CHARACTERIZATION AND DETERMINATION OF EROSION RESISTANCE

A symposium
presented at the
Seventy-second Annual Meeting
AMERICAN SOCIETY FOR
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Foreword

This publication is a collection of most of the papers presented at the Symposium on Characterization and Determination of Erosion Resistance, organized by Committee G-2 on Erosion by Cavitation or Impingement in co-operation with the U. S. Office of Naval Research, at the Seventy-second Annual Meeting of the American Society for Testing and Materials held at Atlantic City, N. J., 22-27 June 1969. A Thiruvengadam, Hydronautics Inc., now at Catholic University of America, presided as chairman of the symposium, and F. J. Heyman, Westinghouse Electric Corp., presided as co-chairman of the symposium.

Three of the papers presented at this symposium have been published in other ASTM publications as follows: "Surface Damage from High Velocity Flow of Lithium" by L. G. Hays and "Dynamic Response and Adhesion Failures of Rain Erosion Resistant Coatings" by A. F. Conn and A. Thiruvengadam, *Journal of Materials,* Vol. 5, No. 3, Sept. 1970; and "ASTM Round-Robin Test with Vibratory Cavitation and Liquid Impact Facilities of 6061-T 6511 Aluminum Alloys, 316 Stainless Steel, and Commercially Pure Nickel" by C. Chao, F. G. Hammitt, C. L. Kling, T. M. Mitchell, and D. O. Rogers, *Materials Research & Standards,* Vol. 10, No. 10, Oct. 1970. They therefore do not appear in this volume.

Related ASTM Publications

Erosion by Cavitation or Impingement, STP 408 (1967), $20.00

Contents

Introduction

This symposium was the third on the subject of cavitation and impingement erosion to be sponsored by ASTM, the first two having been held in 1961 and 1966, respectively. The advent of modern engineering systems such as supersonic aircraft and missiles, high-speed naval craft, high tip-speed steam turbines, and liquid metal space power plants has stimulated widespread interest in the phenomenon of erosion of materials by cavitation or impingement. This interest is international in scope, as witnessed by similar symposia held in Great Britain in 1965 and in Germany in 1965 and 1967.

The most significant contribution of these symposia has been the establishment of a common forum for scientists and engineers working on cavitation and impingement erosion and the exchange of useful knowledge. As a further step we focused the attention to a specific problem and selected the theme for this symposium as characterization and determination of erosion resistance. This was reflected in several papers presented in this symposium. Some have made significant advances toward definition and characterization of erosion resistance in its own right and toward establishing statistical and physical correlations between this and other material properties.

The ASTM round-robin tests using vibratory cavitation and liquid impact facilities and the comparative erosion tests of steam turbine blade materials in Europe are examples of the recent attempts toward standardization of existing test methods. Besides, new testing techniques also have been advanced. Hopefully these efforts will lead toward the generalization of erosion test results so that they can be applied to the prediction of service performance and toward quantitative and qualitative understanding of the erosion process. A significant number of papers have concerned themselves toward the understanding of the process of erosion itself. It was highly encouraging to note the international response to this symposium and the most enlightened discussions that followed the presentations of papers. These discussions are documented fully in this volume. It is our belief that this symposium has contributed greatly to the scope of the ASTM-G-2 Committee on Erosion which includes "the promotion of knowledge in the area of erosion of materials by cavitation or impingement; the development, evaluation, and correlation of test methods; and the establishment of standards."

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Phillip Eisenberg[1]

Cavitation and Impact Erosion—Concepts, Correlations, Controversies

REFERENCE: Eisenberg, Phillip, "**Cavitation and Impact Erosion—Concepts, Correlations, Controversies,**" *Characterization and Determination of Erosin Resistance, ASTM STP 474*, American Society for Testing and Materials, 1970, pp. 3–28.

