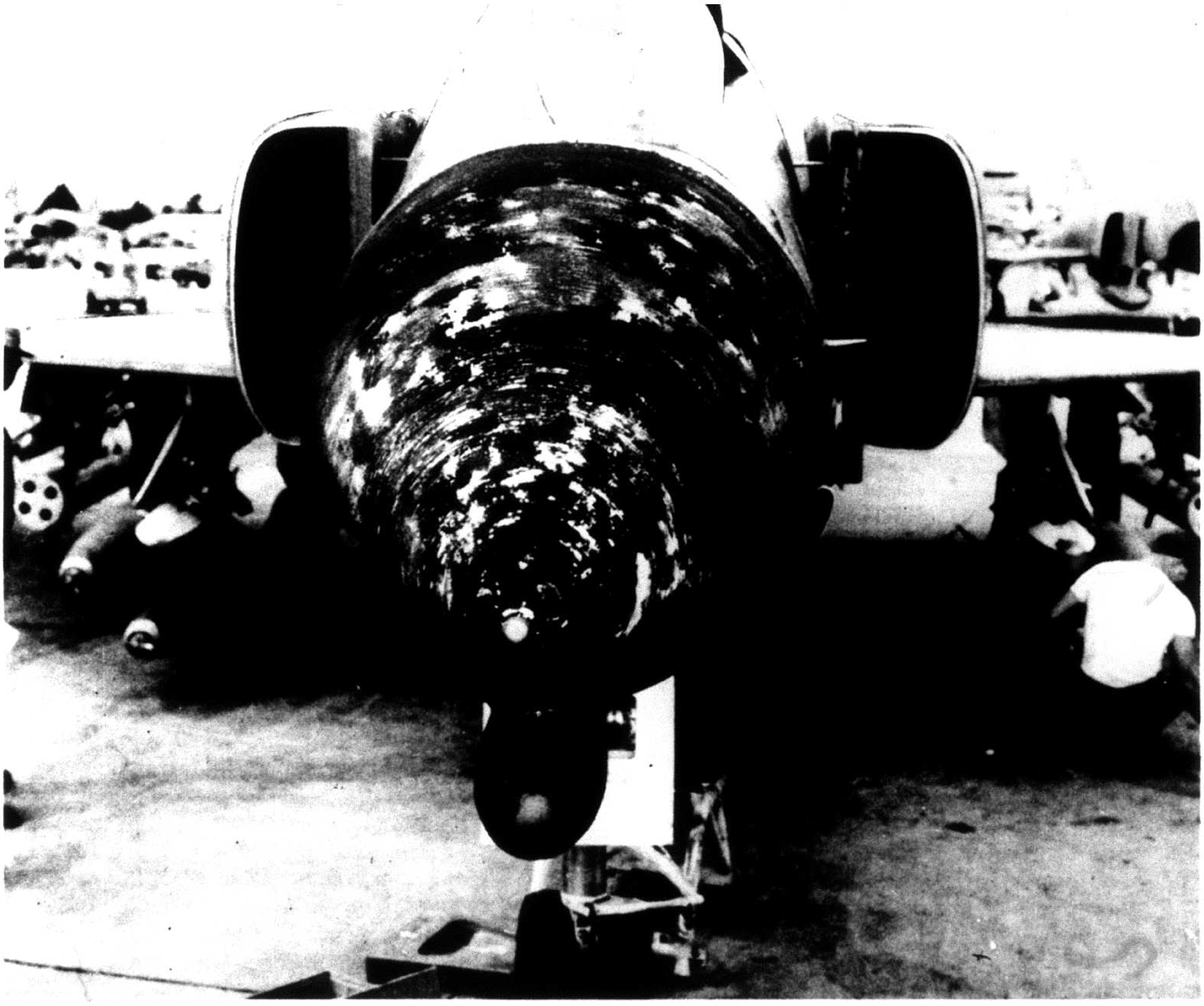

Fighter aircraft radome eroded by flight through rain. The damage shown can cause serious degradation of the radar performance as well as weakening of the structure itself. The radome is made of fiberglass-epoxy laminate and is protected by an elastomeric coating which offers some erosion resistance. Photo, courtesy Air Force Materials Laboratory.

Erosion by Liquids

...the mysterious

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Erosion by cavitation and liquid impingement seems to be the Achilles' heel of many new, advanced materials. For example, an aircraft flying through a rainstorm at 600 mph can suffer serious damage in only a few minutes. The most important research goal is to gain an understanding of these complex forms of erosion. Here is a summary of what is known about cavitation and liquid impingement along with the theories and speculations that look most promising.

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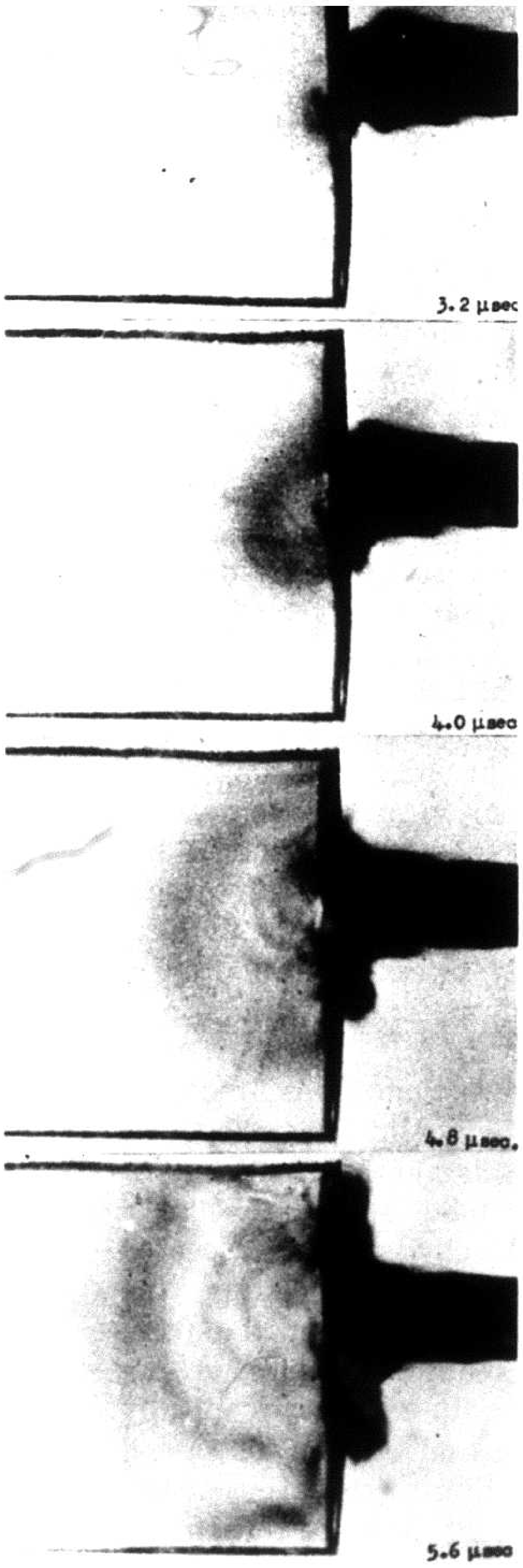


