and phone calls received. A true reading for the improved level of failures can be made only by comparison before and after this work using the 3M (Maintenance, Materials, and Management) computer system to search out improvements in replacement rates and maintenance man hours.

DISCUSSION

G. F. Schmitt, Jr., Wright-Patterson Air Force Base: Does that radome damage repair kit have a Federal Stock Number?

K. Foulke: Yes. It is available from the Federal Stock. It can be ordered now.

GOVERNMENT-INDUSTRY DATA EXCHANGE PROGRAM
(GIDEP)

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The Government-Industry Data Exchange Program (GIDEP) was originated in 1959 by the Army, Navy, and Air Force Ballistic Missile Agencies. Known at that time as IDEP--Interservice Data Exchange Program--its intent was to eliminate duplicate testing of parts and components by disseminating pertinent test data among Department of Defense contractors and various government agencies.

In 1966 both the National Aeronautics and Space Administration and the Canadian Military Electronics Standards Agency (CAMESA) recognized the value of the data provided by the program and became participants. Today, GIDEP provides the interchange of specialized technical data to all the military services, participating government contractors and numerous government agencies such as the Atomic Energy Commission, Federal Aviation Administration, Defense Supply Agency, and the Small Business Administration.

GIDEP operates under a charter agreed upon by the Army and Navy Materiel Commands, the Air Force Systems and Logistics Commands and NASA. The Program Manager, organizationally located within the Department of the Navy, is responsible for policies and procedures, both national and international. In addition, he is responsible for establishing funding requirements and reporting on the cost effectiveness of the program. The GIDEP Administration Office is the operational arm of the program. Working directly under, and responsible to, the Program Manager, the Administration Office maintains the GIDEP data banks and is responsible for all operational phases of the program. The GIDEP program management team includes government and industry advisory groups, which are made up of representatives from government agencies and industry participants. They act in an advisory capacity, presenting the requirements of the participants to the Program Manager and the Administration Office.

The objectives of the GIDEP program are to: reduce or eliminate duplicate expenditures for development parts and components; increase the confidence level in the reliability of systems utilizing these parts and components; expedite research and development projects by avoiding repetition of tests previously accomplished; assist in the preparation of more realistic proposals; standardize procedures for reporting test information; encourage direct inter-contractor communications among technical personnel working on related projects; generate information for an alternate source of parts through more dependable data; create a general source for test data; and provide for the exchange of test equipment calibration procedures and related data. Mechanical and electronic failure prevention and warning of potential problems are part of GIDEP's operational system.

GIDEP data are contained in four separate information banks: the Engineering Data Bank, the Failure Experience Data Bank, the Failure Rate Data Bank, and the Metrology Data Bank. No classified or company proprietary data is included.

The Engineering Data Bank contains primarily laboratory data relating to parts, components and materials. These data cover Qualification and Environmental Testing, Research and Development, Evaluation Reports, and other meaningful engineering data such as non-standard parts justification, test planning, and manufacturing processes.

The Failure Experience Data Bank contains failure data and failure analysis reports from the field, laboratory and production line. It also contains all of the information from the Air Force Defective Parts and Components Control Program which contains failure analysis data by component types derived from an operation and maintenance level.

Part of the Failure Experience Data Bank is an important program known as the ALERT system. The ALERT is a highly effective means of rapidly providing all participants with information concerning an actual or potential problem involving a part, material, test equipment, process or safety problem. Any participant who finds a situation which he feels to be of general concern to other participants fills out an ALERT form. The ALERT form is submitted to the Administration Office where it is reviewed and distributed to all participants as an ALERT. Generally, this process is completed within twenty-four hours.

The ALERT system may be used for any type of pertinent information relating to any of the data banks. It is issued to identify such items as faulty design, faulty test equipment or calibration procedures, or other production and processing problems. The advantage of a short notification time in the ALERT system provides cost savings to participants by avoiding the repetition of problems which have been previously identified or solved.

The Failure Rate Data Bank contains field performance data relating to parts, components and materials. Detailed information concerning failure rates, stress levels, mean time to repair, level of test specification, failure mode, test environment and other pertinent information is contained in the Failure Rate Data Bank.

The Metrology Data Bank contains calibration procedures and general information on test equipment. Calibration procedures prepared by both the military and industry, covering most electrical and mechanical test equipment, are available to participants. In addition, under a program called SETE (Secretariat for Electronic Test Equipment), other types of information such as test equipment evaluation reports are available.

An additional function of GIDEP is an International Data Exchange Program called EXACT. Functioning at an international level, EXACT provides for the exchange of reliability test data with a dozen foreign countries. As our current national policy encourages foreign trade and the sale of American goods overseas, the EXACT program is one means of providing greater visibility of our products to potential overseas customers. Therefore, GIDEP is providing test reports to EXACT which document successful test results on parts and materials. In addition, we are increasing our use of foreign-made parts in our military systems. The availability of information on those materials is of obvious value. EXACT provides for data exchange among all member countries, with no increase in overall cost to GIDEP operations.

The GIDEP program operates as a self-regenerating, closed-loop system. Engineering, failure, and metrology data are submitted by government or industry participants to the Administration Office for inclusion into the GIDEP Data Banks. Only data that is germane to the objectives of the GIDEP program and will be of use to others in the program may be submitted. Once the data has been screened and indexed, the index is placed in the GIDEP computer. In addition, the full report is placed in microfilm cartridges which are distributed along with a hard copy index bi-weekly to all participants. The Administration Office also distributes a complete updated index to all participants on an annual basis.

The unique combination of data returned via computerized indexing and microfilmed reports provides all participants with rapid access to all GIDEP data. This is accomplished by utilizing their in-house computer terminal and microfilm reader. Participants may also at their discretion request a computer index search and copies of various reports directly from the Administration Office.