ABSTRACT: Increasingly severe requirements for materials in modern high performance applications have re-emphasized the need for fundamental understanding of erosion processes associated with cavitation and liquid impingement. In recent years, there has been disclosed a number of concepts which are proving helpful in the description of both types of erosion in a wide range of hostile environments (high temperatures, corrosive liquids, etc.). Such probings are providing a framework for development of useful methods of analysis and prediction of the response of materials under cavitation attack and liquid impact. In spite of the ingenuity of these ideas and investigations, however, the nature of the complex interactions among the many parameters involved inevitably has resulted in controversies which have yet to be resolved.

Perhaps the most important concepts which have made possible rational correlation attempts and show promise of a unified treatment of erosion are those of energy absorption. In both types of erosion, very useful results have been obtained based on static strain energy, but a more complete and critical evaluation of these ideas must await the accumulation of data on behavior of materials at high strain rates. Strain rates of interest are those associated with cavitation bubble collapse and with liquid droplet velocities typical of rain impact on high-speed aircraft and droplets in wet steam or vapor turbines.

Whether cavitation damage descriptions can be treated independently of the manner in which the pressures of collapsing cavities are applied—shock waves or internal jet formation—still requires investigation. Internal jet impact is analogous to droplet impingement. These problems are connected intimately with the hydrodynamics of cavitation bubbles, droplet deformation, and the physical properties of the liquid environment. In the latter connection, recent work in hot liquid alkali metals has added to the background information needed to achieve useful correlations.

The dependence of rate of erosion on exposure time and the existence of definite "zones" of erosion (incubation, accumulation, attenuation, steady state,) now seem clearly established for both cavitation and impingement attack. The mechanisms which account for this behavior, however, whether hydrodynamic, mechanical, metallurgical, or combinations of these, still require clarification. Very impressive correlations have been achieved for data in the so-called steady-state zone using strain energy concepts, but even here there is a question about the "steadiness" of this zone. Phenomenological fatigue

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theories have been adapted to describe the history of damage progression with good results. Here again further research is required to clarify whether the role assigned to fatigue is truly governing in the context of these theories or whether the correlations based on statistical fatigue theories are physically correct.

KEY WORDS: cavitation, erosion, impingement, evaluation, tests

It is a great pleasure and indeed an honor to be given the privilege of delivering the opening paper to this Symposium on Characterization and Determination of Erosion Resistance. The fact that these meetings, sponsored by the ASTM Committee on Erosion by Cavitation or Impingement, can attract the type of participation that it does is indicative of the importance of the field and the great activity now being devoted to cavitation and impingement erosion. The international character of the meeting is a tribute to the American Society of Testing and Materials for its foresight in sponsoring these stimulating forums. The Committee also deserves praise for its recognition of the intimate connection between cavitation erosion and liquid impingement and the benefits to be derived from the intersection of those working in the separate subjects for exchange of views, opinions, and criticisms. The frequency of the conference also guarantees that each family does not become so enamored of its ideas that it loses sight of shortcomings, and the exposure thus ensured is crucial to continuing progress toward understanding of the physical phenomena as well as application in engineering contexts. What has happened, of course, is the stimulation of those previously devoted to impingement erosion to give their attention also to cavitation erosion phenomena and vice versa, with the result that, properly, an attempt to achieve unification of treatment is underway.

Increasingly severe requirements for materials in high performance applications have re-emphasized the need for fundamental understanding of the erosion processes associated with cavitation and liquid impingement. I believe it is fair to say that recent probings and concepts are providing a framework for development of useful methods of analysis, characterization, and prediction of the response of materials under cavitation attack and liquid impact in a wide range of hostile environments. In spite of the ingenuity of these ideas and investigations, however, the nature of the complex interactions among the very many parameters involved inevitably has resulted in controversies which will undoubtedly rage for some time to come.