Fig. 1—Impact of a water jet (0.086-in. diam) against a clear plastic block. The initial impact actually occurred at a time of 2.4 sec, and the impact velocity was 2,240 fps. Note the stress waves in the plastic due to the impact pressure. Also, note the delayed (but very fast) outflow on the upper side of the jet where the head of the jet is curved similarly to a drop. Photo, courtesy Dr. J. H. Brunton, the University of Cambridge, England.

murderer of metals

A BRIEF SUMMARY of cavitation and liquid impingement technology is difficult without being too superficial. The subject is complex, involving the interaction of many phenomena—hydrodynamic, mechanical, metallurgical, and chemical. Also, because there still exist controversies and gaps in our knowledge, any review must reflect some of the opinions of the author. For this reason, an extensive list of references is included to help in digging deeper.

Dynamics of Erosion

Erosion can be defined as the gradual loss of material from a surface, usually in the form of small particles or fragments, due to repeated dynamic or impulsive forces acting on the surface. Chemical or other actions may play a role in the damage mechanism, but the primary concern here is where mechanical stressing is present and where erosion, in its absence, would be negligible.

Liquid impingement is the collision between a solid surface and liquid drops, or jets, at high relative velocities. (This is not the same as "impingement attack" which is corrosion accelerated by the impingement of gas or vapor bubbles carried by a liquid stream.)

Cavitation is the formation and violent collapse of bubbles within a liquid, generally as a result of rapid changes in its static pressure. If this happens adjacent to a part surface, that surface may erode.

Cavitation and liquid impingement both exert hydrodynamic forces on a surface, and the nature of the damage from the two is similar as are the material properties required to resist damage. Thus, cavitation erosion tests and impingement erosion tests are often considered interchangeable.

Occurrences of Erosion: Cavitation first appeared as a serious problem with the introduction of high-speed propellers for ship propulsion in the last years of the 19th century, and it is still a problem with ship propellers and underwater appendages. Hydraulic pumps and turbines are also classical victims of cavitation erosion; now hydrofoils must also be added to the list.

Cavitation can occur in any high-speed flow situation where static pressures vary abruptly due to hydrodynamic loading (as in the previous examples) or due to constrictions in valves, orifices, and inlets to heat exchanger tubes, bearings, and seals. The general requirement is that the local static pressure drops below the vapor pressure of the liquid. This can also be brought about by a vibrating solid surface in contact with a liquid —the principle behind a widely used type of cavitation erosion test device. Vibration is also the cause of cavitation erosion in diesel engine cylinder liners.

Liquid impingement has long been a problem in low-pressure steam turbines which operate in wet steam (see Fig. 2), and is of concern to designers of liquid-metal power plants for space application. It also is a dramatic problem today for supersonic aircraft and missiles which must survive flight through rainstorms, as evidenced by the 3,000 hp, Mach 3, rain-erosion test facility recently completed at Bell Aerospace Co.

Liquid Impingement: Most of what is known about liquid drop impacts with a solid surface has been derived from high-speed photographs,[1, 2] Fig. 1. There are two phenomena which are the major contributors to impingement damage: the high pressure generated at the initial impact area to bring the liquid to a sudden stop, and the high-velocity lateral flow of the liquid subsequently