The participant may, through a terminal, address any of the four GIDEP data banks individually or collectively. Further, he may enter a year date to restrict his data search to relatively current information, or if he desires, he may also run an entire historical search of all data in a particular area. The GIDEP computer will automatically search the Data Banks and if pertinent items are found, the participant will be provided with an index number and, in the case of an ALERT, a brief abstract of what the report contains.

The GIDEP computer is programmed so a participant may initiate a search using any of several approaches: The computer may be addressed to search by GIDEP generic code, manufacturer's part number, key word, industry standard part number, environmental code, or any other fields contained in the data banks. Once information is located, the computer provides the participant with a microfilm reel and access number in addition to a report number. All participants are provided with microfilm indexes. Thus, if a participant does not maintain microfilm records, he may request copies of specific reports or the loan of a microfilm reel from the Administration Office.

If an index and computer search fails to identify participant-required data in the GIDEP Data Banks, he may initiate an Urgent Data Request. One of the most powerful tools of the GIDEP program, the Urgent Data Request is a means by which a participant may submit an informal request to all other participants for information on a specific part, component, material or test instrument. The Urgent Data Request form is initiated by the participant which he submits to the GIDEP Administration Office. The GIDEP Administration Office, upon receipt of the Urgent Data Request, reproduces the form and distributes it to all participants generally within a period of twenty-four hours.

When a participant, upon receipt of an Urgent Data Request, finds information pertaining to the particular problem addressed, he forwards the information directly to the requester. When data are received in response to an Urgent Data Request, the requester forwards a copy to the Administration Office for inclusion in the GIDEP Data Banks.

The GIDEP program is much more than technical information and data banks. It is people cooperating for the benefit of all. One of the key people in the GIDEP program is the GIDEP Representative. Assigned by each new participant from its in-house staff, his responsibility is to determine who in his organization can use and will generate GIDEP data. He, more than any other person in the program, can directly influence his company's success or failure within the scope of the GIDEP program. He must continually promote the system and inform his associates of its values and advantages. As a GIDEP Representative he also acts as liaison among his in-house departments and other GIDEP Representatives and the GIDEP Data Banks. The GIDEP Representative is also the key to documenting the cost effectiveness of the program. An effective GIDEP Representative is synonymous with an efficient GIDEP program.

The GIDEP program provides participants with the vehicle to maintain and improve the reliability of their product and simultaneously minimize research time and eliminate duplicate testing of parts, components and materials. The GIDEP program, properly implemented and utilized, produces impressive cost effectiveness. In 1966 when the program was relatively new, the documented cost savings to participants, both government and industry, was $5 million. By 1970, the cost savings had risen to over $7 million, and last year the GIDEP program had a cost effectiveness of over $10 million.

Increased cost savings is only maintained through participant cooperation and efficiency. Examples of past cost savings are numerous and well documented. One typical case history concerns an engineer who in 1972 was using the GIDEP Data Banks to obtain failure analysis data on a particular microcircuit. The GIDEP analysis data indicated the microcircuit exhibited excessive leakage but the problem had been corrected by replacing one of the materials used in its construction. Aware that this particular microcircuit was currently being used by another company for production of Minuteman ground support equipment, the engineer recognized a potential problem and issued a GIDEP ALERT. The ALERT was picked up by the company using the microcircuit, and, as a result, issued a change order for some 200 systems still in production. Thus, the repair cost of 200 systems was avoided, at an estimated cost savings to the company of over $1,300,000. In addition, if these parts had gotten into the field, the replacement costs would have been astronomical.

Literally hundreds of major cost avoidance cases are documented each year by participants in the GIDEP program. As more industry and government activities become involved with GIDEP, the effectiveness and efficiency of the program increase. Organizations involved with the Mechanical Failures Prevention Group may participate in GIDEP. To apply for participation, direct a letter of request to the GIDEP Administration Office. The letter should be signed by an official duly authorized to commit the company or agency to the obligations associated with participant status.

Requests for GIDEP program information and participation requirements should be directed to:

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Fleet Missile Systems Analysis and Evaluation Group Annex

Attn: GIDEP Administration Office

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MECHANICAL FAILURES PREVENTION GROUP

19th MEETING

The Role of Cavitation in Mechanical Failures

National Bureau of Standards, Boulder, Colorado
October 31, November 1 and 2, 1973

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NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO. NBS SP-394

2. Gov't Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE The Role of Cavitation in Mechanical Failures. Proceedings of the 19th Meeting of the Mechanical Failures Prevention Group, National Bureau of Standards, Boulder, Colorado, October 31 and November 1 and 2, 1973

5. Publication Date April 1974

6. Performing Organization Code

7. ~~AUTHOR(S)~~ Editors T. R. Shives and W. A. Willard

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 3120400

11. Contract/Grant No.
ONR NAonr 70-74
NASA S-55581A

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Office of Naval Research, Arlington, VA 22217
NASA Goddard Space Flight Center, Greenbelt, MD 20771
NBS Institute for Materials Research, Washington, DC 20234

13. Type of Report & Period Covered Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 74-7057.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

These proceedings consist of a group of sixteen submitted papers and discussions from the 19th meeting of the Mechanical Failures Prevention Group which was held at the National Bureau of Standards on October 31 and November 1 and 2, 1973. The central theme of the proceedings is the role of cavitation in mechanical failures.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Bubble collapse; cavitation; cavitation damage; cavitation erosion prevention; erosion; surface roughness.

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.10:394

☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED

21. NO. OF PAGES 183

22. Price $2.25

USCOMM-DC 29042-P74

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