It is not my intention, nor would it be feasible, to try to give a complete review and critique of the status of knowledge in these fields. The subject is just too complex and merits more than the superficial treatment that would be the outcome in the time available. In fact, I would not have the temerity to make such an attempt before this audience. Furthermore, the remarkable scope and excellence of the papers and discussions of the previous symposium sponsored by the ASTM Committee in 1966 [*1*],[2] the meeting on *Deformation of Solids by Impact of Liquids* sponsored by the Royal Society of London in 1966 [*2*], and the *Second Meersburg Conference on Rain Erosion and Allied Phenomena* in 1967 [*3*] make a new review rather premature. Consequently, it is my purpose to touch on just a few points that I believe are particularly interesting and important and which require further clarification and research. I think it also would be of interest to trace the development of the ideas which have brought our understanding of these problems to its present state of activity and which, coincidentally, are the sources of some of the severest controversy at the present time. Yet, these are just the topics which must be understood if rational characterization methods are to be achieved.

More than three decades ago, De Haller and Ackeret [*4*] pointed out the similarity between cavitation damage and liquid impact erosion. For many years, starting with Rayleigh's computation, it was assumed that cavitation bubbles, as long as they remain spherical, collapse with sufficient force to produce pressures high enough to cause damage. Ackeret [*5*], however, pointed out that in general cavitation bubbles do not collapse spherically, at least in the flow conditions that he observed, and consequently the collapse pressures must be too small to cause damage. Even in the case of spherical collapse, it has been shown that collapsing bubbles must be so close to the attacked surface that it is unlikely that very many will ever reach a strategic position. Knapp [*6*] estimated that only one in 30,000 cavitation bubbles reached the surface of the body on which he made his observations of the dependence of damage on stream velocity. More recently, Ivany [*7*] and Hickling and Plesset [*8*] calculated that bubbles, in order to cause damage, must be well within a distance of one bubble radius from the wall before the pressures developed by spherical collapse will be high enough to cause damage. In any event, collapsing bubbles become unstable and do not collapse spherically. Thus, they produce much smaller pressures, and various attempts have been made to prove that the collapse of cavities cannot be the cause of damage. (Parenthetically, it might be said at least that the early controversies concerning nonmechanical origins seem to have been laid to rest.) A very closely reasoned discussion of this problem is contained in an outstanding paper by Benjamin and Ellis [*9*] in the proceedings of the Royal Society meeting mentioned earlier, and I recommend that to you. In addition, it is a beautifully written paper.

During an investigation of ultrasonic cavitation, Kornfeld and Suvorov in 1944 [*10*], observed that air bubbles underwent forced oscillations in the acoustic pressure field which resulted in distortions leading to insta-

[2] The italic numbers in brackets refer to the list of references appended to this paper.