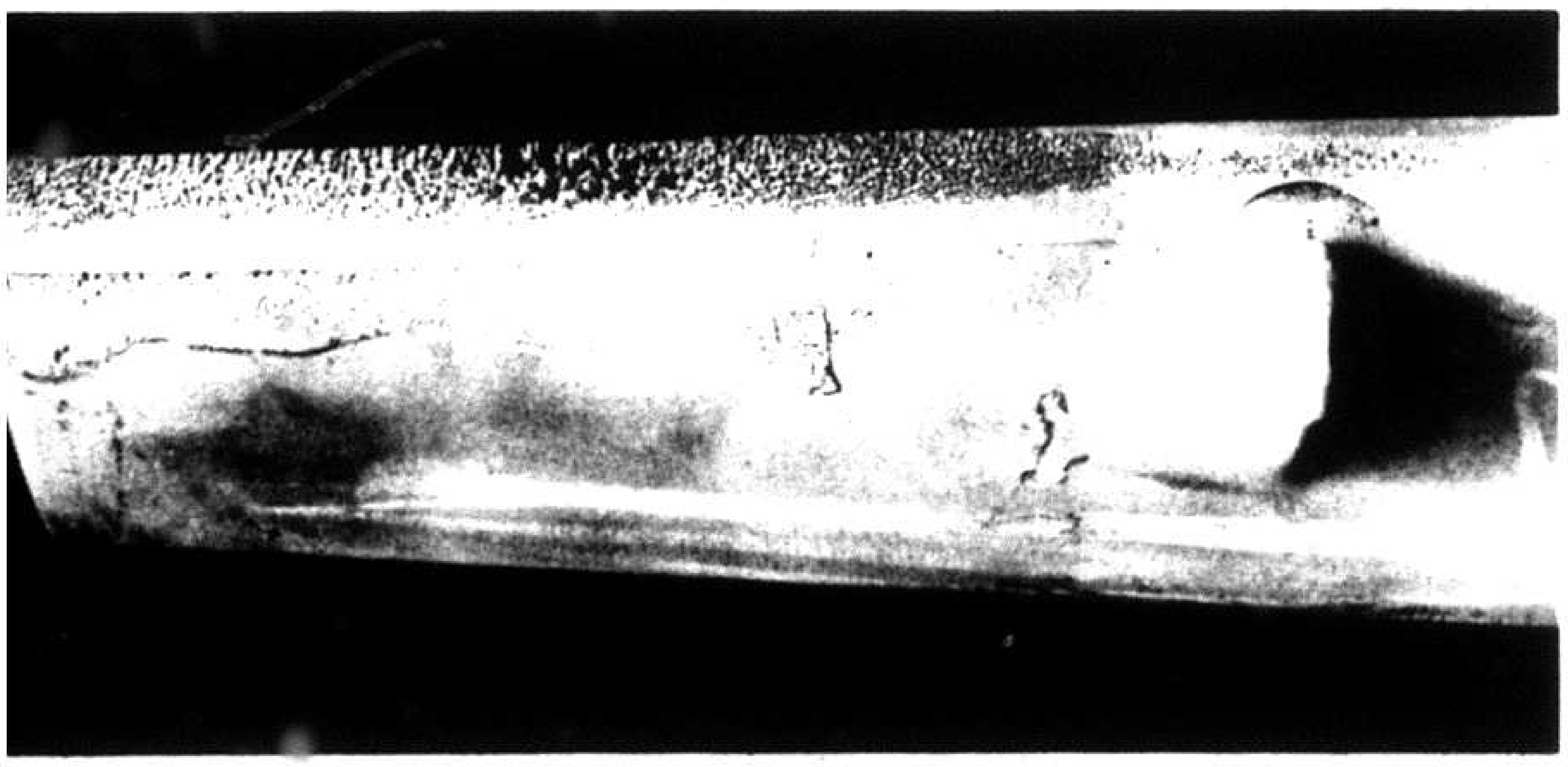


Fig. 2—Badly eroded tip of a low-pressure steam turbine blade showing characteristic honeycomb-like appearance. Steam turbine blade erosion first became a concern in the 1920's, and today most manufacturers use protective measures such as stellite strips or flame-hardened regions in those blades most suscptible to erosion. However, in the blade shown, note that the stellite erosion shield has been eroded through in some locations.

escaping from this high-pressure zone (See *Box*, p. 121).

Calculations of impact pressures[3] show, for example, that a drop impacting a rigid surface at 1,500 fps generates a pressure which reaches 160,000 psi at the center of the impact area, and peaks at 300,000 psi at the edge of the liquid/solid interface before gross spreading of the drop begins. Thus, the impact pressure can easily exceed the target's elastic limit and cause plastic deformation of a ductile solid or cracking if brittle. In ductile metals, the deformation usually consists of a shallow central depression with a diameter nearly that of the drop or jet, surrounded by an annular region of roughening and circumferential ripples. The resulting small surface irregularities then interact with the high-speed lateral liquid out-flow, which causes additional deformation and removes material by shearing and tearing. Central and annular cracks can be formed in brittle materials.

Cavitation: The precise phenomena responsible for cavitation damage have been subject to much speculation and dispute. The two major theories are: cavitation damage is primarily a form of corrosion, aided and abetted by local turbulence and mechanical forces due to bubble collapse[4]; and mechanical forces due to bubble collapse constitute a necessary and sufficient cause for cavitation damage, though it may be augmented by chemical action. Local heating effects, electrical discharge effects, and other effects[5] have also been suggested as major contributors.

Most researchers agree that there is severe mechanical stressing in cavitation attack. What has not yet been resolved is whether this is due to shock waves generated within the liquid by the collapse and rebound of cavitation bubbles,[6] or whether the damage is caused by the unsymmetrical collapse of bubbles in contact with the solid surface, such that the "back" of the bubble jets forward and impinges on the surface.[7] Numerous recent studies have sought to clarify this point.

Development of Damage

Incubation Period: In both cavitation and liquid impingement, the solid surface is subjected to a multitude of sharp pressure pulses, each of very short duration, each acting on a very small area. These areas may, under some circumstances, be on the same order of magnitude as the grain sizes and inhomogeneities of the material structure. Thus, statistical variations in the mechanical "microproperties," as well as the mean properties normally of importance, can be expected to influence the response of the material to this kind of attack. Deformation can therefore occur initially in local weak spots or unfavorably oriented grains, or in the weaker component of materials with a pronounced nonuniform structure.

Except under very severe conditions, material loss is usually preceded by an incubation period during which material loss is absent or negligible. Sensitive optical methods have shown that in a ductile surface subjected to cavitation or repeated liquid impact (at relatively low intensities) the first geometrical changes are often in the form of randomly distributed shallow dimples or depressions. The breaking out of microscopically small isolated particles has also been observed. Metallographic observations reveal marked changes in the structure of the surface during the incubation period. Deformation within crystals is evidenced by slip lines and twin formations, even for the most resistant materials. X-ray diffraction studies have revealed that plastic deformation eventually occurs. The depth of this region of plastic deformation is approximately 30-40 μm;[8, 9] the time to attain this depth varies with the erosion resistance of the material but seems to be comparable to the incubation time. The depth of the work-hardened layer remains approximately constant as actual erosion of the surface begins and continues.[10]

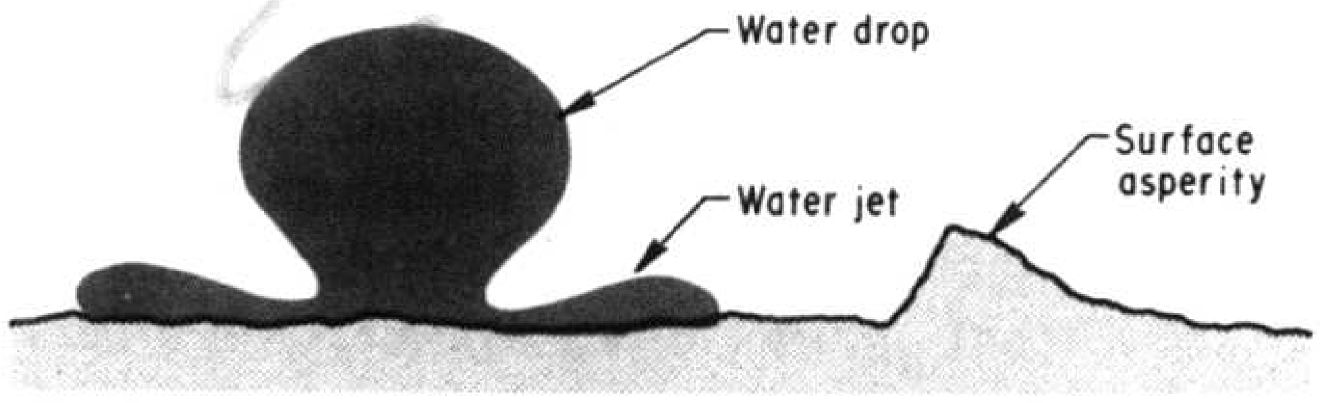
Processes of Material Removal: The end of the incubation period, while not rigidly defined, signifies the beginning of more serious material loss and of the rapid increase of erosion rate. The precise mechanisms, and sequences of events, which lead from the incubation-period damage to the systematic removal of eroded particles from the surface, vary according to the severity of the attack and the properties and microstructure of the material. Generally, when the limit of plastic deformation and work hardening is reached, further energy input to the surface results in the initiation and propagation of fatigue-like cracks, which eventually intersect and release erosion particles. Erosion failures are generally transcrystalline.