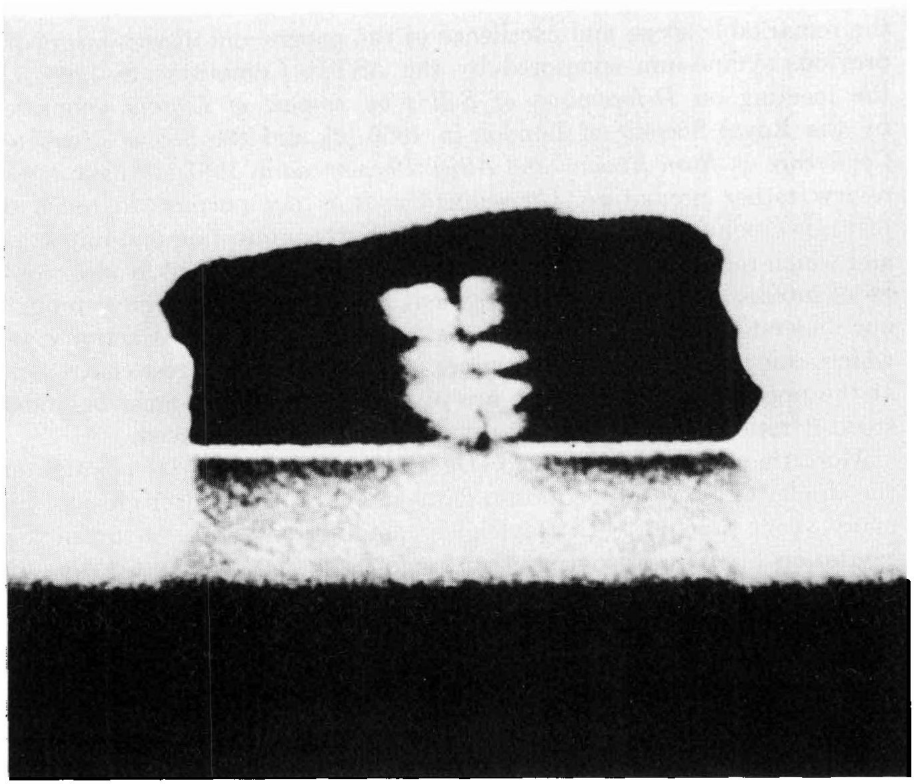

FIG. 1—*Internal jet formed during collapse of a spark-generated bubble collapsing on a solid boundary (after Naude and Ellis, Ref* 12).

bility and disintegration. In some cases, these bubbles broke apart, and it was inferred that the flow of water between the new bubbles produced jets. They found further that cavitation bubbles behaved in the same way and again attributed the formation of jets to unstable and non-spherical collapse. They deduced that such jets could cause damage. Since this is a completely random process, it seems unlikely that the jets thus formed, that is, due to unstable collapse, even if close to a wall, very often will be directed toward the wall. Consequently, there seems to be a very small probability that such a mechanism can account for very much of the observed damage in a cavitating flow. In the late 1940's, it occurred to me [*11*], on the basis of underwater explosion bubble phenomena, that it was more likely that *directed* jets could be formed in pressure gradients and near a wall (which is equivalent) and an instability mechanism need not be dominant or present, at least initially. Evidently, this was a bold idea at the time; it remained for Naude and Ellis [*12*] about ten years later to show that this does indeed happen. Their photographs of a cavity collapsing near a wall are now classical. One frame of a series of high-speed photographs of a spark-generated bubble collapsing on a wall is shown in Fig. 1. The internal jet directed toward the wall can be seen plainly. More recent photographs of a cavity collapsing in a gravity gradient taken by Benjamin and Ellis [9] is shown in Fig. 2. The photo-

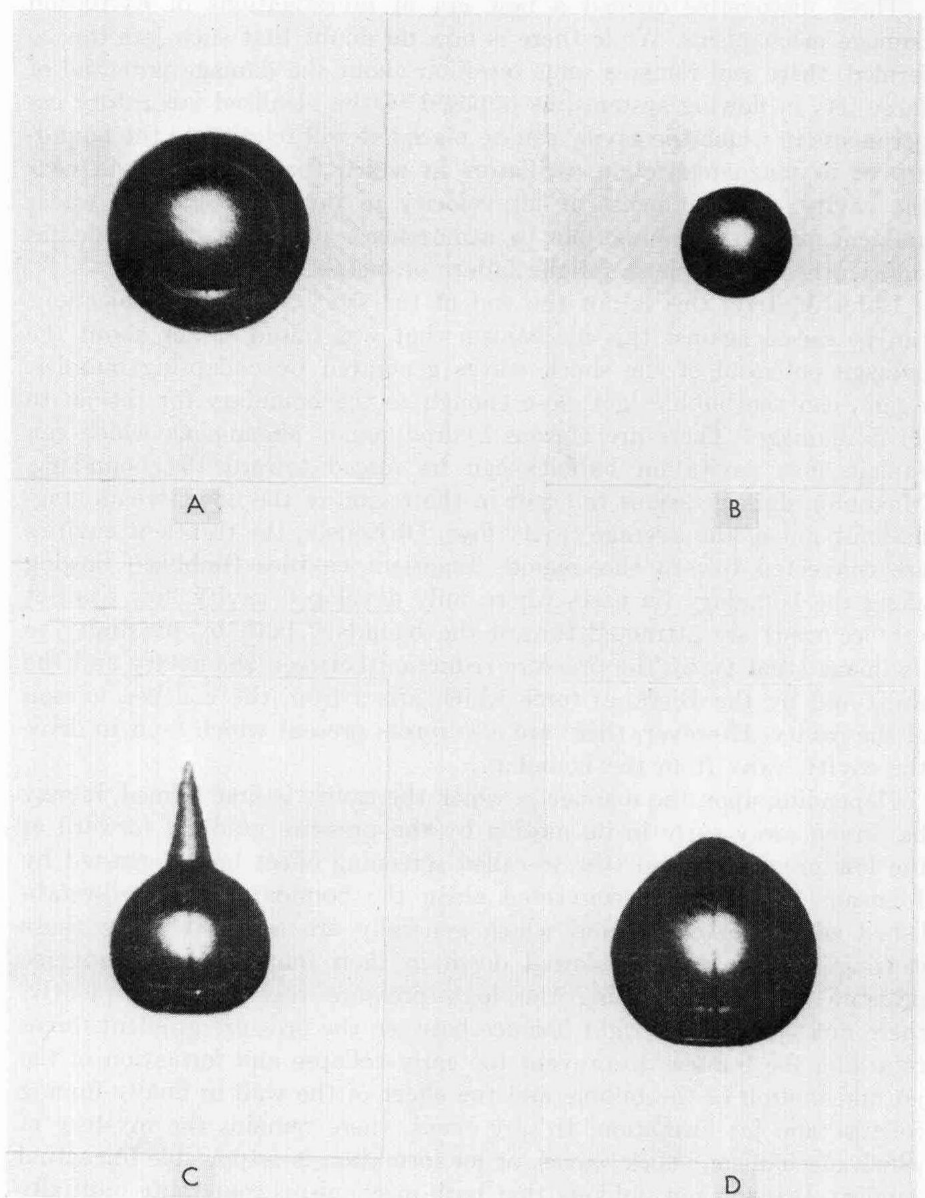

FIG 2—*Photographs taken by Benjamin and Ellis (Ref 9) during collapse (A and B) and rebound (C and D) of a cavity under gravity far from boundaries of liquid.*

graphs at the top show successive stages during collapse. The lower photographs show the growth cycle. Between *B* and *C* (near the minimum radius) an internal jet was formed that was so strong that it continued to persist even during the growth cycle. Such jets would be expected to form in any pressure gradients.

These discoveries opened a new era of investigations of cavitation damage mechanisms. While there is now no doubt that such jets can be formed, there still remains some question about the damage potential of these jets in flowing systems, as opposed to the idealized laboratory experiments in which the cavity can be placed at will relative to the boundary or in magnetostriction oscillators in which the wall is placed near the cavity. Measurements of jet velocity in bubbles collapsing under ambient pressures comparable to atmospheric pressure show velocities sufficiently high to cause fatigue failure of metals.

Unfortunately, this is not the end of the story. The same objections can be raised against this mechanism that was raised earlier about the damage potential of the shock waves generated by collapsing bubbles. Again, can the bubbles get close enough to the boundary for the jet to do its damage? There are various hydrodynamic phenomena which can explain how cavitation bubbles can be forced toward the boundary. Maximum damage seems to occur in the region of the downstream stagnation point of the average cavity flow. Obviously, the transient cavities are convected toward this region. Transient cavities (bubbles) flowing along the boundary (in cases where fully developed cavity flow has not yet occurred) are attracted toward the boundary both by proximity to its image (that is, by the pressure reduction between the cavity and the wall) and by the Bjerknes force which arises from the collapse motion of the cavity. However, there are also forces present which tend to drive the cavity away from the boundary.

Depending upon the manner in which the cavity is first formed, it may be driven away early in its motion by the pressure gradient forward of the low pressure region (the so-called screening effect first suggested by Johnson [*13*]). Cavities convected along the boundary of a well-established cavitation region and which generally are assumed to be those causing the damage are slowed down in their motion by the adverse pressure gradients entering the high pressure regions. Consequently, there must be just the right balance between the pressure gradient forces retarding the bubbles to prevent too early collapse and formation of the jet and motion of the bubble and the effect of the wall in finally forcing collapse and jet formation. In any event, there remains the mystery of which mechanism, shock waves, or jet formation is responsible for actual damage. It seems not unlikely that both mechanisms contribute mutually to the rapid damage that is observed.