Erosion by cavitation, as well as by multiple-

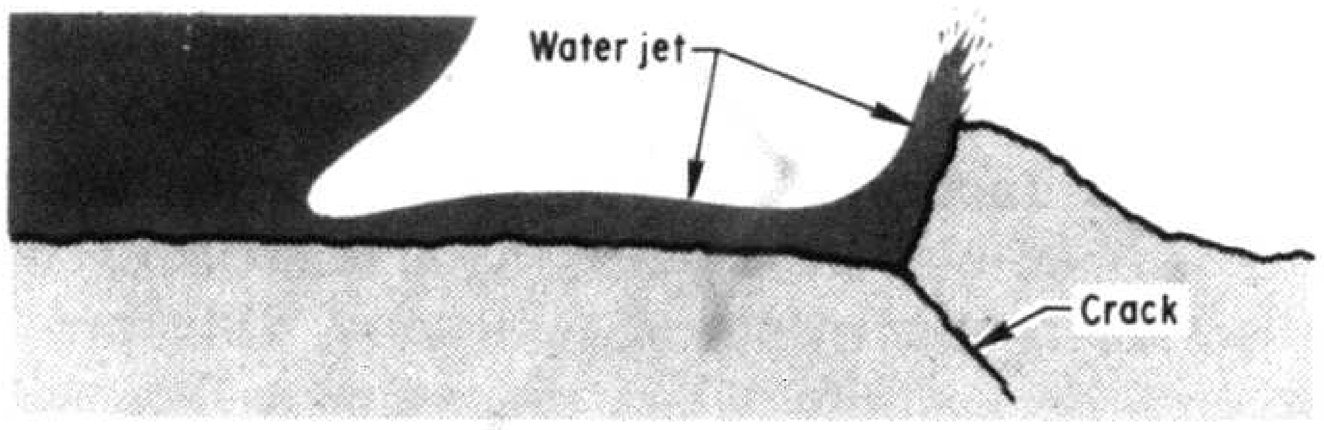
At Supersonic Speeds, There's No Such Thing as a Gentle Rain

The effect of rain impinging on the surface of a high-speed aircraft is a major area of current research. The erosion mechanism illustrated here pertains to aluminum alloys at raindrop impact speeds near 1,120 fps (Mach 1.0). This concept is the result of comprehensive electron microscope examinations and analyses of test specimens at Bell Aerospace Division of Textron.

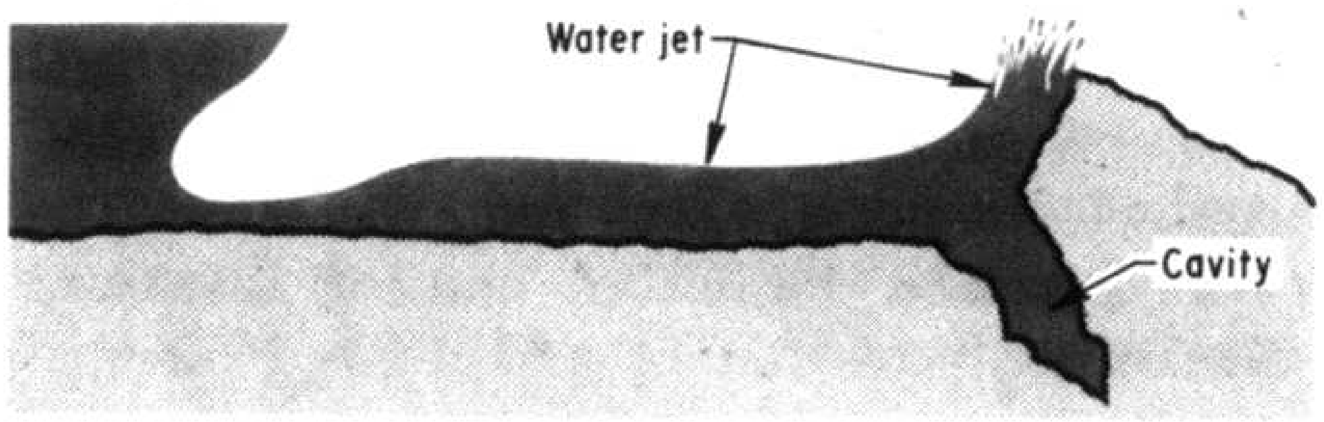
Upon impact with a solid surface, a water drop sends out lateral water jets that can travel across the surface at velocities up to 10 times the speed of impact. These water jets strike the microscopic irregularities or asperities that are found in all solid surfaces due to machining or other influences.



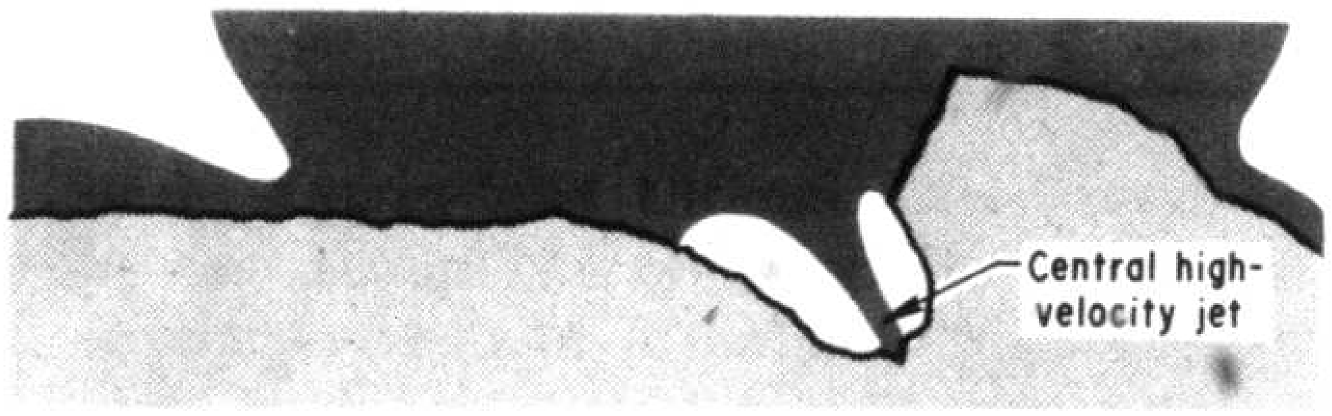
As a result of the force of repeated water-jet impacts, the asperity tends to crack at its base.



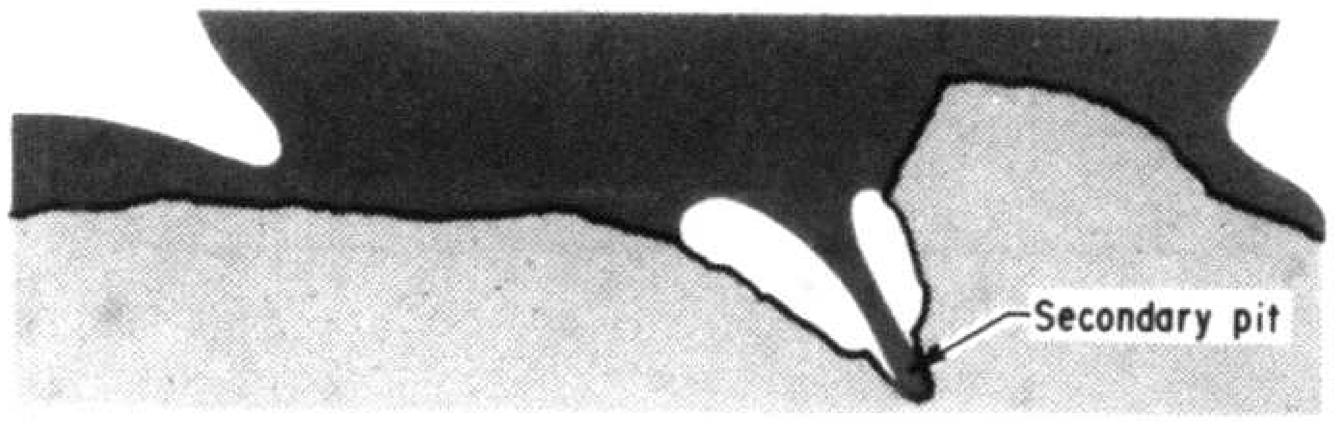
Subsequent water-jet impacts ultimately open up the crack, leaving a cavity in the surface that will deepen with time.



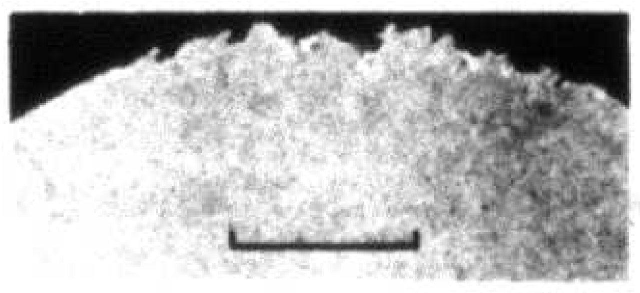
Erosion is then hastened by those water droplets that impinge directly on the cavity. In this case, shock waves coming from the walls of the cavity have a tendency to compress the water entering the cavity into a single spear-like central jet that strikes the bottom of the cavity with several times the force of the initial droplet impact.

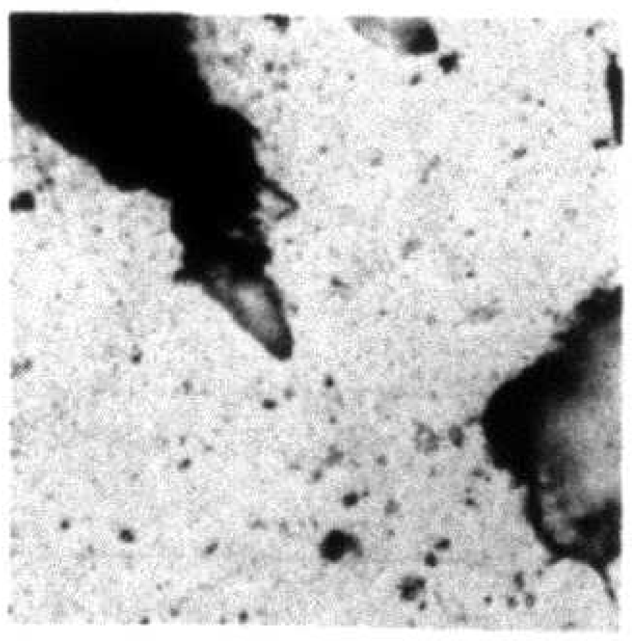


The central water jet bores a secondary pit into the floor of the original cavity.



The final step in this form of erosion occurs when pits intersect and sever the surface material between them as shown in these two micrographs of an aluminum sample after being subjected to a standard rainfall for 20 minutes at 500 mph. At left is a cross section of the sample enlarged 10 times. At right is a portion of the sample surface enlarged 700 times, illustrating tunnel pits and an intervening chunk of surface material.





droplet impingement, progresses by the continual deepening of discrete pits, leading to a characteristic honeycomb-like appearance, such as shown in Fig. 2.

The rate of material loss in erosion, due either to liquid impingement or to flow cavitation, depends on the fifth to sixth power of the relative velocity between the liquid and the eroding solid.[11, 12] No complete theory to explain this dependence has yet been advanced.

Mechanical and Corrosive Effects: As we mentioned earlier, some researchers attribute cavitation damage primarily to corrosion. However, cavitation tests of plastics in water and aluminum in toluene show that cavitation erosion takes place even in the absence of any probable chemical effects. Also, the mechanical effects of relatively intense cavitation and of liquid impingement, even in very hard and resistant materials, are well documented.