Another possibility connected with jet formation but unrelated to the

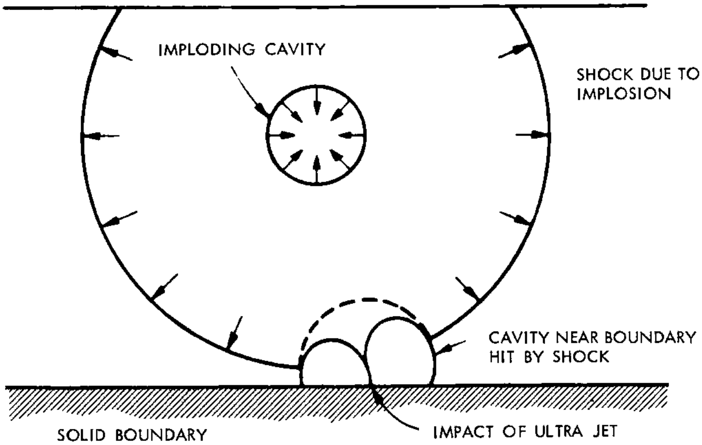

FIG. 3—*Tulin's suggested mechanism of cavitation damage by ultra jets* (*Ref* 14).

mechanisms discussed so far has been suggested by Tulin [*14*] in a paper published in the Sedov 60th anniversary volume. Tulin arrived at this suggestion from a theoretical investigation motivated by an interest in the generation of so-called "ultra jets" by means of weak shocks impinging on a bubble. Ultra jets are jets having a velocity greater than half the sound speed in the liquid. Such ultra jets have been demonstrated by Bowden and Brunton [*15*]. Tulin demonstrated that weak shocks can indeed give rise to ultra jets and that such jets have an upper bound approximately equal to twice the sound speed in the liquid. His suggestion is that a weak shock which may not be damaging in itself, because it originates too far from the boundary, may induce an ultra jet in a cavity on or near enough to the wall for the jet thus formed to strike the boundary, Fig. 3. This question remains to be investigated.

One final word about the damage of collapsing cavities. This is a relatively new observation, I believe. Van Manen [*16*] observed a severe bending of the trailing edge of a propeller blade in the region where cavitation damage to the blade material also occurred, Fig. 4. He postulated that this bending failure was associated with the loading induced by the collapsing mass of transient cavities. Wijngaarden [*17*] has shown theoretically that a water-bubble mixture of cavitation bubbles containing a permanent gas is highly dispersive and can give rise to very high average pressures which could account for the failure seen in Fig. 4. I point out this observation not because it contributes very much to our knowledge of impact phenomena but because thin foils often are used in the laboratory, and care must be taken that erosion measurements are not obscured by the failure and loss of material associated with this mechanism.

From the material damage standpoint, the existence of internal jets and their damage potential brings together the diverse interests in damage

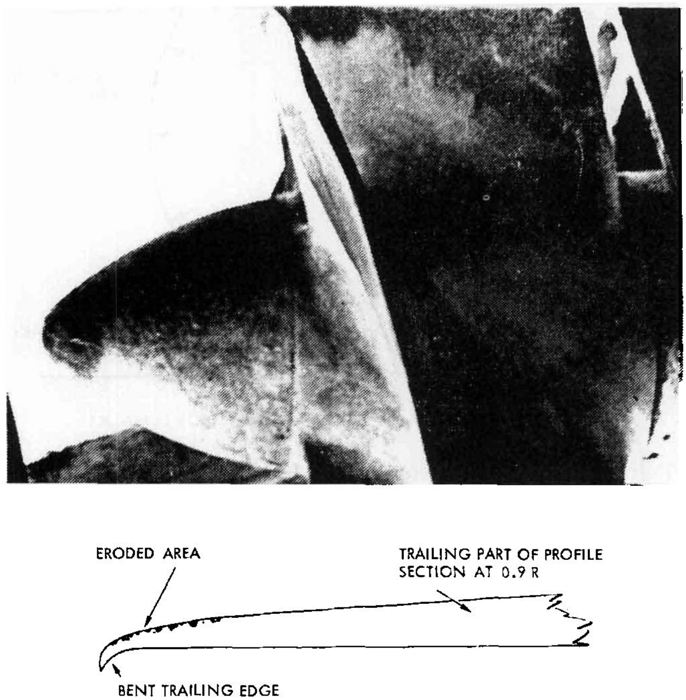

FIG. 4—*Bent and eroded trailing edge of a propeller blade* (*Van Manen, Ref* 16).