Cathodic protection that reduces cavitation erosion has sometimes been cited as evidence of a strong corrosive contribution. However, this protection may occur only when the current density is sufficient to generate hydrogen bubbles on the specimen, which provide a mechanical cushion against cavitation attack.[13] The presence of salts increases the erosion of materials which are susceptible to corrosion, and corrosion-inhibiting additives usually—but not always—reduce erosion. The effects of corrosion inhibitors and of dissolved gases are difficult to predict and depend on specific materials and conditions.[14]

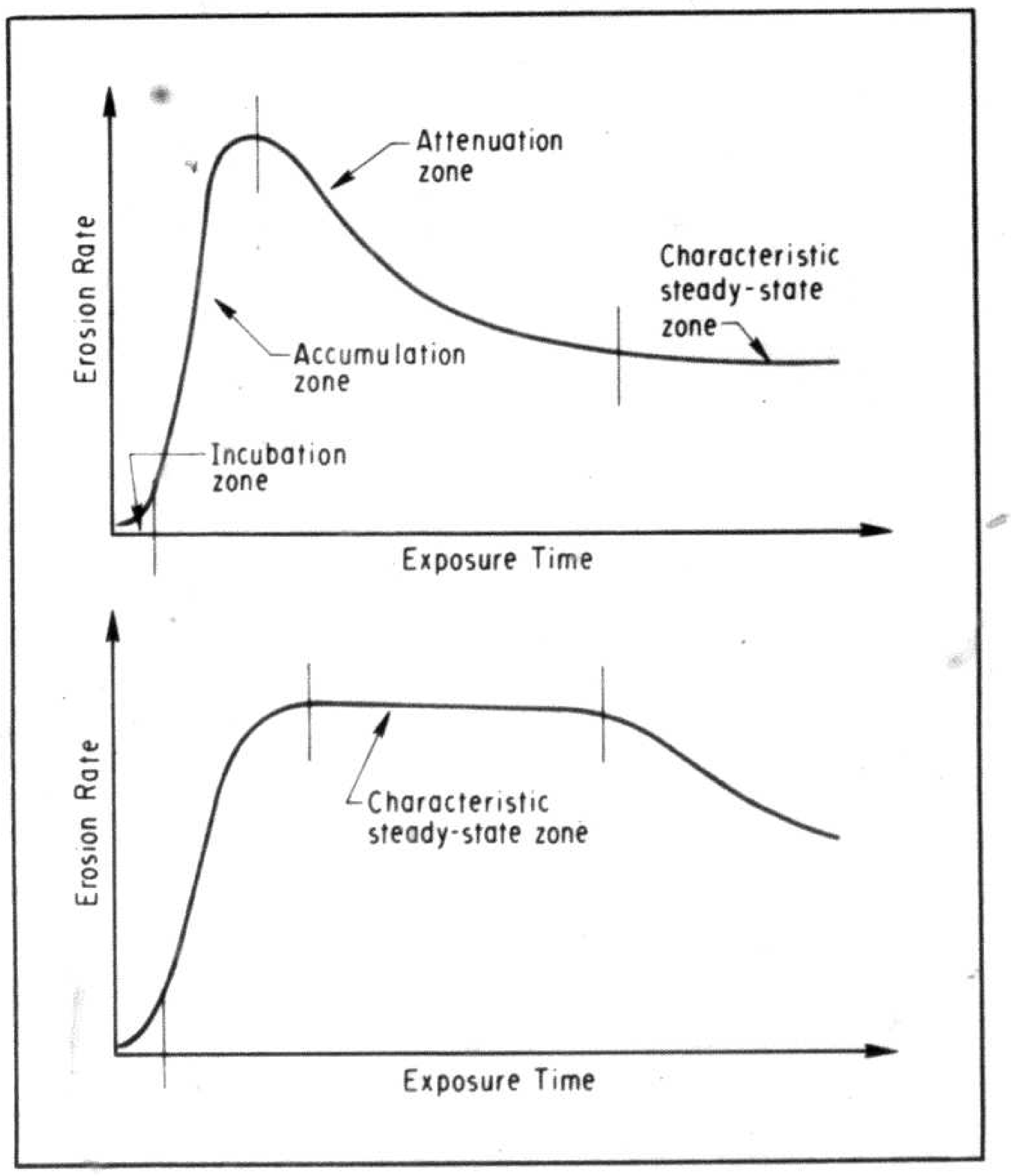


Fig. 3—Typical time-rate curves showing various erosion rate zones.

Thus it seems that the magnitude of the corrosive contribution to erosion depends upon both the severity of the hydrodynamic or mechanical attack, and upon the chemical compatibility of the material and the fluid concerned. Stress and corrosion effects can interact to produce failure when either environment by itself would have been harmless. Stress corrosion and corrosion fatigue are the most prominent examples of such so-called "conjoint actions," but many researchers place cavitation and liquid impingement in the same category. However, as the severity of mechanical action is increased, the relative effect of liquid corrosivity is decreased. This is consistent with the findings in corrosion fatigue, for which *S-N* curves converge to those of dry fatigue at high stress (low cycle values).

Erosion Testing

Liquid impingement erosion tests are generally performed with rotating-wheel or whirling-arm devices, in which specimens pass through liquid sprays or jets. The Air Force has also used rocket sleds to project a specimen carrier through a simulated rainfield.

Cavitation erosion tests are commonly performed by any one of three different methods:

- Vibratory method where a specimen immersed in a liquid is vibrated, usually by an ultrasonic transducer-and-horn assembly.
- The rotating-disc method where a disc is immersed and rotated in a liquid, and protrusions or holes in it cause cavitation and damage on specimens set in the disc.
- The cavitating-tunnel method where cavitation is caused by a constriction or obstruction in a confined flowing stream of liquid.

There are, however, no widely accepted standard test methods for erosion resistance, nor even a standard approach to interpreting and reporting test data. Thus, there is no clearly defined property called "erosion resistance," since a physical property can be defined only in terms of the method used to measure it.

Two peculiarities about cavitation and liquid-impingement erosion not only aggravate the difficulty in correlating different test results, but also make it unlikely that erosion resistance can be adequately defined in terms of one measurement.

First, different damage mechanisms become predominant as the severity of mechanical attack is varied, so that different intrinsic properties or combinations of properties may be involved depending on the erosion environment.

As previously discussed, at low hydrodynamic intensities the principal mechanism of destruction of the original material may be accelerated corrosion, and the primary role of the hydrodynamic impulses is to remove corrosion products and thus prevent the buildup of a protective layer. At higher intensities a fatigue-like process becomes predominant, sometimes aggravated by corrosive action as in corrosion fatigue. At even higher intensities, severe plastic deformation results from each impulse, which induces work hardening to the point where ductility is lost and further blows cause brittle fractures. Obviously these various regimes merge into one another and cannot be clearly distinguished, but, it is also obvious that a low-intensity test will not measure the same mix of material properties as a high-intensity test.

Second, the erosion rate under given conditions does not remain constant, so that no single value can completely describe the test results. Some assumption must then be made as to the most significant portion of the erosion-time curve in order to report the result in terms of one characteristic number.

This time effect has long been known; but only recently have its causes, and its implications for test data correlation and extrapolation been seriously examined.[15, 10, 16] The most characteristic erosion rate/time pattern starts with an initial or incubation period in which no significant material loss occurs. Then, erosion rate increases rapidly to a maximum value which may be a fleeting peak or may persist for some time as an approximately constant rate. From this maximum the erosion rate begins to decrease once more and, according to some experimenters, levels out to a final steady-state value (others suggest it continues to decrease). Sometimes fluctuations are superimposed on this overall pattern. Fig. 3 shows some typical patterns.

Erosion Resistance

Fairly consistent values of what might be called "normalized erosion resistance," Fig. 4, have been obtained despite the variety of test methods and the experimental and interpretive difficulties just outlined. Normalized erosion resistance is defined as the rate of volume loss of a standard reference material divided by the rate of volume loss of the material to be evaluated from the same test.

Note that the erosion resistance of engineering materials encompasses a range of some 2,000 to 1, far wider than conventional strength properties.

Investigators have tried to correlate erosion resistance with common material properties such as hardness, work hardenability, high strain energy to fracture, fine microstructure, and resistance to corrosion and corrosion fatigue.

No one property or combination of properties has yet been proposed which offers a satisfactory quantitative index of erosion resistance for a wide range of engineering materials or even for metals.

Hardness: Hardness has traditionally been considered a good index to erosion resistance and results for the same or similar materials usually show a fairly consistent increase of erosion resistance with about the second to third power of hardness. However, when curves for different materials or alloy types are superimposed, they do not coincide and a considerable amount of scatter ensues.[12]

A certain degree of work hardening (by pressing, rolling, or hammering) prior to exposure to erosion is beneficial but too much can be detrimental. Shot-peening has been found mildly beneficial in some cases, but has little effect in the long run because only a shallow surface layer is initially affected.

Apparently the pressure pulses experienced during erosion itself can strengthen some materials considerably: reports from the Soviet Union claim success with unstable austenitic chrome-manganese steels which develop a highly erosion-resistant martensitic structure on their surface as a result of impacts. Such an effect, of course, does not wear through.

Strain Energy and Ultimate Resilience: Several years ago strain energy (work to cause fracture in a tension test) of a material was suggested as a good index to its erosion resistance.[5, 17] However, recent studies have shown that strain energy