by cavitation and by liquid impact. One might say that as far as the fluid dynamics of erosion is concerned, the problem has now found quite common ground.

The fluid dynamics of impacting jets and droplets seems to present problems which are even more difficult to solve and phenomena which still defy adequate quantitative description. The starting point is still the one-dimensional water-hammer pressure ρcv as first discussed by Honegger [*18*]. The work by Ackeret and De Haller considered similar ideas. More detailed analyses and contributions have been made by Heymann [*19, 20*], Jolliffe [21], and Jenkins and Booker [*22*].

Extensive discussions and descriptions of the various physical phenomena occurring during droplet impingement and jet impact have been given by Olive Engel in an impressive series of papers over the course of about fifteen years (see, for example, Ref *23*), and, in recent years Brunton [*24*], Bowden and Field [*25*], Bowden and Brunton [*15*], Hoff et al [*26*], Heymann [*27*], and Fyall [*28*] to name only a few, and it would be superfluous to try to give a more up-to-date story here. Suffice it to say that much more detailed and sophisticated studies of the fluid dynamics of impacting and spreading droplets and jets remains to be done. Even then we may not have the full story. In addition to the direct impact pressures produced by droplets, secondary hydrodynamic phenomena may contribute to erosion. I refer to the possibility of inducing cavitation either within the droplet during its motion following initial impact or in the radial flow over surface roughnesses during spreading. I believe that these possibilities were first pointed out by Olive Engel. At least I became aware of them during discussions with her some 15 years ago. In the first case, cavitation bubbles may be formed because of the reflection of rarefaction waves at the surface of the solid after impact and propagation of the initial compression wave. In the second case, surface roughness of sufficient height to cause local pressure reduction in the radial flow or locally separated regions must be present. The first mechanism seems conceptually possible with each impact. The second would seem to be possible only after some initial roughening takes place. Whether any of this occurs is still a matter of conjecture.

Cavitation in liquid films impacted by droplets or jets is, however, not a matter of conjecture any longer. It has been demonstrated by Brunton [*29*] that cavitation can be produced at nuclei within a liquid layer by the pressure wave propagated through the liquid layer by the impacting droplet. Furthermore, although liquid layers are often cited as providing a cushion against damage by impingement, Brunton showed that craters can be formed by the collapse of such cavitation bubbles even when held at a distance from the surface. Brunton showed further that the collapse of the small air bubbles indicated a motion from which he deduced that internal jets would be formed, which can perhaps be described by the type of analysis suggested by Tulin.

Turning now to the problem of response of materials to cavitation or impingement attack and erosion, it is necessary to distinguish between the basic physical phenomena occurring in the materials during the processes which lead to failure and the correlating parameters which hopefully will ultimately allow a complete description method suitable for characterization and prediction, whether based on basic principles or phenomenological deductions. For ductile materials at least, there seems now to be little controversy that initial failure is associated with fatigue mechanisms. It is only necessary to recall the X-ray diffraction patterns obtained by Plesset [*30*] some years ago as a convincing demonstration. Otherwise, tension or compression failures in brittle materials still endorse the ideas of mechanical action in both cavitation and liquid impact erosion. It is easy enough to make a general remark such as this one, but, having said this, I hasten to add that a great deal has been left unsaid. There is still a considerable gap and disagreement concerning the properties of materials which are most important in determining whether a material will be susceptible to massive erosion under the types of attack we are discussing. Much has been written about this subject, and you are