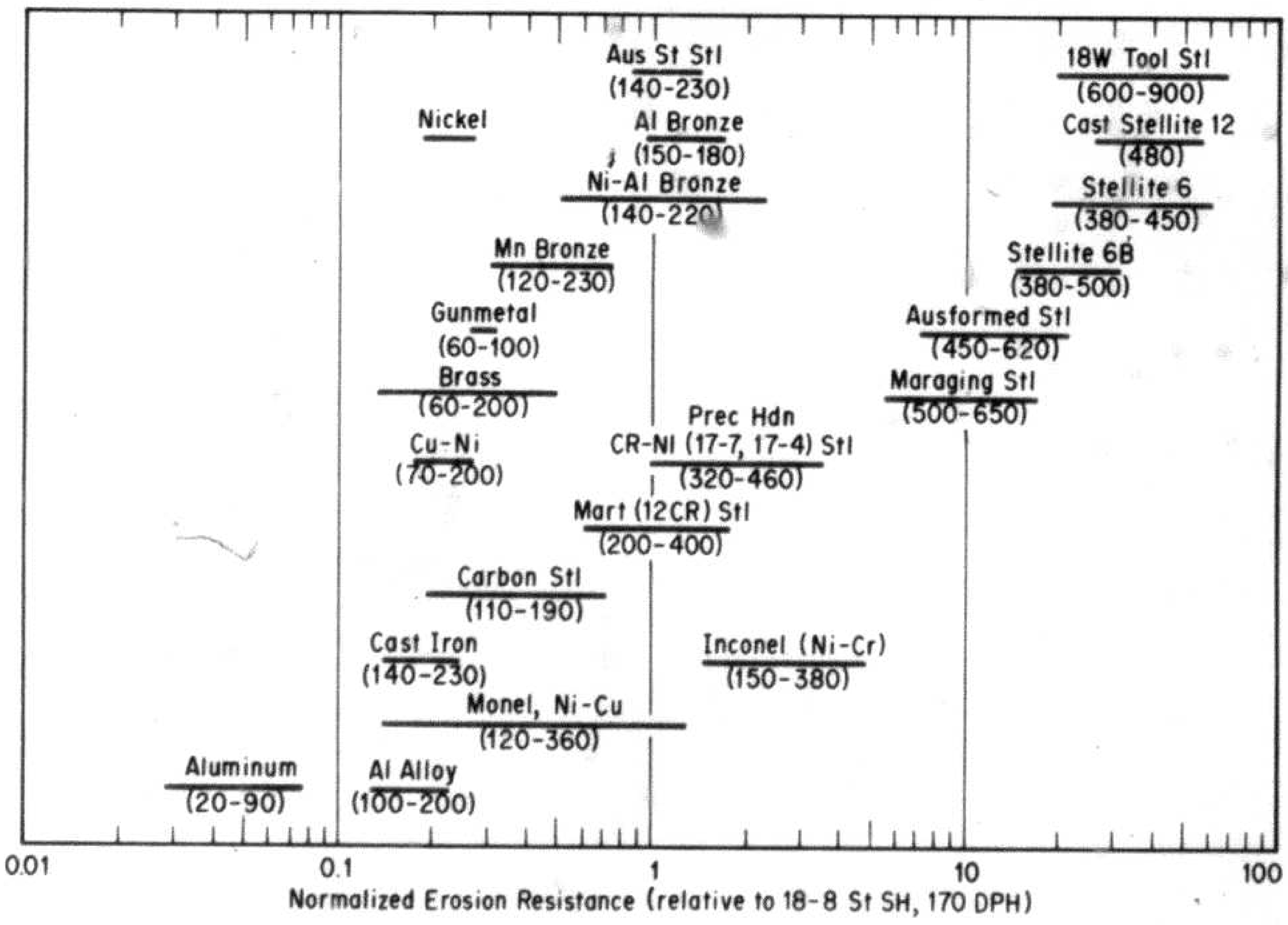
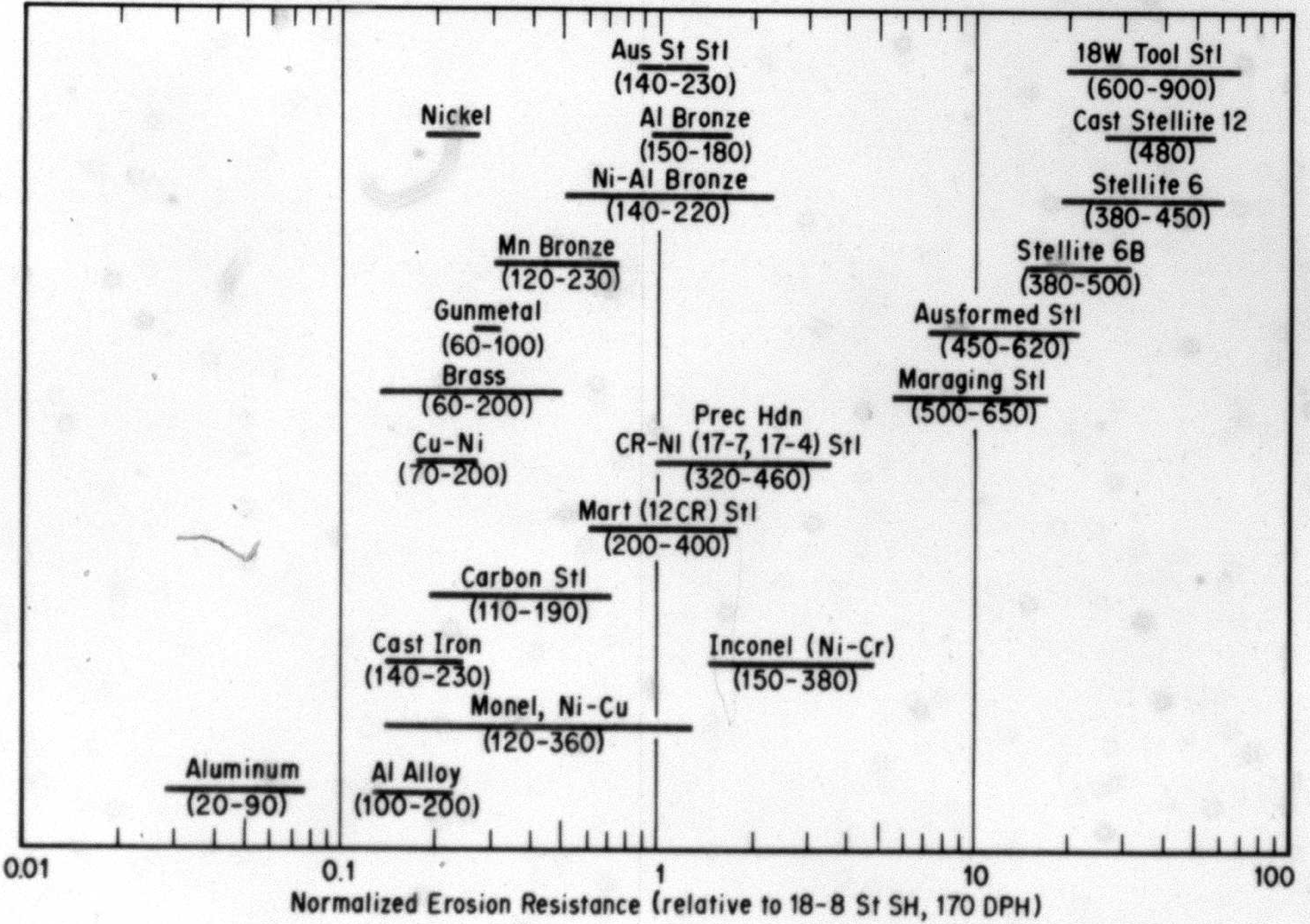


Fig. 4—Normalized erosion resistance relative to 18-8 stainless steel (170 DPH). Hardness of various materials (in parentheses) is in Brinell or Vickers hardness numbers.



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is, in fact, one of the poorest predictors of erosion resistance, when applied to a broad spectrum of materials and heat treatments.[18, 12, 19]

Another parameter of the energy type, called "ultimate resilience" has shown a trend toward linear correlation with erosion resistance.[19, 18, 12] Ultimate resilience is: $U_r = S_u^2/2E$, where S_u = ultimate tensile strength and E = modulus of elasticity.

Correlations With Fatigue Properties: Since erosion may be caused by fatigue-like failures (at least for a wide range of attack severities), some comparison between fatigue and erosion is possible, particularly for impingement erosion where a more accurate estimate of impact stresses can be made than for cavitation erosion.

Analogies and comparisons have been suggested between a "threshold impact velocity," below which no erosion occurs, and the endurance limit below which no fatigue failure occurs. Direct correlations have not been achieved, however.

Microstructure and Grain Size: Most experimental investigations into the effect of grain size have found that decreasing the grain size improves erosion resistance.

It has also been found that materials containing finely dispersed small and hard particles, in a more elastic and ductile matrix, are resistant to erosion. This accounts, at least partially, for the excellent erosion resistance of stellites, which cannot be explained on the basis of hardness or other independent bulk properties. However, very recent studies at the General Electric Co. have concluded that stellite owes its exceptional erosion resistance to crystallographic transformations induced by the impacts.

In conclusion, it seems that, with our present state of knowledge, erosion resistance cannot be reliably predicted from independent properties but must be measured in erosion tests. The normalized-erosion resistance approach provides a convenient method for quantifying and correlating results from diverse test methods.

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Relation Between Corrosion and Erosion	8, 21, 34, 35, 36
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